### International Scientific-Technical and Production Journal



January 2005 #

Founders: E.O. Paton Electric Welding Institute of the NAS of Ukraine

Publisher: International Association «Welding»

#### Editor-in-Chief B.E.Paton

International Association «Welding»

#### Editorial board:

Yu.S.Borisov V.F.Grabin Yu.Ya.Gretskii A.Ya.Ishchenko B.V.Khitrovskaya V.F.Khorunov I.V.Krivtsun S.I.Kuchuk-Yatsenko Yu.N.Lankin V.K.Lebedev V.N.Lipodaev L.M.Lobanov V.I.Makhnenko A.A.Mazur V.F.Moshkin O.K.Nazarenko I.K.Pokhodnya I.A.Ryabtsev Yu.A.Sterenbogen N.M.Voropai K.A.Yushchenko V.N.Zamkov A.T.Zelnichenko

#### International editorial council:

D. von Hofe (Germany) Zhang Yanmin (China)	N.P.Alyoshin B.Braithwaite C.Boucher Guan Qiao U.Diltey P.Seyffarth A.S.Zubchenko T.Eagar K.Inoue N.I.Nikiforov B.E.Paton Ya.Pilarczyk	(Russia) (UK) (France) (China) (Germany) (Germany) (Russia) (USA) (Japan) (Russia) (Ukraine) (Poland)
V.K.Sheleg (Belarus)	B.E.Paton Ya.Pilarczyk D. von Hofe Zhang Yanmin V.K.Sheleg	(Ukraine) (Poland) (Germany) (China) (Belarus)

Promotion group: V.N.Lipodaev, V.I.Lokteva A.T.Zelnichenko (exec. director) *Translators:* S.A.Fomina, I.N.Kutianova, T.K.Vasilenko Editor N.A.Dmitrieva *Electron galley:* I.S.Batasheva, T.Yu.Snegiryova

#### Address:

Hodress:
E.O. Paton Electric Welding Institute, International Association «Welding»,
11, Bozhenko str., 03680, Kyiv, Ukraine Tel.: (38044) 287 67 57 Fax: (38044) 528 04 86
Employeetee kiew up E-mail: journal@paton.kiev.ua http://www.nas.gov.ua/pwj

> State Registration Certificate KV 4790 of 09.01.2001

#### Subscriptions:

\$460, 12 issues per year, postage and packaging included. Back issues available. All rights reserved. This publication and each of the articles contained herein are protected by copyright. Permission to reproduce material contained in this journal must be obtained in writing from the Publisher. Copies of individual articles may be obtained from the Publisher.

### CONTENTS

#### SCIENTIFIC AND TECHNICAL

Kuchuk-Yatsenko S.I., Shvets Yu.V., Dumchev E.A., Shvets V.I., Mikitin Ya.I., Taranenko S.D. and Nikitina N.N. Flash-butt welding of railway frogs with rail ends using an intermediate insert	2
Yushchenko K.A. and Derlomenko V.V. Analysis of modern views on weldability	5
Ishchenko A.Ya., Mashin V.S. and Pashulya M.P. Technological features of twin-arc consumable electrode pulsed welding of aluminium alloys	10
Savitsky A.M., Vasiliev V.G., Savitsky M.M. and Vashchenko V.N. Influence of the heating stage on structure formation of welded joints on hardening steels	15
Markashova L.I., Grigorenko G.M., Valevich M.I. and Petrov S.V. Features of the structure of surface metal layers in railway wheel treads after plasma treatment	18
Palamarchuk B.I., Pashchin N.A. and Manchenko A.N. Improvement of fatigue fracture resistance of sheet structures by the method of local pulse action	22
INDUSTRIAL	
Bernadsky V.N. and Makovetskaya O.K. Current status of welding fabrication in China	26
Nazarenko O.K. and Lokshin V.E. Dynamic characteristics of high-voltage power sources for electron beam welding	31
<b>Denikin E.I., Netesa Yu.D.</b> and <b>Netesa A.D.</b> Carbon dioxide gas heaters for mechanised arc welding	34
Zhadkevich A.M. Electric heat sources for brazing	40
Automated pipeline welding	46
BRIEF INFORMATION	

Kasatkin O.G.	Estimation of impact strength of low-alloy	
weld metal		50

## FLASH-BUTT WELDING OF RAILWAY FROGS WITH RAIL ENDS USING AN INTERMEDIATE INSERT

S.I. KUCHUK-YATSENKO<sup>1</sup>, Yu.V. SHVETS<sup>1</sup>, E.A. DUMCHEV<sup>1</sup>, V.I. SHVETS<sup>1</sup>,

Ya.I. MIKITIN<sup>2</sup>, S.D. TARANENKO<sup>3</sup> and N.N. NIKITINA<sup>3</sup>
 <sup>1</sup>E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
 <sup>2</sup>OJSC «Kakhovka Plant of Electric Welding Equipment», Kakhovka, Ukraine
 <sup>3</sup>OJSC «Dnepropetrovsk Railway Switch Manufacturing Plant», Dnepropetrovsk, Ukraine

Information is given about the technology of a pulsed flash-butt welding of railway frogs using inserts of austenitic steels. Technology provides extension of the frog life even without application of postweld heat treatment of joints.

**Keywords:** flash-butt welding, pulsed flashing, frog, rail end, austenitic insert, high-manganese steel, rail steel, core

One of the actual problems of increasing the service characteristics and reliability of track switches is the replacement of bolted joints by welded joints. The most promising method of increasing the life of a frog and adjacent rails consists in use of the flash-butt welding. Over the recent years the welded designs of the frogs find the more and more wide spreading throughout the world.

The development of the technology of welded frogs was started by company Vereinigte Osterreichische Eisen- und Stahlwerke Alpine Montan AG (Austria). In 1977--1990 this company carried out a complex of works on the development of the technology of the flash-butt welding of frogs with rail ends [1, 2].

The technology of manufacture of welded frogs, used by the company at the present stage, envisages the use of an austenitic insert, stabilized by niobium or titanium, having the following (approximate) chemical composition, %: up to 0.06C, 17.5Cr, 9.5Ni. At first, the rail steel is welded to the austenitic insert. Then, the joint is subjected to a diffusion annealing at 350–100 °C temperature for 2–5 h with air cooling. After heat treatment, the insert is welded with a cast manganese core with a subsequent air cooling.

The E.O. Paton Electric Welding Institute started the works for the development of technology of the flash-butt welding of high-manganese steel with rail steel using an insert from austenitic steel at the end of the 1980s. They resulted in the creation of the first welding machines K840 and K924, implemented at



Figure 1. Welding machine K924M

Novosibirsk and Murom railway switch manufacturing plants, and using the conditions of a pulsed flashing in welding of frogs.

The use of a pulsed flashing [3, 4] made it possible to provide an optimum heating of the rail and austenitic steels, greatly differing by their thermophysical properties and, as a consequence, their uniform deformation in upsetting.

Investigations, carried out at the E.O. Paton Electric Welding Institute, showed that the satisfactory properties of welded joints can be produced without an auxiliary heat treatment. During the metallographic investigations of welds without heat treatment it was established that there are no dangerous structures in the HAZ of the welded joint of manganese steel and austenitic insert, and that in welds of austenitic insert with rail steel the formation of sources of martensitic inclusions can be reduced to minimum sizes, not influencing the load-carrying ability of welded joint, by selection of welding conditions.

On the basis of the experience of an industrial service of the first model of the welding machine K924, the designs of its mechanical part and hydraulic drive were somewhat updated. In particular, the rigidity of clamping bodies was improved and quickresponse of the flashing drive was increased.

A specialized welding machine K924M for welding of frogs represents a machine of a console type with a lateral loading (Figure 1).

#### Technical characteristic of the machine K924M

Capacity (at 50 % duty cycle), kV·A	180
Maximum upsetting force, kN	1500
Maximum clamping force, kN	4000
Maximum rate of upsetting, mm/s	200
Rate of flashing, mm/s	0.2-8.0
Horizontal alignment of ends of parts being	
welded in as-clamped state, mm	± 10
Vertical alignment of ends of parts being	
welded in as-clamped state, mm	± 10
Maximum section being welded, mm <sup>2</sup>	. 15000
Mass of welding machine, kg	. 42000

It was manufactured at OJSC «Kakhovka Plant of Electric Welding Equipment» and implemented at OJSC «Dnepropetrovsk Railway Switch Manufacturing Plant» (DSZ) in 2002.

© S.I. KUCHUK-YATSENKO, Yu.V. SHVETS, E.A. DUMCHEV, V.I. SHVETS, Ya.I. MIKITIN, S.D. TARANENKO and N.N. NIKITINA, 2005



Figure 2. Distribution of hardness in welded joint made using insert; L ---- area of measurement

Technology of welding of frogs was developed in the process of shop trials of the machine using rail steel M76, manganese steel of 110G13L type. Austenitic steels of 12Kh18N9, 12Kh18N10, 12Kh18N9T, 12Kh18N10T type with a limiting content of carbon up to 0.08 % produced in CIS countries were used for the insert.

Before welding of an experimental batch of railway frogs at DSZ, the check welding of specimens of rails of R65 type with a manganese rail using an austenitic insert was made.

The duration of the process of welding of the first and second welds was 90--110 s, tolerance for welding was  $(30 \pm 1.5)$  mm, width of insert in welded joint was 18--20 mm.

Mechanical tests for static bending were made in hydraulic press MPS-300 (distance between supports was 1000 mm) using a punch of 80 mm diameter at 0.1 mm/s rate of loading. Experimental batch of specimens in the amount of 10 pieces was subjected to tests. Fracture force was  $(98-.154)\cdot10^4$  N, mean value ---- 124·10<sup>4</sup> N. Sagging was 2-40 mm, mean value ---- 22 mm. The above-mentioned parameters are in compliance with requirements specified to welded frogs [5].

To evaluate the resistance of weld metal to the formation of transverse fatigue cracks, two specimens were tested for a cyclic strength at a frequency of alternative loading 5 Hz, coefficient of asymmetry of cycle by sagging ---- 0.1, sagging range ---- 1.5 mm. Specimens withstood 2 mln cycles of loading without formation of fatigue cracks.

Figure 2 shows the distribution of Brinell hardness in welded joint made using insert, a ball of 10 mm diameter was used in measurements.

From the results of the metallographic analysis, the following regions were distinguished in the structure of welded joint:



Figure 3. Microstructure of HAZ of manganese steel (region of carbide formation) ( $\times 200$ )



Figure 4. Microstructure of HAZ of insert of austenitic steel 12Kh18N10T ( $\times 200)$ 

• HAZ of manganese steel;

• HAZ of insert of austenitic steel;

• HAZ of rail steel;

• high-manganese steel--austenitic insert transition zone;

• rail steel--austenitic insert transition zone.

High-manganese steel in HAZ is remained austenitic. Changes in microstructure of HAZ are started with precipitation of carbides along the grain boundaries. With increase in temperature this process is intensified: carbide network becomes wider, the acicular carbides are appeared in the grain volume (Figure 3).

At the higher temperatures the carbide formation is delayed and the austenitic grains formed in the process of a selective recrystallization are observed in a near-contact layer of the high-manganese steel.

This is correlated with literature data about transformations in austenitic high-manganese steels [6]: formation of carbide (Fe, Mn)<sub>3</sub>C is proceeding within the 250--800 °C temperature interval. At the higher temperatures the carbides are dissolved in matrix. This process is most intensive at 500--600 °C.

Metallographic examinations of the austenitic insert showed that its middle part of about 10 mm width has a polyhedral structure with elongated along rolling inclusions of  $\delta$ -ferrite located along the boundaries of austenitic grains.

In the near-contact region of insert metal of about 7 mm width the phase transformations are proceeding at the boundary both of rail and also high-manganese



**Figure 5.** Microstructure of HAZ of rail steel near contact boundary (×500)



SCIENTIFIC AND TECHNICAL



Figure 6. Microstructure of transition zone at the boundary of high-manganese steel with austenitic insert (×200)



Figure 7. Microstructure of transition zone at the boundary of rail steel with austenitic insert (×200)

steels. Firstly the process of  $\delta$ -ferrite decay is proceeding. With approaching to butt the decay of  $\delta$ -ferrite is intensified, the process of phase recrysiallization with the formation of a ferritic-austenitic structure is started (Figure 4). The forming structures do not decrease the values of strength characteristics of the joints.

Rail steel in HAZ, as in a homogeneous joint, preserves a sorbite-like structure. In a near-contact layer the laminar sorbite is transformed into grained sorbite. The size of grains is increased (Figure 5).

The transition zones at contact boundaries of Cr--Ni steel with rail and high-manganese steel are formed as a result of fusion of edges of parts being welded and subsequent stirring in upsetting and melt extrusion into a flash. In this case the structural constituents of intermediate chemical composition are formed. The austenitic steel of insert-high-manganese steel transition zone has a stable austenitic structure (Figure 6).

In the rail steel--austenitic insert transition zone (Figure 7) the instable austenitic structures are formed, in which the martensitic transformation is possible in cooling.

Examination of hardness of structure constituents of the transition zone showed that at the regions with an acicular phase the microhardness was HV0.5--5490 MPa. These values of microhardness are typical of martensite. Regions with an acicular structure have a local nature and cannot have a great influence on design strength of the joint.

Joints in tests are fractured in case of exceeding of parameters, indicated in technical specifications [5], in transition zone of rail steel--insert from the side of the rail steel at 2--3 mm from the joint line.



Figure 8. General view of cores with welded-on rail ends Dn 040 (a) and Dn 210 (b)

By the task of «Ukrzaliznytsa» the DSZ the designs of welded frogs with welded-on rail end Dn 040 and Dn 210 and technology of their manufacture were developed. The experimental specimens of welded frogs were manufactured and subjected to field tests in the Institute for Rail Transport tack experimental (Russia). After passing a definite tonnage, established by standards, of a rolling stock on welded frogs, the fatigue fractures in welded joints were not revealed. Figure 8 shows the general view of cores with weldedon rail end Dn 040 and Dn 210.

#### CONCLUSIONS

1. The developed technology of welding and machine K924M make it possible to produce joints corresponding to the requirements of technical specifications, without application of auxiliary heat treatment.

2. Critical structural constituents (from the point of view of strength) were not observed in HAZ of steels being joined.

3. Structural constituents with a lowered ductility, representing separate isolated inclusions, were observed in transition zones of the welded joints. Therefore, the joints have a sufficiently high design strength and serviceability.

- Genkin, I.Z., Kuchuk-Yatsenko, S.I., Shur, E.A. et al. Method of flash-butt welding. USSR author's cert. 663278. Int. Cl. B 23 K 9/00. Publ. 06.09.90. 1.
- Blulsayir, I. Method of joining of switch parts of austenite high-manganese steel castings to rail of carbon steel. Europe appl. 91890157.0. Int. Cl. 0 467 881 A1. Publ. 22.01.92. 2.
- Kuchuk-Yatsenko, S.I., Krivenko, V.G., Bondaruk, A.V. et al. (2003) Flash-butt welding of rails. Experience of application and prospects for improvement. *The Paton Welding J.*, **12**, 27–33. 3.
- prospects for improvement. The Paton Weiding J., 12, 27–33. Kuchuk-Yatsenko, S.I., Didkovsky, O.V., Bogorsky, M.V. et al. Method of flash-butt welding. Pat. 46820 Ukraine. Int. Cl. B 23 K 11/04. Publ. 17.06.02. TU U DP 32-4520.13.500-007-2002. Frog and core with welded rail ends of type R65, R50 and UIC60 with insert and without it. Pilot run. Valid from 01.01.2003 to 01.01.2006. Gruzin, P.L., Grigorkin, V.I., Mural, V.V. et al. (1969) Transformations in austenitic manganese steel. Metal-lovedenie i Term. Obrab. Metallov, 1, 5–9.
- 6.



### ANALYSIS OF MODERN VIEWS ON WELDABILITY

**K.A. YUSHCHENKO** and **V.V. DERLOMENKO** E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Analysed are some international and national standards, as well as publications on definition and evaluation of weldability. The analysis conducted is summarised and key points are highlighted by an example of standards ISO 581–1980 and DSTU 3761.1--98. It is shown that the existing views on weldability (joinability) of materials do not correspond to modern approaches to making permanent joints and require revision.

**Keywords:** arc welding, weldability, standards, evaluation of weldbality, joinability, hard-to-weld materials, welding technology, service conditions

Modern engineering is characterised by increasingly wide application fields of welding and ranges of materials used for the fabrication of welded structures. This leads to utilisation of different welding (joining) methods, including fusion welding, solid-state joining and various brazing and soldering techniques. The joints are made to an increasing degree of the materials with special properties (metals, alloys, composites, polymers, metal-polymers, etc.). Proceeding from the existing notions of weldability, many of them are considered hard-to-weld or totally unweldable. Nevertheless, joining of such brittle materials as ceramics, glass, high-strength steels and alloys, cast irons or composites is a today's reality.

In this connection, such a characteristic of material as weldability is gaining in importance, especially if it can be controlled [1]. It is evident that the term «welding» is gradually more and more replaced by the term «joining» of materials. These are not just mere changes in terminology. They are of a conceptual character, implying a more general understanding of the process of making permanent joints in any materials, where the «weld» can be formed without the stage of fusion of materials and have no clearly defined sizes and attributes.

The existing notion of weldability (joinability) does not correspond to modern approaches to making permanent joints and requires revision. For this, it is necessary first of all to specify the meaning attached to the term «weldability». In the simplest interpretation, weldability is understood as fitness of a material for welding or ability to form a permanent joint. However, knowing that the possibility of making a permanent joint depends first of all upon the welding technology, this commonly accepted interpretation seems to be biased. Consider some of the definitions of weldability characterising the modern views of this term, and analyse a number of international and national standards, as well as some known publications on this matter.

*DIN 8528*: «Weldability of parts of a metallic material takes place if joining of materials is achieved by using a certain welding method and by keeping to

a certain technology. Herewith the welds should comply with the corresponding requirements for properties and influence on a structure a part of which they are». This standard deals only with metals, although other structural materials can also be welded. Joining of materials can be achieved by different welding methods and technologies. Accordingly, properties of the joints will be different. At the same time, all of them can meet requirements imposed on a joint. This interpretation does not account for this fact, i.e. weldability is evaluated on the qualitative principle (there is a joint/ there is no joint).

*TWI*, Great Britain: «A perfect weldability is the ability of material to be welded by any method and using no special measures to produce a joint with properties allowing a complete utilisation of the material». The boundary between a welding method and «special measures» is of a subjective character. The phrase «complete utilisation of the material» can also be treated differently, as no criteria are given. Weldability in this interpretation is not related to requirements a welded joint should meet. With this definition a large number of the materials may have or not have a perfect weldability. But, depending upon the welding method, there is a difference between them, i.e. again it is a qualitative evaluation of weldability.

Bratislava Institute of Welding, Slovakia: «Weldability is the ability of a material that enables welded joints with required properties to be produced by welding under certain technological conditions». This definition gives no clear indication to a specific welding technology, while the phrase «certain technological conditions» can be read differently. In this case again the weldability is a qualitative characteristic (there is a welded joint/ there is no welded joint).

GOST 2601--84: «Weldability is the property of metal or a combination of metals to form a welded joint by an established technology to meet requirements stipulated by design and service conditions of a product». This standard is 20 years old and covers only metals, although other materials can also be subjected to welding. The standard states without any substantiation that this characteristic is a property. At the same time, it gives no recommendations on how to determine or evaluate this property. Like in

<sup>©</sup> K.A. YUSHCHENKO and V.V. DERLOMENKO, 2005

#### SCIENTIFIC AND TECHNICAL

the previous standards, here the weldability is regarded as a qualitative characteristic.

Consider some definitions from a number of publications dedicated to weldability.

I. Hrivnak, one of the key specialists in the field, considers the issue of weldability as follows [2]: «Fitness of steel for welding is determined by the weldability tests. Not all the steels are fit for welding to the same extent. Some steels can be welded without any limitations, whereas in other cases it is necessary to use preheating, keep to heat input limitations or assign heat treatment of welded joints. Therefore, the property of steel we call «weldability» may be different. And different opinions exist concerning the definition of weldability. However, most of them are based on the principle of «fitness for purpose». In all the weldability definitions it is emphasised that a welded joint made by using a standard technology should be continuous and have required properties. The requirement for continuity and, often, for useful properties also depends upon the type of a welded structure and complexity of configuration of a weldment, which can be expressed simplistically in terms of the rigidity intensity. Naturally, the problem of continuity and properties of a welded joint will be solved from the standpoint of the required safety of a welded structure. Therefore, the concept of weldability should include four interrelated and feedbacked factors: material factor, structural factor, required useful properties and, finally, required safety of a welded structure during its specified service life. However, the concept of weldability cannot be divided into technological and structural. Despite the above interpretations, which are commonly accepted and applied now, the main notion of weldability, moreover a perfect weldability, is still related to manual arc welding. Steel can be considered to have a perfect weldability if a welded joint equivalent in its properties to the base metal can be made by this method without any constraining factors».

The following weak points can be noted in the above interpretation by I. Hrivnak. Requirements can be made not only to the rigidity of a structure. The required safety of a welded structure and structural factor mean exactly «the required properties». Many steels will have a perfect weldability by this criterion, but still there is a difference between them. The perfect weldability depends not only upon the manual arc welding as a welding method, but also upon its technology. The author considers only metals.

I. Hrivnak and V.I. Makhnenko give the following interpretation of this notion in study [3]: «Weldability is a research area dealing with investigation of ways of imparting a welded joint an assigned set of physical-mechanical properties required for specific service conditions. The assigned set of physical-mechanical properties usually implies an appropriate structural state, mechanical properties of different zones in a joint and absence of discontinuities of the type of hot and cold cracks, which may have a substantial effect on performance of the welded joint. Herewith it is assumed that the discontinuities of the type of pores, lacks of fusion, etc. affect the quality of the welded joint and are the subject of investigation of the other research area called «formation of a welded joint».

It should be noted that discontinuities of the type of pores, lacks of fusion, etc. influence mechanical properties of the welded joint and, to a large degree, its performance, i.e. they also should be taken into account in evaluation of weldability.

A.E. Asnis [4] defines the weldability as follows: «Weldability of materials is regarded now as a collective notion characterised by fitness for welding and reliability of a welded joint. Fitness for welding depends primarily upon the properties of a material and corresponding welding consumables. As far as the reliability of a welded joint is concerned, the standard tensile, bend and impact toughness tests in use now fail to determine this parameter in full measure».

There are many different materials fit for welding, but it is difficult to distinguish them by weldability. Reliability of a welded joint depends upon the service conditions. So, the tests of the joints should be equivalent.

Ya. Yu. Shkriniar [5] is of the opinion that «fitness of steel for fabrication of welded structures can be defined as follows. The necessary but insufficient condition for service of a welded joint is that it should be continuous. It means that the sufficient condition is the presence of a combination of properties required for service. Based on this postulate, the issues associated with behaviour of steels in welding can be subdivided into two large groups: formation of cracks (a) and properties of welded joints (b)».

Sometimes certain discontinuities in a welded joint are permitted. It is necessary to allow for the requirements imposed on a welded joint as a whole, rather than on discontinuities as a particular attribute. Consideration is given only to steels, rather than to many structural materials that can be subjected to welding. Behaviour of steels in welding in terms of cracking depends greatly upon the joining technology, and not only upon the steel welded.

Analysis of the above standards and publications [6--16] allows a conclusion that no agreement exists as to interpretation of the notion of weldability. Let us highlight general, most important approaches to definition of this notion and consider their main drawbacks.

# 1. Metal is considered weldable if a welded joint has no cracks (discontinuities).

Authors' comment. Cracks (discontinuities) may be absent, but a welded joint may not meet service requirements as to other functional characteristics (e.g. corrosion resistance).

2. Ability of material to joining by different welding methods.

Authors' comment. This is a subjective characteristic that the larger the number of the welding



methods which can be used to make a joint, the better the weldability of a given material, as much depends upon the welding technology.

#### 3. Fitness for purpose.

Authors' comment. Material is considered weldable if a welded joint meets all requirements imposed on using a given welding technology. This is a qualitative evaluation. Many materials with a given welding technology or technologies using a given material can provide a welded joint with the required service properties, but different variants will give different results.

# 4. Ability of materials to be mutually diluted (joined) or to form a metallic bond.

Authors' comment. It is evaluated by chemical affinity of materials welded, and greatly depends upon the joining technology, and not only upon the physical properties of a material.

Summarise this analysis by an example of ISO 581--1980 and DSTU 3761.1--98 through emphasising the key points.

According to these documents «metallic material is considered to be susceptible to welding to an established extent with given processes and for given purposes when welding provides metal integrity by a corresponding technological process for welded parts to meet technical requirements as to their own qualities as well as to their influence on a structure they form».

Authors' comments.

• Here only metals are considered, despite the fact that welding of other materials (e.g. ceramics, plastics) has long been in use in industry;

• «...for given purposes...» and «...for welded parts to meet technical requirements». Indeed, a perfectly joined material will work perfectly well under conditions for which it was intended (e.g. general corrosion), i.e. have good weldability. If the conditions are changed, the same material in a welded joint may not work at all (e.g. under intensive local corrosion conditions), i.e. it will be evaluated as having unsatisfactory weldability;

• «...with given processes...» and «...by a corresponding technological process...». With the up-todate theoretical and practical development of welding the quality of a resulting welded joint (certain weldability level) depends first of all upon the selected welding process, method, approaches, conditions, etc., i.e. technology;

• «...to an established extent...». Providing that service requirements are met, one joint made by a certain technology will work for a specified time, while the other made by using optimised welding parameters will have a double life time. Therefore, the second joint has a better quality or higher «weldability to an established extent». These standards do not specify a method to be used to evaluate the extent of weldability (quantitative determination of weldability). Analyse variants of evaluation of weldability (joinability) suggested by different authors allowing for the above comments.

I. Hrivnak [2] suggests that weldability should be evaluated as follows: «In fact, most weldability tests are the crack resistance tests. In addition to the crack resistance tests, the most common weldability tests are the tests to embrittlement of the heat-affected zone caused by structural transformations».

The cracks and embrittlement of the heat-affected zone are by no means all the requirements a welded joint should meet. Evaluation on the principles of presence or absence of cracks, i.e. yes or no, is qualitative, and as such it does not allow evaluation of the result of the absence of cracks with the system of the material--technology--requirements variables.

A.E. Asnis [17] evaluates weldability as follows: «It is premised in evaluation of weldability of steels that a welded joint should have no macro and microcracks, lacks of fusion, pores, etc. As shown by experience, this criterion is insufficient. A welded joint should have such a combination of properties that would meet service requirements, i.e. performance. It is considered that one of the important criteria of weldability is a certain value of carbon equivalent. However, it does not always determine operational reliability of a structure. Performance is evaluated to an insufficiently full measure also by the other criteria that determine quality of the base metal. Depending upon the heat input, meta-stable structures having high hardness are formed in the near-weld zone, which may lead to formation of cracks in the heat-affected zone. The issue under consideration currently is that it is better to characterise a welded joint by hardness of the HAZ metal, which is undoubtedly correct. The definition of weldability does not allow a comprehensive evaluation of performance of a welded structure. It is necessary to evaluate reliability of a welded structure depending upon its type, loading, service conditions, etc., as well as its fabricability».

Note that hardness of the HAZ metal cannot characterise in full a joint in terms of weldability as an integrated quality of base material, requirements to a product and effect of the welding technology. Hardness of the HAZ metal may remain unchanged or insignificantly change in welding of a number of steels.

M.Kh. Shorshorov, T.A. Chernyshova and A.I. Krasovsky [8] consider evaluation of weldability as follows: «The larger the number of welding methods which can be applied to a given metal, the simpler their technology and the wider (for each method) the ranges of permissible welding parameters providing the desirable properties of a welded joint, the higher the weldability of this metal».

Applicability of welding methods to certain materials depends primarily upon the optimality of the selected welding parameters. The level of simplicity of a technology is a subjective notion.



SCIENTIFIC AND TECHNICAL

Principles of evaluation of weldability

Reference	Weldability (joinability) evaluation criterion	Weldability (joinability) evaluation parameters	Material evaluated	Author's comment
GOST 2601-84 Bratislava Institute of Welding [3, 10, 14]	Meeting requirements	Yes/No	Metal or combination of metals	Qualitative
DIN 8528 [6, 8]	Joining of metals is achieved	Yes/No	Parts of metallic material	Same
ISO 5811980 DSTU 3761.1-98	Metal integrity and meeting of requirements are achieved	«To an established extent»	Metallic material	Subjective. No criterion for evaluation of the extent of weldability is given
[2, 3, 19, 25]	Absence / presence of cracks	Yes/No	Metal	Semi-qualitative. Calculation using carbon equivalent is possible for some classes of materials
[3, 6, 9, 10, 14, 26 etc.]	Joining of metal is achieved	Points (excellent, good, satisfactory, poor)	Same	Subjective. Based on the authors' personal experience
[8, 11, 14, 27]	Specified values of properties are achieved	Extent of corre- spondence to properties	»	Quantitative, uncertain. Values of base metal or those dictated by service conditions are taken as the rated qualities

L.V. Verkhovenko and A.K. Tukin [10] suggest the following evaluation of weldability: «There are no absolutely unweldable steels, but some steels can be readily welded by all welding methods using no sophisticated technological measures and providing a high-quality welded joint, whereas the other steels, although being weldable by some welding methods, require the use of special, more complicated measures, often not entirely studied, the quality of welded joints being decreased in this case. Weldability can be preliminarily evaluated from chemical composition of steel. The generalised effect of chemical composition of base metal on weldability can be expressed in terms of carbon equivalent using the following empirical formula:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Si}{24} + \frac{Ni}{10} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14},$$

where C, Mn, Si, Ni, Cr, Mo and V are the contents of these elements in steel, %.

Total of ele- ments, % (Mn + Si + + Cr + Ni + + 4Mo)	I	Veldability at ca	arbon content,	%
	Good	Satisfactory	Limited	Poor
Up to 1	< 0.25	0.25-0.30	0.300.45	< 0.45
1–3	< 0.20	0.25-0.30	0.300.40	< 0.40
Above 3	< 0.18	0.18-0.28	0.280.38	< 0.38

If  $C_{eq} > 0.45$  %, welding should be performed with preheating to a temperature of 100–200 °C. In welding of metal of a small thickness, the value of  $C_{eq}$  can be increased to 0.55 %».

This interpretation of weldibility does not explain how to evaluate complexity of a technological process in practice. «Decreased quality» of a joint is a relative rather than absolute term. Therefore, this interpretation is not free of drawbacks. Weldability can be evaluated using carbon equivalent only for certain classes of metals. But properties of a welded joint depend not only upon the carbon equivalent, but also upon the method used to produce metal, as well as the welding technology.

V.F. Musiyachenko and L.I. Mikhoduj [18] suggest that weldability should be evaluated as follows: «Evaluation of weldability of high-strength steels is reduced to identification of optimal welding conditions, where the probability of formation of cracks in a welded joint is eliminated and metal of the near-weld zone retains required ductility, strength and cold resistance».

It can be objected here that the presence of a certain amount of cracks is permitted, and not only the above ductility, strength and cold resistance should be retained in the joint. The definition «optimal welding conditions» is also of a subjective character.

Principles of evaluation of weldability are generalised in the Table, allowing for the above analysis based on publications [14, 19--24].

#### CONCLUSIONS

1. No generally accepted definition of weldability (joinability) is available.

2. The absolute majority of regulatory documents give a subjective or qualitative definition of weldabil-





ity (joinability) based on the «weldable/ unweldable material» principle.

3. In the majority of cases no methodology and quantitative evaluation of weldability (joinability) is present, or they are of a limited application.

4. The term «weldability» finds a philosophical interpretation mainly for metallic materials, and does not cover such materials as ceramics, glass, high-strength steels and alloys, cast irons, metal-polymers, etc.

- Yushchenko, K.A. (2004) Weldability and advanced processes for materials welding. *The Paton Welding J.*, 9, 39–44.
   Hrivnak, I. (1984) *Weldability of steels*. Ed. by E.L. Makarov. Moscow: Mashinostroenie.
- Hrivnak, I., Makhnenko, V.I. (1983) Application of compu-tational methods for investigation of steel weldability. In: *Call. pap. of 2nd Symp. of CMEA on Application of Mathematical Methods for Investigation of Weldability*, Sozopol, Bulgaria, Oct. 3-5, 1983, Sofia: V.I. Lenin VMEI.
- (1976) Weldability of semi-killed steels. Ed. by A.E. Asnis. **Řiev: PWI**
- Shkriniar, Ya.Yu. (1970) Problems of weldability of steels produced by current methods. In: *Call. pap. of Int. Symp. devoted to 100th Anniversary of E.O. Paton on Scientific Problems of Welding and Special Electrometallurgy.* Part 1: Problems of weldability and technology of welding of metals. Kiev: Naukova Dumka. 5.
- Lashko, N.F., Lashko, S.V. (1963) Some problems of weld-ability of metals. Moscow: Mashgiz. 6.
- Modzhun, M., Zhiznyakov, S. (1991) Weldability of low-alloy high-strength steels. In: *Proc. of Seminar on Metal-lurgical Requirements of Manufacturers and Consumers to Weldability of Steel Structure*, Kiev, Sept. 16–20, 1991. 7. Kiev: PWI.
- Shorshorov, M.Kh., Chernyshova, T.A., Krasovsky, A.I. (1972) Weldability tests of metals. Moscow: Metallurgiya. Shorshorov, M.Kh. (1960) Weldability of metals. Moscow: 8.
- 9. Profizdat.
- Verkhovenko, L.B., Tukin, A.K. (1977) Reference book of a welder. Minsk: Vyshejshaya Shkola. 10.
- 11. Livshits, L.S., Khakimov, A.N. (1989) Metals science in welding and heat treatment of welded joints. Moscow: Mashinostroenie.

- 12. Makarov, E.L. (1981) Cold cracks in welding of alloyed steels. Moscow: Mashinostroenie.
- Shorshorov, M.Kh. (1965) Metals science in welding of steel and titanium alloys. Moscow: Nauka. 13.
- (1976) Reference book of a metal-worker. Ed. by A.G. Rakhshtadt, V.A. Brostrem. Moscow: Mashinostroenie. 14.
- Quian, M., Lippold, J.C. (2002) The effect of multiple postweld heat treatment cycles on the weldability of Wespalloy. Welding J., 11, 233–238.
- 16. Feng, Z., Zacharia, T., David, S.A. (1997) Thermal stress development in a nickel based superalloy during weldability test. *Ibid.*, **11**, 470-482.
- (1985) Weldability and technology of welding of structural 17.
- steels and cast irons. Ed. by A.E. Asnis. Kiev: PWI. Musiyachenko, V.F., Mikhoduj, L.I. (1987) Arc welding of high-strength alloyed steels. Moscow: Mashinostroenie. 18.
- Frantov, I., Kireeva, T., Nazarov, A. (1991) Complex simulation method for investigation of steel weldability and evaluation of HAZ properties. In: *Proc. of Seminar on Met*-19. allurgical Requirements of Manufacturers and Consumers to Weldability of Steel Structure, Kiev, Sept. 16--20, 1991. Kiev: PWI.
- 20. Yushchenko, K., Solokha, A., Kazennov, N. (1991) Highalloy stainless steels of ferritic class: weldability problems. Ibiď.
- Nakamura, H., Naiki, T., Okabayashi, H. (1969) Stress re-lief cracking in the HAZ. IIW Doc. IX-648-69 (X-531-21. **69**).
- 22. Krasovsky, A.I. (1959) Methods for testing structural steel to weldability used in the USSR and abroad. Moscow: VI-NITI SSSR.
- 23 Musiyachenko, V.F. (1983) Weldability and technology of welding of high-strength steels. Kiev: Naukova Dumka
- Dumov, S.I. (1987) Technology of electric fusion welding. Leningrad: Mashinostroenie. 24.
- 25. Hrivnak, I., Pilarczyk, J. (1983) Application of mathematical methods for investigation of cracking of welded joints. In: Call. pap. of 2nd Symp. of CMEA on Application of Mathematical Methods for Investigation of Weldability, Sozopol, Bulgaria, Oct. 3--5, 1983. Sofia: V.I. Lenin VMEI.
- Mikula, J. (2001) Analytyczne metody oceny spawalnosci stali. Krakow: Politechnika Krakowska. 26.
- 27. Musiyachenko, V.F., Zhdanov, S.L. (1987) Structure, mechanical properties and delayed fracture resistance of welded joints of high-strength steel VS-4. Avtomatich. Svarka, 12, 8-11.

## TECHNOLOGICAL FEATURES OF TWIN-ARC CONSUMABLE ELECTRODE PULSED WELDING OF ALUMINIUM ALLOYS

**A.Ya. ISHCHENKO, V.S. MASHIN** and **M.P. PASHULYA** E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Some peculiar features of a pulsed twin-arc consumable electrode welding of aluminium alloy AMg6 using two pulsed power sources with synergic control of process conditions and parameters of the welding torch ensuring feeding of isolated electrode wires are shown.

**Keywords:** single-arc welding, twin-arc pulsed welding, consumable electrodes, aluminium alloys, argon, welding conditions, geometric parameters of welds, defects

To manufacture structures from aluminium alloys, the arc welding with consumable electrode in inert gases (MIG method) is widely used, at which, unlike the welding with non-consumable tungsten electrode, the higher efficiency of the process, decrease in HAZ and reduction in residual deformations of the products, made from thin sheet metal, are guaranteed [1, 2]. Using MIG welding, the multilayer welds into narrow groove of butt joint edges are performed. Economic characteristics of the process are improved with increase in thickness of metal being welded.

To improve the coefficient of deposition, to increase the welding speed and to reduce the angular deformations of products in MIG welding, the twinarc welding with a «split» electrode at a common current supply and with one or two power sources are used [2, 3]. However, in this case the short circuits between one of electrode wires and a pool are occurred and also the arc burning at the second wire is interrupted. High density of current at the first electrode leads to the break in a bridge, causing the increased spattering of metal, instability of the welding process and significant variation in the arc length [2, 4].

To eliminate these drawbacks, the Fronius company has developed the highly-efficient method of twinarc welding with consumable electrodes (TimeTwin method), used in mechanized and robotic processes [4--6]. Using this method, two pulsed power sources with synergic control of melting and electrode metal transfer, device for synchronizing their operation, as well as a torch for feeding two wires, isolated from each other, are used.

In the pulsed power sources of Fronius company the programmed control of the welding process includes a manual correction of welding conditions by changing constituents of a pulsed current (frequency, amplitude and duration of pulses) in the narrow range. Therefore, when welding with two arcs the current pulses can simultaneously enter the electrodes, thus causing the abrupt change in arc length, increased spattering of metal and instability of the weld formation. These negative phenomena in TimeTwin method are eliminated by adding of a synchronizing device into electric circuit, i.e. a link between two supply sources, which records the electric parameters of the arcs and defines the time of pulses feeding to each electrode. Parameters of current pulses have the same values and «shifted» by time  $\tau_{sh}$  for a half of period *t* of their following. This method, as compared with conventional method, increases greatly the amount of deposited metal, increases the welding speed, provides a low spattering of metal, smooth surface of welds and their smooth transitions to the parent metal.

It should be noted that the published materials, referring to TimeTwin method, have an advertising nature and give no recommendations on conditions of welding of aluminium alloys of different systems of alloying, types of joints and thicknesses.

The aim of the present work is to investigate the technological features of the method of twin-arc welding of aluminium alloys with use of two pulsed supply sources and a torch for feeding of two electrode wires, isolated one from another. One of the trends in investigations consisted in determination of rational types and thickness of joints, for which this process of welding can be used.

**Procedure of investigations.** For investigations the sheets from aluminium alloy of AMg6 grade of 8 mm thickness (GOST 4784--74) and electrode wire Sv-AMg6 of 1.2 mm diameter (GOST 7871--75) were used. Argon of a high grade (GOST 10157--79) was used as a shielding gas. Preparation of parent and filler metals was made by chemical etching in alkali solutions and nitric acid using a generally-accepted procedure [7]. Before welding, the parent metal surface being deposited was cleaned by a scraper for the depth of not less than 0.05 mm.

Automated single- and twin-arc welding with consumable electrode was performed from the pulsed supply sources Fronius TPS-2700 (for the first electrode in the direction of welding) and Fronius TPS-450 (for the second electrode) (Figure 1). Power sources pro-

© A.Ya. ISHCHENKO, V.S. MASHIN and M.P. PASHULYA, 2005



vided the synergic control of the electrode metal drop transfer using a principle: one pulse--one drop.

A torch, used for welding, was developed at the E.O. Paton Electric Welding Institute, the design of which made it possible to change the distance between two isolated electrodes, to use different inert gases for each arc and to perform welding with a stationary and pulsed arc at current from 20 up to 250 A at each electrode.

The nozzle of welding torch had an oval shape, 40 mm length, 22 mm width with 10 mm inner radii. Angle of inclination of the torch was 10--15°, distance between the torch nozzle and metal being welded was 8--12 mm. Distance between the electrode wires at the nozzle outlet was 13 mm, and 5--12 mm in the zone of electrodes melting.

Range of mean values of condition parameters of single- and twin-arc welding (for each electrode separately) corresponded to the following values:  $I_w = 20-250 \text{ A}$ ;  $U_a = 13-30 \text{ V}$ ;  $v_{w.f} = 120-780 \text{ m/h}$ ;  $v_w = 23 \text{ m/h}$ ;  $L_a = 4-8 \text{ mm}$ ;  $Q_{Ar} = 15 \text{ l/min}$ . Mean values of parameters of current pulses were as follows: amplitude of current pulses  $I_p = 380-520 \text{ A}$ ; frequency of pulses  $f_p = 45-175 \text{ Hz}$ ; duration of pulses  $\tau_p = 1-3 \text{ ms}$ . Size and shape of current pulses were recorded using a memory two-beam oscillograph S8-13. Parameters of pulses were set by microprocessors of supply sources depending on wire feed speed and arc voltage (arc length) in accordance with equations of synergic control of processes of melting and electrode metal transfer.

Comparative investigations of two processes of welding were performed at similar total power of arcs (total welding current) or welding currents at each electrode. The heat input of welding conditions was calculated by formula  $q = 0.72I_wU_a/v_w$ , kJ/cm. Total values of welding current  $I_{\Sigma}$ , volume of electrode metal entered the pool  $V_{\Sigma}$ , and heat input  $q_{\Sigma}$  at twinarc welding were determined from the sum of the characteristics obtained at the first and second electrodes. Geometric parameters of welds (depth of metal penetration  $h_{weld}$ , width of welds  $b_{weld}$  and height of their convexity  $h_{con}$ ) were measured using transverse and longitudinal macrosections with an error +0.05 mm.

**Results of investigations.** It was established that to form a common welding pool the optimum distance between electrode wires of 1.2 mm diameter in the zone of arc burning should be 8--10 mm. With increase in distance between the electrodes of more than 10 mm at high welding speeds and low welding current the common pool can be divided into two separate pools. In this case the process is a variety of multi-pass welding with a preliminary or concurrent heating of metal.

With decrease in distance between the edges of wires of less than 6 mm and increase in welding currents, a significant effect of heat power of one arc on another was observed. Therefore, at unchanged speeds of wire feed the shapes of external volt-ampere characteristics of arcs in single-arc welding do not corre-



Figure 1. Scheme of process of twin-arc welding with consumable electrodes in inert gases

spond to shapes of external characteristics of arcs, burning in twin-arc welding.

In case of similar sum of welding currents both in conventional and also in twin-arc method the volume of electrode metal entered the weld pool, and also heat input of two mentioned processes correspond to the same values (Figure 2). At similar total power of arcs and application of the same diameters of wires the twin-arc method of welding, as compared with single-arc method, does not give the increase in coefficient of deposition and does not, respectively, provide the increase in the efficiency of the welding process.

Figure 3 shows the effect of current value at the first electrode in twin-arc welding on the electric pa-



**Figure 2.** Effect of total welding current  $I_{\Sigma}$  in single- and twin-arc welding on volume of electrode metal entered the weld pool  $V_{\Sigma}$  (a) and value of heat input  $q_{\Sigma}$  (b)



**Figure 3.** Effect of welding current at the first electrode  $I_1$  in twin-arc welding on current  $I_2$  (a) and arc voltage  $U_2$  (b) at the second electrode at different feeding speed of the second wire: 3 (1); 4.1 (2); 6.3 (3) m/min



**Figure 4.** Effect of welding current in single- and twin-arc welding on width of welds  $b_{weld}$  (*a*), depth of metal penetration  $h_{weld}$  (*b*) and height of convexity of welds  $h_{con}$  (*c*):  $\bigcirc$  — single-arc welding at I = 100 A;  $v_{w.f} = 6.3$  m/min; q = 2.6 kJ/cm;  $\bigcirc$  — twin-arc welding at  $I_{\Sigma} = 200$  A;  $v_{w.f} = 12.5$  m/min; q = 5.2 kJ/cm

Th

rameters of arc of the second electrode. With increase in welding current at the first electrode from 50 up to 200 A (at 7--8 mm distance wire edges) the current at the second electrode is decreased by 5--10 A and arc voltage is increased by 2--4 V. The more powerful arc pre-melts the edge of the second wire and promotes the increase in arc length on it. The lower wire feed speed at the second electrode or the distance between electrodes, the larger manifestation of this relation. The growth in voltage (arc length) at the less powerful electrode is interrupted at appearance of equilibrium between heat energy supplied to electrodes and melting rate of wires.

Dependence of geometric parameters of welds on values of welding currents in single- and twin-arc welding is given in Figures 4-6. It is seen from Figures that at similar welding currents the twin-arc welding at each of electrodes, as compared with a single-arc welding, allows increase in the depth and width of metal melting, and also in the convexity of welds (Figure 4). At similar total power of arcs (total value of welding currents) the rising-falling relationships with local extremes in the region of maximum welding currents at a single-arc welding  $(I_1 = 200 \text{ A})$ or  $I_2 = 200$  A) and also in the region of similar welding currents at each electrode ( $I_1 = I_2 = 100$  A) in twin-arc welding are observed. Thus, in welding at mean currents 200 A with an increase in current at the second electrode from zero up to 100 A and current decrease at the first electrode from 200 down to 100 A the width of welds and depth of metal penetration are decreased (Figures 4, 5). Minimum depth of penetration and width of welds are set at equal welding currents (power of arcs) at the first and second electrodes. With a further increase in current at the second electrode up to 200 A and current decrease at the first



Figure 5. Scheme of penetration of aluminium alloy AMg6 of 8 mm thickness in single- and twin-arc welding depending on welding current at each electrode

IRNAL

electrode to zero the geometric parameters of welds are increased to values obtained in welding by one arc using the first electrode.

Decrease in depth of metal penetration in two-arc welding ( $I_{\Sigma}$  = const) is associated, first of all, with decrease in total pressure of two arcs to the pool. In welding of aluminium alloys the pressure of arcs (depth of penetration) is proportional to the sum of squares of value of welding currents at each electrode and determined by formula

$$h_{\text{weld}} = K(I_{1\text{el}}^2 + I_{2\text{el}}^2),$$

where K is the coefficient, accounting for thermophysical properties of parent and electrode metal, welding speed, metal thickness, wire diameter, type of shielding gas and so on [9]. Therefore, in conventional single-arc welding the pressure of arcs to the pool is approximately 1.8--2 times higher than that in twin-arc welding. Thus, the single-arc welding with consumable electrode, as compared with twin-arc welding, at similar heat input, provides the more concentrated supply of the heat into metal being welded, increases the depth and width of penetration of joints and decreases the reinforcement of welds.

Decrease in total pressure of two arcs in welding of thin-sheet structures from aluminium alloys can refer to advantages of this process, as at any random changes in voltage at the output of supply sources or violation of wire feed speed the abrupt change in depth of metal penetration and formation of burn-outs in metal being welded do not occur.

The advantage of twin-arc welding into a common pool is also a feasibility of the more precise control of chemical composition of weld metal by using two standard welding wires of different systems of alloying. Thus, for example, it is rational to use simultaneously two wires of grades Sv-AK5 and Sv-1201 for welding and surfacing of high-alloy casting aluminium alloys, containing 4–8 % Si and 1–8 % Cu (alloys AL5, AK5M7, AK7M2).

Investigations showed that in replacement of conventional single-arc welding by twin-arc welding and preserving here the same depth of metal penetration it is necessary to increase the welding current at each electrode and to increase the total heat input of the welding process (see Figures 2 and 6). In this case, the heat input of the twin-arc welding in the range of welding currents from 200 up to 300 A is 1.7--1.9 times increased, and the volume of electrode metal entered the weld pool, is 1.5--1.7 times increased. This leads to the increase in width of welds by 3--4 mm and in height of their convexity ---- by 0.7--1.0 mm (see Figure 6).

It should be noted that to increase the efficiency of the single-arc process and to reduce the distortions of products made from thin-sheet aluminium alloys, it is recommended to perform welding at maximum possible welding currents and extremely high speeds of the process. There are limiting admissible currents for each diameter of electrode wires, exceeding of



**Figure 6.** Effect of welding current in single- and twin-arc welding on  $b_{weld}$  (a),  $h_{weld}$  (b) and  $h_{con}$  (c) at different feed speed of the second wire: 0 (1); 3 (2); 6.3 (3) m/min

which is accompanied by metal oxidation for all the depth of penetration and appearance of open and closed cavities in them. The twin-arc welding allows prevention of these phenomena and increase in efficiency of the process as a result of a negligible decrease in welding currents at each electrode by 50-60 A.

Thus, the twin-arc method of welding is rational to be used to prevent the occurrence of burn-outs of thin-sheet metal in automated single-pass welding of butt and lock joints, as well as in welding of T- and overlap joints when it is necessary to provide large legs of welds and where the deep metal penetration is not required.

It should be noted that at high rates of welding-on of stiffeners in T-joints the welding arcs can be shifted to one of edges being welded due to disturbances of any kinds and deteriorate their fusion. It is possible to provide the required sizes of the weld legs by shifting two arcs to each edge by rotation of the welding torch around its axis for 10--30° angle. To increase the efficiency of the process of multi-pass welding (surfacing) of aluminium alloys of mean thickness into V-shaped groove the rotation of welding torch around its axis can amount to 45--90°.

In other cases, for example, in multi-pass welding of massive metal with a narrow gap edge preparation, this method is not suitable because of a high heat input of the process, large convexity of welds and probability of appearance of non-fusions between the edges of metal welded and/or welds themselves.

#### CONCLUSIONS

1. Peculiar features of twin-arc welding with consumable electrode in inert gases using two pulsed supply sources with a synergic control and welding torch, providing the feeding of electrode wires, isolated one from another, are defined. It was established that with similar welding current at each electrode the twin-arc welding of aluminum alloys, as compared with conventional single-arc welding, allows increase the depth and width of penetration of metal and decrease the height of reinforcement of welds.

2. It is shown that at similar total power of arcs the single-arc welding, as compared with twin-arc welding, provides the more concentrated heat input into the parent metal, increases the depth and width of welds and decreases the height of their convexity. In replacement of the single-arc method of welding by twin-arc welding and preserving the same depth of metal penetration it is necessary to increase the welding current and to rise 1.7--1.9 times the total heat input of the process that promotes the growth in width of welds and height of their convexity.

3. It is shown that the twin-arc pulsed method of welding is rational to be used for prevention of burnouts of thin-sheet metal in automated single-pass welding of butt and lock joints, and also for fulfillment of T- and overlap joints when it is necessary to produce large legs of welds and the deep penetration of metal is not required.

- 1. Ishchenko, A.Ya., Lozovskaya, A.V., Poklyatsky, A.G. et al. (2002) Increase in strength of welds in arc welding of alloy 1420 using the Sc-containing fillers. The Paton Welding J., 1, 10-14.
- 2. Dilthey, U., Stein, L., Woeste, K. et al. (2003) Latest developments and trends in high-efficient welding technolo-gies. *Ibid.*, **10/11**, 146--152.
- Miyazaki, H., Miyauchi, H., Sugiyama, Y. et al. (1994) Puckering phenomenon and its prevention in GMA welding of aluminum alloys. *Welding Res.*, 12, 277–284.
   (2003) TIMETWIN high performance method of weld-ing. Avtomatich. Svarka, 4, 39–42.
- Lutz, W. (1999) Aluminiumschweissen fuer den schnellen ICE 3. Praktiker, 4, 138–142.
   Trommer, G. (2001) Schweissen von Aluminiumwerkstoffen im Schienenfahrzeugben. *Ibid.*, 4, 146–151.
   Derbing D.W. Jarking V.C. Derbinkelsen I.V. (1992)
- Rabkin, D.M., Ignatiev, V.G., Dovbishchenko, I.V. (1982) Arc welding of aluminium and its alloys. Moscow: Mashinostroenie.
- Voropaj, N.M., Ilyushenko, V.M., Lankin, Yu.N. (1999) Particularities of pulsed-arc welding with synergetic control of parameters. Avtomatich. Svarka, **6**, 26–32. 8.
- Ishchenko, A.Ya., Mashin, V.S., Dovbishchenko, I.V. et al. (1994) Mean temperature of pool metal in inert-gas arc welding of aluminium alloys. *Ibid.*, **11**, 15–19. 9.

## INFLUENCE OF THE HEATING STAGE ON STRUCTURE FORMATION OF WELDED JOINTS ON HARDENING STEELS

A.M. SAVITSKY, V.G. VASILIEV, M.M. SAVITSKY and V.N. VASHCHENKO E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Studies have proved that formation of structure of a welded joint on high-strength steels starts at the stage of its heating at temperatures above  $A_{c3}$ , while at the cooling stage this process ends in overcooled austenite transformation. The main factor determining the role of the heating stage in formation of metal structure is the rate of heating of the welded joint, which is responsible for temperature  $A_{c3}$ .

**Keywords:** arc welding, hardening steels, welded joints, structure formation, kinetics, thermal cycle, heating rate, cooling

In keeping with the traditional concepts, formation of welded joint structure is related to its cooling stage. However, investigation results [1, 2] suggest that formation of welded joint structure starts at the stage of their heating, and at the cooling stage this process is completed by transformation of overcooled austenite. As the welded joint structure is the main factor, determining their properties, studies in the field of structure formation kinetics are highly urgent and important.

The purpose of this study consisted in determination of the degree and mechanism of the influence of the heating stage of hardening steel welded joints in arc welding on the kinetics of their structure formation.

As in the traditional welding processes the conditions of welded joint heating are determined mainly by their heating rates, the features of their influence on the kinetics of structural transformations during heating and subsequent cooling of the joints were studied. Investigations were conducted on special samples of high-strength steel by simulation of thermal cycles of welding with different heating rates and a fixed cooling rate. The values of temperature of critical points  $A_{c_1}$  and  $A_{c_3}$  were determined during heating and cooling. Samples were heated at the rates of 500 to 3100 °C/s.

Results of these studies for steel 40KhN given in Figure 1, demonstrate the influence of heating rates on the values of temperature of the start and end of austenitizing at heating and austenite transformation at the stage of welded joint cooling. It is established that increase of the heating rate is accompanied by increase of temperatures  $A_{c_1}$  and  $A_{c_3}$ , as well as those of the start and end of overcooled austenite transformation at the cooling rate of 105 °C/s in the temperature range of 800--600 °C. For instance, at heating at the rate of 500 °C/s, austenite formation starts

approximately at 760 °C, and ends at 805 °C. Temperature range of austenitizing is 45 °C.

Transformation of overcooled austenite formed under these conditions proceeds in the temperature range of 210--110 °C, which is equal to 100 °C. In the case of heating at the rate of 1000 °C/s, austenitizing starts at the temperature of 850 and ends at 910 °C, and its temperature range is 60 °C. Under these conditions transformation of overcooled austenite starts at 235 °C and is over at 130 °C. Temperature range of the transformation is 105 °C.

If the heating rate is increased up to 2000 °C/s, this will lead to higher values of temperature of the start and end of austenitizing at 900 and 1015 °C, as well as widening of its temperature range up to 115 °C. Austenite transformation at the cooling stage will also shift into the region of higher temperature values. It will start at 255 °C and will end at 145 °C. Temperature range of transformation will be equal to 110 °C.



**Figure 1.** Influence of heating rates on temperatures of phase transformations in steel 40KhN: 1, 2 — temperatures of the start and end of austenitizing, respectively; 3, 5 — temperatures of the start and end of overcooled austenite transformation at  $v_0 = 85 \text{ °C/s}$  in the temperature range of 800–600 °C, respectively; 4, 6 — temperatures of the start and end of overcooled austenite transformation at  $v_0 = 105 \text{ °C/s}$  in the temperature range of 800–600 °C

<sup>©</sup> A.M. SAVITSKY, V.G. VASILIEV, M.M. SAVITSKY and V.N. VASHCHENKO, 2005

#### SCIENTIFIC AND TECHNICAL

If the heating rate is increased up to 3100 °C/s, austenitizing will shift into the range of temperature values close to 940 and 1070 °C. Temperature range of transformation will be equal to approximately 130 °C. In this case, austenite transformation at the cooling stage will start at 300 °C and end at 190 °C. Temperature range of transformation will approximately be 110 °C.

If at the above heating rates the cooling rate is slowed down and fixed at the level of 85 °C/s in the temperature range of 800 to 600 °C, it will only affect the values of temperature of the start and end of overcooled austenite transformation. For instance, at heating rate of 500 °C/s, values of temperature of the start and end of austenitizing will correspond to the previous case, and overcooled austenite transformation will shift to a higher temperature range of 250 to 150 °C. Temperature range of transformation will be equal to 100 °C.

Increase of the heating rate up to 1000 °C/s will raise the values of temperature of the start and end of overcooled austenite transformation to 280 and 175 °C, respectively. Temperature range of transformation will be equal to 105 °C. At heating at the rate of 2000 °C/s overcooled austenite transformation will proceed in the temperature range of 290–185 °C, which is equal to 105 °C. And in the case of increasing the heating rate up to 3100 °C/s overcooled austenite transformation 3100 °C/s overcooled austenite transformation will start at approximately 310–320 °C, and end at 220–230 °C. Temperature range of transformation will be approximately 100 °C.

In this case transformation of overcooled austenite will proceed at higher temperatures compared to the previous case. This corresponds to the known concepts of the influence of cooling rates on the structural transformation kinetics.

Error of the above calculation results is up to  $\pm 5$  %, because of approximately the same error of recording the above temperature values due to the features of the recording instrument (light-beam oscillograph H071.5M).

The above data enable evaluation of the influence of the stage of welded joint heating on structure formation in it. It is established that increase of the rates of welded joint heating enables increasing temperature  $A_{c_3}$  and reducing the temperature interval of austenite homogenizing. In this case, in view of the features of the welding process, duration of metal staying in this range is also shortened, thus promoting a lowering of the level of austenite homogenizing and increasing of the values of temperature of the start and end of its transformation at the cooling stage, and this, in its turn, reduces the probability of cracking and is favourable for welded joints properties.

Thus, the results of the conducted studies indicate that formation of the welded joint structure starts already at the heating stage at temperature values above  $A_{c_3}$ , where the level of austenite homogeneity and further kinetics of its transformation at the cooling stage are chiefly determined. The heating rate determines the values of temperature  $A_{c_3}$ , which is responsible for the width of the temperature range of austenite homogenizing. The higher the heating rate and temperature  $A_{c_3}$ , the narrower is the temperature range of austenite homogenizing.

As this range and duration of welded metal staying in it are shortened, the level of austenite homogenizing will drop. Lowering of the level of austenite homogeneity will lead to its transformation shifting to the region of higher temperature values. Therefore, adjustment of the conditions of welded joint heating enables implementing a purposeful impact on the kinetics of austenite transformation at the stage of the joint cooling.

Results of the conducted studies indicate that in welding of hardening steels it is necessary to try to increase the heating rates as this is favourable for the kinetics of formation of welded joint metal structure.

In [3] the calculation and experimental methods are used to demonstrate the possibilities of arc welding for increasing the heating rate (up to 3000 °C/s). However, as the heating rate depends on the welding heat input and rises with its decrease, such heating rates are achievable at heat inputs of about 6000-7000 J/cm. This is comparable with the coated-electrode welding at currents of up to 150 A at the speeds of 15 m/h and higher.

Use of such heat input values markedly lowers the welding efficiency and impairs the welded joint quality due to a high probability of lacks-of-fusion and lacks-of-penetration, and producing sound welded joints with the traditional arc welding processes at such low values of the heat input is highly problematic.

As follows from studies [4, 5] arc activation in tungsten electrode welding enables increasing the depth of penetration by 2 to 3 times without raising the welding current. Therefore, at the same penetration depth as in the traditional technique arc activation enables 2 to 3 times reduction of welding current, and, hence, of welding heat input. Thus, the sugges-

Influence of arc activation on welding heat input of 10 mm thick material

Thermal cycle number	Welding process	Factor of penetration depth increase	I, À	U, V	v <sub>w</sub> , m∕h	q∕v <sub>w</sub> , J∕cm
1	Without arc activation	1	550	4042	25	24964
2	With arc activation	1.82	400	34	40	9189
3	Same	22.5	300	30	30	8103
4	»	34	220	25	36	4400



**Figure 2.** Thermal cycles in the HAZ of welded joints: 1-4 — numbers of heat cycles acc. to the Table

tion of the possibility of solving the problem of combining the high welding efficiency and quality of welded joints at a simultaneous lowering of welding heat input using arc activation, is correct. It was confirmed in development of activators for consumable electrode welding. Results of these investigations given in the Table, indicate that single-pass welding of 10 mm thick metal without arc activation requires a heat input of 24964 J/cm. Consumable electrode welding in pure argon provides a minimum penetration depth, compared to all the processes of mechanized gas-shielded consumable electrode welding.

Application of the activator, providing a greater penetration depth by 1.8 to 2 times, enables welding metal 10 mm thick at the heat input of 9189 J/cm, which is 2.7 times less that in welding without activation.

In the case of activator application, providing 2 to 3 times increase of the penetration depth in argonarc welding, a heat input of 8103 J/cm is required for single-pass welding of the above thickness, which is 3 times less than in welding without arc activation.

Use of the activator providing a 3 to 4 times increase of the penetration depth allows decreasing the welding heat input to 4400 J/cm. This is 5.7 times less than in welding without arc activation.

Influence of arc activation on the conditions of the welded joint heating and cooling can be evaluated by the thermal cycles of welding for each of the considered cases. As decrease of welding heat input ensured by arc activation drastically reduces the HAZ and hinders experimental determination of the thermal cycle, it is rational to use calculation-analytical methods for this purpose [6]. In addition, these methods provide the same maximum temperature of the thermal cycle, which is practically unachievable under the experimental conditions. Therefore, in order to evaluate the influence of arc activation on the conditions of welded joint heating and cooling the thermal cycles of welding with the maximum temperature of 1380 °C were calculated, using a calculation procedure of a powerful fast moving linear heat source. Mode parameters determined experimentally were used as the initial data. Calculation results given in Figure 2 enable evaluation of the influence of activation on the thermal condition of the welded joint.

#### CONCLUSIONS

1. Formation of welded joint structure starts at the stage of its heating at temperatures above  $A_{c_3}$  which is where the level of austenite homogeneity and kinetics of its further transformations are mainly determined. This process is completed at the stage of cooling by overcooled austenite transformation.

2. Increase of the rate of welded joint heating is accompanied by rising of  $A_{c_3}$  temperature, narrowing of the temperature range of austenite homogenizing and lowering of the level of its homogeneity, which results in overcooled austenite transformation shifting to the region of higher temperature values.

3. As the heating rate depends on the welding heat input and rises as the heat input is decreased, it is rational to lower the heat input in order to improve the conditions for welded joint structure formation.

4. It is rational to lower the welding heat input under the conditions of activation of the arc, which is capable of providing the high efficiency and quality of welded joints with the simultaneous reduction of the heat input by 2.7 to 6.7 times.

- 1. Gridnev, V.N., Meshkov, Yu.Ya., Oshkaderov, S.P. et al. (1973) *Physical principles of electrothermal strengthening* of steel. Kiev: Naukova Dumka.
- 2. Shorshorov, M.Kh., Belov, V.V. (1972) Phase transformations and changes of steel properties in welding. Moscow: Nauka.
- Savitsky, A.M., Savitsky, M.M., Dudko, D.A. (2000) Effect of welding parameters on the rate of heating of the weld zone metal. *The Paton Welding J.*, 11, 22-25.
- Savitsky, M.M., Leskov, G.I. (1980) Mechanism of effect of electronegative elements on penetration capability of the arc with tungsten cathode. Avtomatich. Svarka, 9, 17–22.
- Savitsky, M.M., Melnichuk, G.M., Karida, V.L. et al. (1981) Application of activating flux in welding of position butts of pipelines in mounting of nuclear stations. *Ibid.*, **11**, 71–72.
- Rykalin, N.N., Pugin, A.I. (1959) Thermal processes in fusion welding. Moscow: Profizdat.

## FEATURES OF THE STRUCTURE OF SURFACE METAL LAYERS IN RAILWAY WHEEL TREADS AFTER PLASMA TREATMENT

L.I. MARKASHOVA<sup>1</sup>, G.M. GRIGORENKO<sup>1</sup>, M.L. VALEVICH<sup>1</sup> and S.V. PETROV<sup>2</sup> <sup>1</sup>E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine <sup>2</sup>Institute of Gas, NASU, Kiev, Ukraine

It is shown that adjustment of the temperature-rate modes of wheel heating and cooling in the range of working parameters of plasma equipment enables variation of the structural-phase condition of the surface, thus allowing microstructure optimization and providing high values of mechanical properties.

**Keywords:** plasma surface treatment, finely-dispersed structure, phase distribution, scanning and transmission microscopy, fractography, troostosorbite, martensite, microcracks, dislocation density, internal stress gradients

Cases of catastrophic failure of wheel flanges and side surfaces of rails are observed in the railways under unfavourable changes of operating conditions. However, the causes for this phenomenon have not been finally determined, as the problem of side wear is related to uncontrollable change of a whole number of external, in particular, operational factors, namely parameters of the track and rolling stock (track condition) [1--4], as well as structural parameters of the material under load.

There exists a whole list of methods of eliminating the greater wear of the wheels, as well as rails. First of all, stabilization and lowering of wear intensity can be achieved by lowering the side pressure proper in the zone of contact of the wheel--rail pair by design measures, as well as a result of lowering the friction coefficient of the mated pair by applying the appropriate lubrication materials, as friction is the main reason for marked wear of the wheels and rails, and in a number of cases also derailment of carriages.

Comparison of diverse methods of increasing the resistance to wheel and rail wear by their hardening showed that the flanges hardened by high-frequency currents, laser or plasma, have similar structure and properties. Laser technologies have not become widely accepted so far, because of the high cost and complexity of the used equipment. Plasma hardening along two paths and electric-arc hardening, as a rule, promote pronounced wear of the mated body [5]. The best results have so far been demonstrated by the methods of magneto-plasma and plasma-flame hardening. However, plasma surface hardening offers an advantage, as it yields a hard surface layer of a specified depth and width, providing a high resistance of hardened treads in service. In addition, the structure of the surface layer metal formed during treatment has a decisive role on the strength, fatigue life and

reliability of the wheels as a whole in case of a favourable pattern of residual stresses [6].

After manufacture the locomotive wheel tires preserve a high level of triaxial tensile stresses with components reaching the yield point of the tire material (axial stresses of 461, hoop stresses of 1030 MPa). In the region of transition from the roll surface to the flange, exhaustion of material ductility and a high stress gradient are observed [5].

The main aspect of the problem of the rationality of applying plasma surface hardening of the working surface of the wheel pair flange is increase of operating reliability and life of the wheel without any deterioration of the interaction of wheel--rail pair. Plasma treatment leads to redistribution of the residual stress fields, change of the material structure and its hardness. In one case (with an accurate following of the technology) such a tretment promotes recovery of the material with improvement of all the mechanical characteristics, in an other case (at technology violations) it leads to property degradation and even fracture of the treads.

Practical work shows that the metal structure has a special influence on the strength, fatigue life and reliability of the hardened parts. It should be emphasized that formation of a particular kind of the structure at plasma treatment depends, on the one hand, on the technology (rate of part heating, cooling, temperature of heating for hardening), and on the other hand ---- on the metal condition (steel composition, determining the features of overcooled austenite transformation, presence of inhomogeneities, etc.).

Treads of steel 60 to GOST 398--81 (composition, wt.%: 0.57--0.65C; 0.20--0.42Si; 0.60--0.90Mn; not more than 0.035P; not more than 0.94S) were studied, which operate in the freight and yard locomotives.

The range of the studied modes of plasma treatment was as follows: plasmatron arc current of 150--220 A, arc voltage of 170--230 V, plasma mixture flow rate of 4--10 nm<sup>3</sup>/h, content of methane in a mixture with air of 7 to 15 %, linear velocity of wheel rotation

<sup>©</sup> L.I. MARKASHOVA, G.M. GRIGORENKO, M.L. VALEVICH and S.V. PETROV, 2005



**Figure 1.** Schematic of cutting out samples for investigations by the methods of transmission electron microscopy (TEM), scanning (SCAN) and optical microscopy

of 8 to 20 mm/s, maximum surface temperature of 800 to 1450  $^{\circ}$ C.

Experimental information on the features of the change in the structural-phase condition of the wheel tread metal at hardening plasma treatment was obtained from a comprehensive study, including optical metallography, analytical scanning electron microscopy, fractographic analysis of the nature of fracture, as well as direct studies of the fine structure by the methods of transmission electron microdiffraction microscopy, conducted in the Philips unit SEM-515 and the JEOL unit JEM-200CX. Figure 1 shows the schematic of cutting out the samples.

Studies revealed that the structure-phase condition of the HAZ, extending to the depth of approximately 1600--2000  $\mu m$  in samples, optimum in terms of their mechanical properties and not prone to cracking, is characterized by a more finely dispersed and comparatively homogeneous fine platy troostosorbite structure and structureless martensite.

The above-mentioned structure types are distributed at the distance of approximately 0--500  $\mu$ m from the treated surface (Figure 2). Microhardness of structureless martensite is equal to HV0.25 3830--3510 MPa. At about 500--1100  $\mu$ m distance from the surface the fraction of martensite component decreases and that of sorbite increases. Microhardness of the martensite component varies from HV0.25 3510 to 3220 MPa. At 1100--2000  $\mu$ m distance from the surface a homogeneous finely dispersed structure of sorbite forms. Ferrite fringes along grain boundaries are



**Figure 2.** Microstructure of sample surface which has no cracks: a — sample schematic; b — ×200; c — ×500

formed on the interface with the base metal, these fringes being the smooth transition link to the base metal microstructure in the form of a mixture of ferrite and pearlite with ferrite fringe precipitates along the grain boundaries.

A positive feature for the structural condition of the metal experiencing complex stress states in the friction zone, is absence of non-metallic inclusions such as sulfides, which is due to the purity of the initial metal as regards non-metallic and other inclusions. Although the metal in the treated zone has a somewhat higher microhardness, distribution of dislocation density is quite uniform, according to transmission microscope studies of the fine structure. No formation of dislocation clusters or other internal stress raisers was found (Figure 3, a).

For the metal of the hardened layer, prone to cracking, microstructure of HAZ metal (approximately to 2300  $\mu$ m depth) has significant distinctive features. First, the ferrite-pearlite structure is characterized by coarse platy pearlite and more massive ferrite fringes. Microhardness of the ferrite component reaches HV0.25 1810--1680 MPa, that of the pearlite HV0.25 2090--1810 MPa. Note, in particular, the presence of non-metalic inclusions of sulfide type (Figure 4).



1/2005

SCIENTIFIC AND TECHNICAL



**Figure 3.** Fine structure of metal (steel 60) not prone to  $(a - \times 20000)$  and prone to microcracking  $(b - - \times 15000)$  at plasma surface hardening

In addition, samples of this group are further characterized by nonuniformity of dislocation distribution, which leads to formation of marked gradients of dislocation density and internal stresses. Stress gradients form as a rule in the region of contact of the hard and soft structural components, for instance, cementite plates with ferrite interlayers in pearlite or on the boundaries of pearlite grains with ferrite fringes, etc. (Figure 3, *b*). Thus, the metal clearly displays marked gradients of phase heterogeneity, microhardness and internal stresses.

It should be noted that (for the case of crack formation and without cracks) in plasma treatment a structure, which is a finely dispersed uniform ferritecarbide mixture usually forms in the local surface and near-surface layers ( $\delta > 0$ --10 µm). No cracking was recorded in this local near-surface region with a structure of such a type. Dislocation clusters (concentrators of local internal stresses) are also absent. Proneness to cracking starts to be manifested as the distance from the treated surface increases (particularly, at the distance of approximately up to 100  $\mu m$ ). Manifestation of cracking is due to the following main factors:

• formation of «flattened» extended non-metallic inclusions of sulfide type, oriented parallel to the external treated surface. This interrelation is clearly traceable in fractographic studies of the fracture nature, which demonstrated that the fracture is a transcrystalline brittle fracture and initiates on grain boundaries (fracture surface clearly shows line precipitations of oxides and sulfides) (Figure 5);

• formation of cracks related to generation at about 100  $\mu m$  depth of local internal stresses in the zones of mating of coarse platy structural components, in this case pearlite grains. Presence of stress concentrators is indicated by bending extinction contours of 1.0--0.5  $\mu m$  size, against the background of which the high dislocation density ( $\rho > 1\cdot 10^{11}~{\rm cm^{-2}}$ ) is manifested.

Quantitative estimate of the level of local internal stresses  $\tau$  by dislocation density and presence of extinction bending contours for a steel of ferrite-pearlite class by the dependence given in [7] is

$$\tau = Gbh\rho / \pi (1 - \nu),$$

where *G* is the shear modulus (84000 MPa); *b* is the Burgers vector (2.5  $\cdot 10^{-8}$  cm); *h* is the foil thickness (2.10<sup>-5</sup> cm); v is the Poisson's ratio (0.28), indicates that at about 100 µm depth from the surface, local deformation  $\varepsilon_1$  rises and has the value > 40 %. In addition, at  $\rho > 1 \cdot 10^{-12}$  cm<sup>-2</sup>  $\tau$  rises abruptly and is equal to approximately *G*/12, which is close to the values of theoretical strength of the material [8].

#### **CONCLUSIONS**

1. It is established that adjustment of the temperature-time modes of surface heating and cooling of wheels in the real range of operating parameters of



Figure 4. Microstructure of near-surface layers of wheel tread metal, which may develop microcracks:  $a - \times 655$ ;  $b - \times 2020$ 



**Figure 5.** Schematic (a) and fractographic pattern of sample fracture:  $b - \times 163$ ;  $c - \times 655$ ;  $d - \times 1310$ 

the plasma equipment leads to significant changes of the structural-phase condition of the treated surface.

2. It is shown that use of optimum modes of plasma treatment in the surface hardened layer of the wheel pairs leads to formation of finely dispersed structures without any gradients of the structure, phase distribution or dislocation density. Initial condition of the metal, characterized by purity in terms of non-metallic inclusions, promotes high values of operating characteristics of the treated wheel pairs.

3. The optimum mode was established, in which the plasmatron arc current is equal to 180 A, arc voltage to 190 V, plasma mixture flow rate is 6 nm<sup>3</sup>/ h, methane content in the mixture with air is 11 %, linear velocity of wheel rotation is 12 mm/s, maximum surface temperature is 1250 °C. This provides the hardness of HV 4300 MPa of the flange working surface (initial value of HV 2690 MPa), required proceeding from the conditions of optimum contact interaction of the wheel and rail, at the width of the hardened zone of 35 mm and depth of 2 mm.

- Bogdanov, V.M., Evdokimov, Yu.A., Kashnikov, V.N. et al. (1996) Problems of wear of wheels and rails: possible solutions. *Zh/d Transport*, **12**, 30–31.
- 2. Pevzner, V.O. (1996) Influence of track gauge. Ibid., 12, 36-39.
- 3. Verigo, M.F. (1997) Analysis of methods of mathematical modeling of dynamic processes in studies of intensity of lateral wear of rails and wheel flanges. *Vestnik VNIIZhT*, **6**, 24--33.
- Bogdanov, V.M., Evdokimov, Yu.A., Kashnikov, V.N. et al. (1995) Means of reduction of wear of railroad equipment. *Zh/d Transport*, **12**, 23–25.
- 5. Kiselyov, S.N. (2000) Different methods of plasma quenching. Lokomotiv, 1, 27--29.
- Paristy, I.L., Troitsky, A.A., Isakaev, E.Kh. et al. (1999) Plasma strengthening of wheel pairs. *Ibid.*, **3**, 32–33.
- Konstantinova, T.E., Primisler, V.B., Dobrikov, A.A. et al. (1991) Mechanisms of plastic deformation of high-strength maraging steel. *Metallofizika*, 13(5), 62--68.
- 8. Hirt, J., Lote, I. (1972) Theory of dislocations. Ed. by E.M. Nagorny, Yu.A. Osipian. Moscow: Atomizdat.

21

Paton Burnal

## IMPROVEMENT OF FATIGUE FRACTURE RESISTANCE OF SHEET STRUCTURES BY THE METHOD OF LOCAL PULSE ACTION

**B.I. PALAMARCHUK, N.A. PASHCHIN** and **A.N. MANCHENKO** E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper gives the results of studying pulsed explosion treatment of flat samples of D16 alloy to prevent initiation and propagation of fatigue cracks. Treatment is based on a practically instantaneous generation of configuration fields of residual compression stresses, that prevents heating of the treated metal. Special schematics of pulsed treatment were developed to generate fields of a specific configuration.

**Keywords:** shock-wave treatment, sheet aluminium, fatigue crack, spiral schematics, stressed state, compressive residual stresses, barrier zones, crack propagation

Advance of modern aircraft and shipbuilding, as well as vehicle construction, necessitates development of new approaches to improvement of strength and reliability of structures of high-strength aluminium alloys. A number of sheet structures develop fatigue cracks during service, which are caused by high-cycle loading. Therefore, solving the problem of crack prevention or arresting at fatigue loading is highly important for improvement of advanced equipment performance.

It is known that the so-called reflected zone of plastic deformation forms ahead of a propagating crack, this zone length being significantly smaller than that of the plastic zone, corresponding to static loading [1]. Compressive residual stresses, artificially induced ahead of the fatigue crack tip, slow down development of plastic deformation, reducing it, this leading to arresting or retarding the crack growth [1]. On the other hand, investigations conducted on models of polycarbonate [2] and aluminium alloys [3], demonstrated that presence of a circular zone of plastic deformations induced around the cracklike defect, is positive for the material stressed state at the crack tip.

There exist several methods to improve the fatigue resistance of structural materials, some of which are based on reducing the stress concentration, and others ---- on redistribution of the residual stress fields in zones prone to brittle fracture. Research showed that for the high-cycle region of alternating loads and elements with a high stress concentration, an effective measure is explosion treatment based on artificially inducing residual compressive stresses in the specified locations in structures [4].

The above treatment method is based on applying to the metal a shock explosion wave, propagating in it at a supersonic velocity. Local plastic deformation at pulsed loading by a shock wave should lead to initiation of stresses exceeding the dynamic yield limit. For the case of low-carbon, low-alloyed and high-strength steels this condition is satisfied, when using cylindrical or flat charges of explosive, placed on the surface of the treated item and detonating in the zero-overshoot mode. Inducing favourable biaxial residual compressive stresses in the surface layer, is provided by explosion treatment by shock waves of a moderate intensity with pressure at the front not higher than  $(1-4) \cdot 10^3$  MPa. The level of compressive stresses in the surface layer of locally deformed metal when using charges of the same type, essentially depends on treatment intensity and thickness of the damping layer. At optimal parameters of pulsed action, its effectiveness is also preserved in the case of a high asymmetry of alternating stresses [2].

The purpose of this work is to study the effectiveness of shock-wave treatment of aluminium alloys as a method to induce residual compressive stresses ahead of the fatigue crack tip to achieve its retardation.

The material used for studies was aluminium alloy D16 2 mm thick, which is widely applied in industry.

In the experiments, the features of explosion treatment of  $450 \times 170 \times 2$  mm samples of alloy D16 were studied using circular and spiral cylindrical cord charges. Selection of charge geometry was dictated by the results yielded by the above models of optically sensitive polycarbonate [2].

At shock-pulse action of the explosive inside a closed contour, converging waves [5] are generated with mass transfer aimed to the center of the circumference, formed by the charge. This results in generation in the closed volume of the so-called non-stationary traveling deformation waves of a higher linear density of condensation  $\rho_{cr}$  [6], given by the following function:

#### $\rho_{\rm cr} = \rho_{\rm cr}(r, t),$

where *r* is the current radius of the charge; *t* is the time of wave traveling to the center of the circumference.

Due to wave processes running at a velocity of up to 8 km/s, compressive stress fields are induced in the middle part of the circumference, preventing brittle fracture of the material subjected to pulsed action.

Evaluation of the action of shock-wave processes on the stress-strain state of D16 alloy was conducted at different parameters of explosion treatment.

In the first stage of investigations the simplest circular treatment schematic of the sample without a



**Figure 1.** Circular schematic of treatment of flat samples: 1 — damping layer; 2 — circular explosive charge; 3 — rigid base; 4 — treated sample

crack-like defect was used with application of a cylindrical charge of 12 to 33 g/m capacity (Figure 1). Evaluation of the metal surface condition after treatment showed the need to apply damping layer 1 of vacuum-tight rubber 0.5 to 2.0 mm thick. After the shock action on D16 alloy by the schematic given in Figure 1 using a damping layer, the treated metal had a smooth shiny surface, but a local bending deformation of up to 3 mm developed inside the treatment zone (Figure 2).

Preliminary evaluation of the stressed state in treatment by the schematic in Figure 1 showed the need to intensify the shock-wave action by increasing the treatment surface area at a certain lowering of the specific capacity of the charge (to improve surface quality), which was implemented in treatment schematics, where the cylindrical charge was laid to form a spiral (Figure 3). Effect of turn number (from 2 to 5) on material stressed state was assessed, as well as the quality of the produced surface.

As was noted above, at circular and spiral treatment schematics a local deformation zone is formed inside a closed contour, which leads to residual change of shape being negative for service properties of aluminium alloy sheet structures. For minimizing the negative impact of explosion energy on distortion of sheet elements, a schematic of mounting the charges in a special fixture was proposed (Figure 4). Use of this schematic allowed reducing deformation of the treated sections of D16 alloy samples to 0.25--0.40 mm and practically eliminate development of cumulative undercuts or other surface defects in them.

At the next stage of investigations, the optimized schematic of the shock-wave action was applied for flat samples containing a centrally located crack-like



**Figure 3.** Arrangement of a charge relative to the stressed state at the crack tip: 1 - treated sample; 2 - crack simulator; 3 - stressed state at the crack tip; 4 - spiral explosive charge

defect in the form of a hole of 4 mm diameter with two «start» notches of up to 10 mm length made by a standard procedure [2].

Performed treatment of a material with a notch demonstrated a satisfactory quality of the treated surface without any influence of the explosive on the crack simulator.

Evaluation of the shock-wave action on the stressed state in the treated zone was conducted on a sound surface and in the presence of a crack-like defect. Residual stresses were evaluated using a mechanical deformation meter of lever type with 25 mm base. Directions of principal axes x, y of stresses  $\sigma_x$  and  $\sigma_y$  were selected normal and parallel to the longitudinal axis of a cracklike defect. Stress measurements along axis  $\sigma_y$  revealed their slight contribution into the plane stressed state of the studied plates. All the subsequent evaluations of the stressed state of D16 alloy samples, treated by shock-wave action, were performed only for stresses  $\sigma_x$  (Figure 5).

Results of measurement of residual stresses inside the treated zone showed that with the circular treatment schematic with variation of the spiral charge diameter from 80 up to 120 mm values  $\sigma_x$  did not exceed 60 MPa at a maximum specific capacity of the charge of 33 g/m (Figure 6, *a*). Based on the data of [1], compressive stress  $\sigma_x$  required for retardation of a fatigue crack, is equal to  $0.5\sigma_{0.2}$ .

Applying a five-turn spiral schematic of charge arrangement allowed raising  $\sigma_x$  level to 80--95 MPa.



Figure 2. General view of a sample treated by a circular schematic



**Figure 4.** Spiral schematic of treatment of flat samples: *1* ---- spiral explosive charge; *2* --- packing of a dense material; *3* ---- rigid base; *4* --- damping layer; *5* ---- treated sample

SCIENTIFIC AND TECHNICAL



Figure 5. General view of a sample after treatment by a spiral schematic

In this case the inner and outer diameters of the spiral were taken to be equal to 70 and 125 mm, respectively.

Maximum effectiveness of the shock-wave action was achieved, when using a four-turn spiral schematic of treatment at a lower (12 g/m) specific power of the charge. When this treatment schematic was used,  $\sigma_x$ level was up to 170--180 MPa (Figure 6, b) with the satisfactory quality of the metal surface. High gradients of compressive stresses at the tip of a cracklike defect are due to narrowing of the inner ring of the spiral charge to 60 to 65 mm. The proposed schematic of pulsed loading of the studied samples of alloy D16 allows reach-



**Figure 6.** Epures of residual stresses after sample treatment by a circular (a) and spiral (b) schematics: L — sample width

The

ing the level of compressive stresses required for retardation of the fatigue fracture process.

The procedure of [1] was used to perform calculations for evaluation of the influence of compressive stresses on the rate of fatigue crack propagation. A crack of half-length l = 10 mm was simulated, which was grown in a  $450 \times 170 \times 2$  mm plate of alloy D16 (corresponding to actual samples treated by explosion), subjected to a cyclic action in the loading–unloading mode, applied normal to the crack plane. Dependence of increase of crack half-length l on loading cycle number N is shown in Figure 7. From the Figure it is seen that compressive stress fields artificially induced ahead of the crack tip and equal to 120 to 150 MPa, allow slowing down its propagation rate 4 to 9 times.

It should be noted that at explosion treatment the sheet metallic materials are subjected to surface work hardening and local hardening in the areas of application of the shock-wave action, which is particularly pronounced in aluminium alloys in view of their high ductility. This allows creating the so-called barrier zones of work-hardened metal, which are located normal to the crack plane and prevent its growth at static loads.

Evaluation of the effectiveness of barrier zone influence on static strength of alloy D16 was performed by the procedure of mechanical testing of flat samples with a sharp notch, developed by Kan [5]. During testing by Kan procedure (Figure 8, *a*) the samples were subjected to off-center tension to fracture. A diagram in load--displacement co-ordinates (Figure 8, *b*) was plotted proceeding from the obtained data. Mechanical characteristics were evaluated by two parameters, namely specific energy of crack propagation  $a_p$  and breaking stresses  $\sigma_b$ . Specific energy  $a_{en}$  was found from the following formula:

$$a_{\rm en} = A_{\rm en} / B(W - a_{\rm n}),$$

where  $A_{en}$  is the energy of crack propagation, determined by the area of the tension diagram under the drooping branch (see Figure 8, *b*); *B*, *W* are the specimen thickness and width, respectively;  $a_n$  is the notch depth.





IRNAL



Figure 8. Schematic of mechanical tests for off-centre tension by Kan procedure (a) and diagram of tension of the tested sample (b): P — applied force;  $\varepsilon$  — deformation; R ---- rounding-off radius in the «consumed sample» (for other designations see the text)

Results of mechanical testing of samples by Kan procedure

Treatment conditions	Charge specific power, g/m	σ <sub>b</sub> , <i>MPa</i>	À <sub>en</sub> , cm²	$\dot{a}_{ m en}$ , $J/cm^2$	à <sub>en</sub> incre ment, %
Untreated (base metal)		265	21.53	23.90	
Two-turn sche- matic	30	286	31.58	35.09	46
Three-turn sche- matic	18	278	29	32.20	37

Breaking stress was determined by the following formula:

#### $\sigma_{\rm b} = 4P_{\rm max}(W - \dot{a}_{\rm n})B,$

where  $P_{\text{max}}$  is the load at which sample fracture starts. The Table gives the results of mechanical tests.

Tabulated data suggest that hardening of D16 alloy at different schematics of pulsed action does not affect breaking stress  $\sigma_b$ . This is related to the fact that barrier zones were at a certain distance from the notch tip and the process of crack initiation at the initial stage was similar both for an untreated alloy and for the material subjected to treatment.

On the other hand, barrier zones increase the fracture resistance at static loading, which is manifested in increase of the specific energy of crack propagation  $a_{\rm en}$ . As is seen from the Table, the need for the crack to pass through the explosion hardened sections of alloy D16 raises values  $A_{en}$ , and, hence, also  $a_{en}$ . An increase of  $a_{en}$  values from 37 to 46 % was obtained at different schematics of charge arrangement and variation of their specific power.

Change of fracture mode in the presence of barrier zones is confirmed by fracture appearance on samples tested by Kan procedure (Figure 9, b). At interaction with a barrier, a marked change of fracture direction to 45--50° is observed relative to the initial one (Figure 9, a), and the crack plane is turned through 90°, when a barrier zone has been reached.

The above-said suggests that creation of barrier zones along with the fields of compressive stresses enables extending the structure life by 4 to 9 times.



Figure 9. General view of untreated samples (a) and samples treated by a spiral schematic (b) after mechanical testing by Kan procedure

Explosive treatment of aluminium alloy D16 is an effective method of retardation of the process of sheet structure failure.

#### **CONCLUSIONS**

1. Developed schematics of explosion treatment allow inducing up to 180 MPa compressive residual stresses in the vicinity of a crack-like defect.

2. Theoretical estimate of the influence of compressive stresses on the fatigue crack growth rate showed that explosion treatment of sheet samples of alloy D16 improves their fatigue resistance by more than an order of magnitude.

3. At static loading the specific work of crack propagation increases by 37 to 46 % due to creation of barrier zones in the material.

- Knysh, V.V. (2003) Determination of cyclic service life of structure elements in retardation of fatigue cracks. Avto-matich. Svarka, 9/10, 73-75.
- (1992) Improvement of welded metal structures. Ed. by M.M. Zherbin. Kiev: Naukova Dumka. 2
- Lobanov, L.M., Pivtorak, V.A., Krotenko, P.D. et al. (2003) Determination of residual stresses using the method of holographic interferometry based on measurement of plane displacements. In: *Abstr. of Int. Conf. on Current Problems in Welding and Life of Structures*, Nov. 24-27, 2003. Kiev: PWI. 3.
- Palamarchuk, B.I., Pashchin, N.A., Manchenko, A.N. (2003) Improvement in fatigue strength of aluminium alloy thin-sheet structures using the method of a local pulsed ac-tion of explosion energy. *Ibid*. Dobrolyubov, A.I. (1999) *Travelling waves of deformation*. Moscow: Nauka i Tekhnika.
- (2002) Methods of control and investigation of light alloys. Refer. book. Moscow: Metallurgiya.



25

## CURRENT STATUS OF WELDING FABRICATION IN CHINA

**V.N. BERNADSKY** and **O.K. MAKOVETSKAYA** E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper presents the data on the status of welding consumable and welding equipment manufacturing, and welding technology market in China, which allows evaluation of the overall current level of welding fabrication and trade in China, and also gives their development prediction.

**Keywords:** economics, welding fabrication, welding technology market, welding consumables, welding equipment, development prediction, China

Over the recent decades the People's Republic of China has achieved outstanding economic success, and has rightfully joined the world leading countries, taking the 7th place in the world by its economic power and the 1st place by the economic growth rate. In 2003 the volume of China's GNP has reached 1378 bln USD, that was by 9.1 % higher than the 2002 level. By evaluation of most of the experts, in 10 to 12 years the volume of China's GNP will reach and maybe even exceed the level of US GNP. In the last decade of the XX century the average annual rate of the Chinese Republic economic growth rose up to 10 %. The government is now already limiting this index: according to the 10th Five Year Plan (2001--2005) the average annual rate of China's economic growth is envisaged to be on the level of 7 %. China's economic development today is based on increased volumes of commercial production, i.e. industrialisation of the country. Industry's contribution to China's GNP rose from 41.6 in 1990 to 52.3 % in 2003, thus giving China 54 % of GNP cumulative growth over this period [1].

China has steadily moved to leading positions also by the scope of its foreign trade, the total volume of which exceeded 740 bln USD in 2003. China takes the 4th place on export volume and 3rd place (after USA and FRG) on import volume in the world. The major share of the Chinese export (157.1 bln USD in 2002) is made up of mechanical engineering and electronic products.

Growing foreign investments are an indirect indication of China's economic activity. By the data of the Organisation for Economic Co-operation and Development in 2003 China for the first time left the US behind by this index. While direct foreign investments into US economy dropped from 72 in 2002 to 40 bln USD in 2003, China's economy received more than 53 bln USD in the form of direct foreign investments in 2003. This is indicative of the current status of China as a country with the world's largest market in terms of capacity and attractiveness.

It should also be noted that growth of direct foreign investments is accompanied by increased in-flow of advanced high technologies into the Chinese economy, and intensifies the innovative activity [1, 2]. Conducted re-organising of the metallurgical industry and availability of a huge internal market enabled China steadily moving to the first place among the world's major steel producers already at the start of this century. In 2003 China reached a record level of steel production of 222.2 mln t, which was promoted by optimisation of the entire metallurgical cycle. In particular, the share of continuous casting in China's black metallurgy was equal to 90 %, and the last open-hearth furnace was taken out of service as far back as at the end of 2001. New up-to-date metallurgical complexes are being intensively constructed [1, 3].

Steel production volumes are not meeting China's growing inner demand so far, primarily in the metalworking industries; the formed deficit is liquidated through increasing the import of steel metal products. Annual steel consumption showed a super high growth rate, 15 % on average over the period of 1980 to 2002. In 2003 steel consumption in China was 237 mln t (2.7 % growth). In 2004 this index is predicted to rise to 290 mln t to reach (30.9 %) of the total world steel consumption (936 mln t) [4].

The main consumers of steel metal products in China currently are such metalworking industries as mechanical engineering, automotive and shipbuilding, which traditionally have the highest level and scopes of welding application. Chinese mechanical engineering, in particular, makes and exports such high class equipment with turn-key delivery as large gas turbines, pumping units, nuclear power units, high-capacity transformers, metallurgical units, petrochemical equipment, rail vehicles, etc. [1, 4]. Despite a certain reduction of activity over the recent years, China's construction sector remains the main consumer of steel rolled stock. These are exactly the industries, where welding and allied processes are no-alternative technologies in fabrication of welded components, structures and constructions. Annual contribution of welding to products of the above industries in China's economy is now tentatively evaluated as 1500 mln USD [5].

<sup>©</sup> V.N. BERNADSKY and O.K. MAKOVETSKAYA, 2005



Mass production of welded structures and welding equipment is closely related to the volumes of consumption of the main structural materials, namely steel and aluminium. Fabrication of welded products, structures and engineering facilities takes up to 70 % of the total volume of the consumed finished steel metal products, mainly rolled stock [6]. Given the high annual growth rate (on the level of 10 %) of China's consumption of rolled stock, there is every ground to speak also of the high rate of welding fabrication development, which primarily implies the volumes of fabrication of welded structures and welding products (welding consumables and welding equipment). Figure 1 shows the dynamics of production of steel and welding consumables in China over the period of 1996--2003. Comparison of the dynamics of manufacture of welding consumables as a whole and of coated electrodes for manual welding, in particular, with that of steel production confirms the high degree of correlation of their annual increase.

Let us consider some tendencies of development of industrial production of welding consumables and equipment in China, giving a certain idea of the overall level of current development of welding fabrication in China [5].

Manufacture of welding filler materials in China covers all of its categories, namely coated electrodes, solid and flux-cored wires, welding and brazing fluxes, filler metals and filler rods. Altogether in 2003 China produced 1.5 mln t of welding consumables and filler materials (Figure 1). Production pattern of the main kinds of welding consumables (coated electrodes, wires and flux), as well as dynamics of its variation during 1993--2001 shown in Figure 2, are indicative of a predominant production of coated electrodes for manual welding. A weak but stable tendency is observed of annual reduction (by about 2%) of electrode manufacture at a simultaneous increase by 2 % of the share of manufacture of wires for the mechanised welding processes and practically stable volume of welding flux manufacture.

Characteristically, development of welding fabrication in China, establishing and increasing the capacities for production of the main welding consumables is very similar to planned development of welding fabrication in FSU in the period from 1950 to 1990. Over this period development of welding fabrication was also determined by five-year programs, and in 1990 FSU produced more than 1200 ths t of welding consumables, including alloyed welding wire --- 220 ths t, flux-cored wire---- 23 ths t, submerged-arc welding wire ---- 90 ths t, and about 180 ths t of welding fluxes.

Welding consumables are a item of active foreign trade. Based on the data of UN statistics (COMTRAD data base), in 2003 the export of the Chinese welding consumables was equal to 146.6 ths t for the sum of 87.6 mln USD, and the import amounted to 35.8 ths t for a sum of 87.2 mln USD. In this case a practically zero trade balance was achieved [7].



**Figure 1.** Dynamics of manufacture of welding consumables A and steel F in China over the period of 1996-2003: 1 - total steel; 2 - total consumables; 3 - electrodes; 4 - wire; 5 - flux

In China the current total production capacity for manual arc welding electrodes manufacture is higher than 1.5 mln t. Planned targets determine the enterprise load and current internal market needs. In 2003 electrode manufacturers delivered 1.2 mln t of electrodes to the Chinese market. Coated electrodes in the country are manufactured by about 500 enterprises, shops and shop sections of different capacity. The major Chinese manufacturers of welding electrodes include Tyandzin Association «Big Bridge», Welding Consumables Association «Kosmos» (Tyansu Province), Shanghai and Shaulin Electrode Works, producing 50 to 100 ths t of electrodes annually. Despite quite high volumes of local coated electrode production, China imports welding electrodes mostly for welding alloyed and high-alloyed steels. In particular, more than 10 ths t of special electrodes are imported annually for manual arc welding of stainless steels. In 2003 export of general purpose coated electrodes was equal to 108.7 ths t or 74 % of the overall export of filler materials [7].

Solid welding wire (general purpose and alloyed) (up to 200 ths t) is supplied by 150 Chinese enterprises, and submerged-arc welding wire (up to 60 ths t annually) by 100 enterprises. Production volumes of regular wire for gas-arc welding of carbon and low-alloyed steels quite closely meet the needs of the Chinese industry. In the range of thin alloyed wire for gas-shielded welding, a deficit of wire for welding high-strength and stainless steels is noted, and this wire is imported. In this connection, future



**Figure 2.** Production share of various kinds of welding consumables *B* in China during 1993--2001 [5]



**Figure 3.** Dynamics of manufacture and import of flux-cored wire *C* in China during 1996--2002 [5]

enhancement of the capacities is planned primarily for manufacture of alloyed welding wires.

Chinese production capacities for flux-cored wire manufacture reached 20 ths t per year in 2002. It is produced by 28 enterprises, four of which manufacture more than 1 ths t of flux-cored wires annually. As is seen from Figure 3, in 2002 the import of flux-cored wire reached the level of 19 ths t, and exceeded the volume of local flux-cored wire manufacture (approximately 18 ths t). In 2003, the import of flux-cored wires for the Chinese welding production rose up to 20.6 ths t, while China exported 12.8 ths t of locally manufactured flux-cored wires in the same year [7].

China has rather large capacities for welding flux manufacture, where the annual output equals 150 ths t (110 ths t of fused and 40 ths t of agglomerated fluxes). They are manufactured by 30 enterprises. Welding flux manufacturing capacities are more than 2 times higher than the volumes of the local production of the corresponding submerged-arc welding wires. It may be assumed that China either exports the flux, or additionally imports some of the wire grades for submerged-arc welding.

The range of the main kinds of manufactured and consumed welding consumables is considerable, as shown in [8]. At the start of 1996 the Chinese welding fabrication industry applied about 370 grades of coated electrodes for welding steels, cast iron, nickel, copper and aluminium alloys, as well as for surfacing, strengthening and other special applications (underwater welding, cutting, gauging, etc.). The range of welding and filler wires, covering 84 grades, includes solid and flux-cored wires for mechanised welding



**Figure 4.** Predicted production *D* of different kinds of welding consumables in China for 2004–2007 [5]: *1* — total; *2*— electrodes; *3*— wires; *4* — flux

and surfacing of steels and non-ferrous alloys, as well as filler rods and wires, also for gas welding. In addition, up to 50 grades of filler wires based on Cu--N, Cu--P, Ag, Sn, etc. are used in soldering and brazing. The range of fluxes is quite diverse (60 grades). They include 22 grades of fused fluxes for welding and 27 agglomerated fluxes. More than 10 flux grades are produced for brazing and gas welding. The national and international certificates usually confirm the quality of the produced welding consumables and filler materials.

The given data on production volumes, as well as export-import allow approximate evaluation of the annual consumption of the main welding consumables in the Chinese welding production. By a tentative estimate about 1510 ths t of welding consumables were consumed in 2003. It is interesting to compare this figure with similar ones for the leading countries and regions of the world. V. Pekkar [9] gives the ESAB data on the weight of metal deposited in 2003 in fabrication of welded structures and items in the above-mentioned regions. A simple recalculation of these data yields tentative volume of aggregate consumption of the main welding consumables (electrodes, solid wires, flux-cored and submerged-arc welding wires), which in Western Europe was equal to 456.6 ths t, in the USA to 419.3 ths t and in Japan to 289.4 ths t. Such a purely comparative estimate of the volume and pattern of the main welding consumable application shows that in 2003 China consumed by about 30 % more than the West European countries, USA and Japan taken together. While in the industrialised countries the share of coated electrodes in the overall volume of welding consumable application is equal to about 20 %, in China the consumption of electrodes for manual arc welding reaches 80 %. In this connection, it is natural that the share of application of the solid and flux-cored wires is much lower in China (12.5 and 2.5 %, respectively), despite comparatively great absolute volumes of their application. The share of consumption of submergedarc welding wires in China (5 %) meets the world average proportions.

The short-term forecast for the near-term period shows a rather high rate (10--12 %) of further increment of the volume of welding consumable manufacture (Figure 4), corresponding to the growing needs of the Chine welding fabrication. The socialist market economy of China is largely based on planning. In this connection, the changes in welding consumable manufacture pattern predicted up to 2007 (Figure 5) were established proceeding from the planed indices of future development of metal-working industries and are quite well substantiated. Over the period of 2005 to 2007, the share of production of manual arc welding electrodes in the overall volume of welding consumable manufacture will drop from 80 to 60--65 %, while the share of welding wires will increase up to 30--35 % on the whole. Over the same period

the share of manufacture of small diameter solid wire for gas-shielded welding will rise by 20 %, that of flux-cored wire by 5--10 %, that of submerged-arc welding wire by 10 %.

In view of the requirements of the leading industries (main users of welding consumables) an improvement of the quality and expansion of manufacture of advanced types of welding electrodes is envisaged, in particular, high-efficient electrodes with iron powder in the coating, electrodes for vertical upward welding, electrodes with a cellulose coating and general-purpose electrodes, to ensure sound all-position welding. In manufacture of special alloyed welding electrodes the focus is on setting up and expansion of the production of coated electrodes, providing a low hydrogen content in the weld metal, electrodes for welding steels of a higher and high strength, electrodes for welding stainless and other alloyed steels with special properties.

In 2000 welding equipment was manufactured in China by more than 900 large and small works, although in 1995 there were about 1500 such enterprises. Over a comparatively short period (from 1995) about 600 enterprises closed, merged or changed their profile. Consolidation and specialisation in the field of manufacture of welding and gas cutting equipment is a continuous process. The range of manufactured welding machines, units, systems and other equipment is quite broad, having 150 types, including 45 types of batch-produced items and more than 500 designtechnological modifications.

Figure 6 gives the pattern of the manufactured welding equipment and dynamics of its change from 1996 to 2000. In 2000 the main share in the overall production of welding equipment manufactured in China (almost 80 %) was made up by AC and DC power sources, which is quite explicable, considering the actual volumes of manual arc welding application. The second place was taken up by equipment for automatic and mechanised arc welding, the share of which is 15 to 20 %. The volume of resistance welding and specialised equipment manufacture is guite small. This accounts for the considerable volumes of welding equipment import: in 2003 China imported welding equipment for the sum of more than 632.3 mln USD, 76 % (481.7 mln USD) of which was the arc welding equipment [7].

By the estimate of Frost and Sullivan Company, the volume of the Chinese market of welding consumables and equipment in 2002 was equal to 705.5 mln USD. Its high annual growth rate should be also noted: in 2001 the growth was equal to 10.5 %. In the overall volume of welding technology market, the share of welding equipment reached 44 % (310.4 mln USD). The company experts anticipate that in 2009 the volume of the Chine welding technology market will exceed 1.36 bln USD [10].

Despite the high level of manual arc welding application in welding fabrication, in the large and medium-sized mechanical engineering enterprises of the



**Figure 5.** Prediction *E* of changes in welding consumable production pattern in China for 2003–2007 [5]

country the proportion of equipment fleets for DC and AC manual arc welding, consumable electrode mechanised welding in  $CO_2$  or gas mixtures, as well as automatic submerged-arc and CO<sub>2</sub> welding is 1:1:1. At these enterprises the volume of application of highly efficient process of mechanised gas-arc welding with small diameter wire is rising steadily. In particular, by the end of this five year period an increase of the volume of manufacture of equipment for mechanised and automatic CO<sub>2</sub> welding is anticipated, so that its share in the overall volume of equipment would reach 25--30 %. Expansion of the volumes and fields of rational application of mechanised CO<sub>2</sub> welding was made one of the priorities for Chinese welding fabrication, in order to replace coated electrode manual arc welding, which provides a lowering of the cost at a simultaneous increase of the productivity and quality of welded structure fabrication [5].

By 2005 it is planed to cut down the manufacture of manual arc welding power sources (transformers and rectifiers) in the overall volume of equipment manufacture to 55--60 %. Development and manufacture of up-to-date local inverter power sources will increase simultaneously, primarily for  $CO_2$  and MIG/MAG processes. To meet the growing demand of such industries, which are the leaders by the scope of welding application, as ship-building, petrochemi-



DC power sources

AC power sources



cal engineering, and automotive and power engineering, China is incrementing the production capacities for manufacturing specialised sets of equipment for automated welding with computer control systems. Application of robotic work stations and industrial spot robots for spot and gas-arc welding has started and is being expanded in the major enterprises, in order to increase the level of mechanisation and automation of welding operations. It should be noted that the Chinese welding scientists are actively pursuing investigations on automation and robotisation of welding processes based on application of modern computer technologies. These developments are needed by the local welded structure fabricators.

China is intensively pursuing research and development and subsequent transfer of electron beam and laser technologies of welding and processing of materials. Several dozens of EBW machines are already operating in the Chinese industry (aerospace, power and other industries), including 15 up-to-date units supplied by PWI. Local manufacturing of individual EBW machines has also been organised. Application of laser technologies of material welding and processing is being expanded, in particular in automotive industry. Such an advanced process as friction stir welding is at the stage of pilot production development. The activity of the joint Chinese-British Center is focused on development of this promising area.

China has set up batch production of gas-oxygen and plasma-arc equipment for severing and gas welding. The output and basic range of such equipment, tools and spare parts are characterised by the following indices of their 2000 output: gantry units for gas cutting ---- 380 pcs; mobile mechanised units for gas cutting ---- 14650 pcs; plasma cutting units ----10500 pcs; cutters and torches for welding and cutting ---- 2.5 mln pcs.

For gas-thermal cutting the industry is supplying both the mobile and general purpose gas-cutting machines, and stationary and mechanised units for plasma-arc cutting of medium-thickness and thick metal. Output of equipment for plasma-arc cutting under a layer of water is increasing, the equipment providing a higher quality of the cut and lowering of adverse environmental impact of the cutting process. The tempo of the increase of manufacture of plasmaarc cutting machines is very moderate; the growth rate of manufacture of small, manual and mechanised gas-cutting machines is much higher ---- up to 6 % per year. Laser severing is finding only limited application so far, mainly in manufacture of super precise billets of steel and non-ferrous metal alloys. Work has begun on development of robotic process complexes for precision cutting, perforation and welding of thin materials, based on a combination of advanced models of robots and lasers with fiber-optic beam guides.

Chinese economic growth based on industrial production, which is accompanied by greater consumption of metallic materials, is the basic factor, determining the level and tempo of development of the modern Chinese welding fabrication. A convincing proof of that is provided by the above data on the achieved and future development of welding consumable and equipment fabrication in China, as well as the scope of research on welding and allied technologies conducted in China.

- 1. (2003) China--2003. Beijing: Sinsin.
- 2. (2004) China-Contact, 2, 9, 31.
- 3. (2004) *Steel statistical yearbook-2003*. Brussels: Committee on Economic Studies.
- 4. Lopukhov, G.A. (2004) Short-term prediction of steel consumption in the world. *Elektrometallurgiya*, 7, 40--42.
- Du Bing (2004) Current situation and development of welding in China. Presentation at the Seminar on Training of Advanced Welding Technology and Equipment, Aug. 2004, Harbin. Harbin.
- Bernadsky, V.N., Makovetskaya, O.K. (2004) Steel and aluminium — the main structural materials of welding production. Svarochn. Proizvodstvo, 1, 3–18.
- COMTRAD the database of Statistics Department of UNO. www.unstats.un.org
- 8. Li Liansheng (1997) The review on Chinese welding consumables in the last decade. *China Welding*, 6(1), 1--11.
- 9. Pekkar, B. (2004) Welding or joining in the future. BID ISIM, 2, 2--7.
- 10. Chinese metallic welding industry powder forward. www.manufacturingtalk.com/news/fro/fro140.html

## DYNAMIC CHARACTERISTICS OF HIGH-VOLTAGE POWER SOURCES FOR ELECTRON BEAM WELDING

**O.K. NAZARENKO** and **V.E. LOKSHIN** 

E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Transient processes occurring in high-voltage circuits of modern power sources of welding guns are considered. It is shown experimentally that with a pulsed change in the beam current the accelerating voltage oscillations in a power source based on the high-frequency transistorized converter exceed to a great degree the limits of requirements of standard ISO 14744-1:2000. The conclusion is made about prospects of equipping these power sources with control electron tubes when a key mode of operation is used.

**Keywords:** electron beam welding, high-voltage power sources, high-frequency transistorized converters, control electron tube, dynamic nature of loading, transient processes

Existing standards for EBW, in particular ISO 14744-1:2000, specify only the values of fluctuations, instabilities and reproducibility of beam current and accelerating voltage, but the admissible time of transient processes at a pulsed (jump-like) change in beam current is not specified. So, the requirements providing the feasibility of a pulsed modulation of beam current, control of beam current in on-line operation of secondary-emission systems of butt tracking [1], interruption of accelerating voltage by a system of protection of power source at breakdowns and discharges in a welding gun and a quick recovery of accelerating voltage to continue the process of welding are not regulated. As the possibilities of improvement of stability of welding guns themselves to breakdowns and discharges have been exhausted long ago, such approach to the prevention of development of breakdown in an accelerating gap of welding gun has been completely justified itself [2].

Over the recent years the power sources on the base of high-frequency transistorized converters («switching») became to be widely used [3, 4]. The specific volume power (ratio of total power of supply source to the unity of volume) 5--10 times increases the similar characteristic of traditional sources. Due to a low stored energy (up to 1-2 J/kW), the transition of spark discharges in an accelerating gap into arc discharges is hindered greatly that prevents the operation of current protection of the power source. It is stated, sometimes, for advertising purposes that only power sources on the base of high-frequency transistorized converters meet the modern technological requirements. At the same time the work [4] notes, from the one side, the softness of external characteristic of power sources on the base of high-frequency transistorized converters depending on external load, and, from the other side, the high effectiveness of use of electron beam valve in the circuit of a high voltage as a protective device.

The aim of the present work was to investigate experimentally the dynamic characteristics of modern power sources for EBW and to discuss these results for the preparation of proposals as additions to State Standard of Ukraine DSTU 3014--95 «Units for electron beam welding. Methods of tests and measurements».

The following objects for investigations were selected:

• power source (60 kV, 6 kW) on the base of highfrequency generator SR 60-N-6.000-EBWS of resonance type at 20–40 kHz frequency of conversion (Figure 1) [5]. Total capacity of filtering capacitors is  $3 \cdot 10^{-9}$  F, that provides, in combination with a distributed capacity of high-voltage cable ( $0.15 \cdot 10^{-9}$  F/m), the coefficient of fluctuations of accelerating voltage of not higher than 0.1 %. The energy stored by generator, as specified by the Technical Certificate of the generator, does not exceed 6 J;

• power source (60 kV, 30 kW) of ELA-30/60 type with a parametric protection by current in the primary circuit of high-voltage transformer [6] and linear controller on the base of electron tube PP-2. The latter is connected in series to welding gun to prevent the occurrence of breakdowns in it, to smooth fluctuations and to control the accelerating voltage



**Figure 1.** Simplified scheme of power source on the base of generator SR 60-N-6.000-EBWS with circuits of measurement and load

1/2005



Figure 2. Simplified scheme of power source ELA-30/60 with circuits of measurement and load

[2]. Scheme of the power source is given in Figure 2. Capacity of the smoothing filter is  $15 \cdot 10^{-9}$  F and coefficient of fluctuations of accelerating voltage does not exceed 0.1 %;

• power source without electron tube (for example, the power sources U-250A [2] and sources, used over many years by Sciaky Company, made by the similar scheme).

In the process of many-year industrial application of power sources of ELA type and sources on the base of high-frequency transistorized converters the high effectiveness of their suppression using anomalous non-stationary process in an accelerating gap of the welding gun was confirmed. As regards to this characteristic both types of sources are superior greatly to the traditional power sources having only one parametric protection.

Let us compare the results of experimental investigations of dynamic characteristics of the sources. Oscillograms of transition processes in a resonance power source are presented in Figure 3, and those in the power source with a linear controller ---- in Figure 4 at an abrupt reduction of beam current to the zero value and its recovery to initial value after 5--6 ms.

At a pulsed disconnection of beam current the accelerating voltage in the power source on the base of the high-frequency generator of a resonance type is increased by 8.6 % and has no time to be recovered for 6 ms of load disconnection. After connection of a rated load the value of accelerating voltage is dropped by 14 % and recovered for 4 ms. These oscillations



Figure 3. Variation of accelerating voltage at a pulsed change of beam current in resonance power source



Figure 4. Variation of accelerating voltage during current pulse in power source ELA-30/60

are far beyond the limits of requirements of standard ISO 14744-1:2000 to instability of accelerating voltage ( $\Delta U_{acc} = \pm 1$ %). In the power source with a control tube the instability of accelerating voltage lies in the ranges of  $\pm 0.5$ %. This allows us, in particular, to perform a pulsed EBW with its use at a frequency of beam current modulation up to 600 Hz and to control it in operation of the secondary-emission system of butt tracking in the real time mode.

Thus, the comparison of oscillograms of transient processes shows that dynamic characteristics of the





URNAL

power source on the base of a high-frequency converter is much worse than that of power source with a control tube. This is clearly manifested after occurrence of breakdown of the accelerating gap when the full release of energy, stored by all the high-voltage circuits of the power source (high-voltage cable, smoothing filter and distributed capacities of the power source itself and cable) takes place. Protective resistance in a high-voltage circuit somewhat limits the value of discharge current at some temporary areas of discharge curve. And, after the recovery of electric strength of gun the charge of filter capacity occurs for a sufficiently long time.

In the power source with a control tube it is impossible to control the discharge of distributed capacities of cable and high-voltage circuits and this process occurs for fractions of microseconds, however, the discharge of the smoothing filter is interrupted effectively by a control tube. The quick response of the similar protection is defined by an input capacity of valve and control circuit power. In this case the passing of emergency current at a given method of protection is only several microseconds.

To confirm the above-said, the Figure 5 gives the experimentally obtained time dependencies of release of the stored energy after forced operation of a current protection in the power source (30 kW, 60 kV) without a linear controller and with a linear controller on the base of a control tube. The pattern of a time dependence of releasing the stored energy after a real breakdown in the gun can greatly differ from the case with a forced operation of the current protection, but

the values of stored energy and the share of its release can be determined at a high precision. It is seen that, though the high-voltage circuits of power source ELA-30/60 store a large energy (54 J at accelerating voltage 80 kV), only 7.5 J are generated at electrodes of welding gun and workpiece being welded due to a rapid operation of the system of a current protection on the base of a control electron tube. The main share of stored energy by the power source is not dissipated due to which the transient process of charge of filter capacity after recovery of electric strength of welding gun is occurred to be almost imperceptible.

In can be noted in conclusion that the challenging future is foreseen for the creation of the new generation of power sources for EBW on the base of highfrequency transistorized converters, but with use of the electron tube as a key. In this mode of operation a low power is dissipated at the tube anode and, therefore, there is no need in its forced cooling.

- 1. Nazarenko, O.K., Shapoval, V.I., Loskutov, G.A. et al. (1993) Observation of electron beam welding process and automatic butt tracking. *Avtomatich. Svarka*, **5**, 35–38.
- Nazarenko, O.K., Kajdalov, A.A., Kovbasenko, S.N. et al. (1987) *Electron beam welding*. Ed. by B.E. Paton. Kiev: Naukova Dumka.
- Romash, E.M., Drabovich, Yu.I., Yurchenko, N.N. et al. (1988) High-frequency transistor converters. Moscow: Radio i Svyaz.
- Kostikov, V.G., Parfyonov, E.M., Shakhnov, V.A. (2001) Electric power sources of electron means. Moscow: Gor. Liniya-Telecom.
- 5. (2003) High-voltage generator model SR-60N-6.000-EBWS, User's Guide. Technix, France.
- Lebedev, V.K., Shelyagin, V.D., Mokhnach, V.K. et al. Power source of electron beam welding unit. USSR author's cert. 465844. Int. Cl. B 23 K 15/00. Publ. 15.12.79.

33

aton,

## CARBON DIOXIDE GAS HEATERS FOR MECHANISED ARC WELDING

E.I. DENIKIN, Yu.D. NETESA and A.D. NETESA

Limited-Liability Research & Production Company «Vibro-Resonance Technologies», St.-Petersburg, Russia

Specifications of carbon dioxide heaters for several types of gas feeding system intended for semi-automatic gas metal arc devices are analysed. The heaters characterised by heat transfer in a viscous sub-layer meet to the fullest degree the main technology and consumer requirements.

**Keywords:** arc welding, semi-automatic welding device, carbon dioxide gas, heat transfer, heater, flow regulator, temperature regulation, gas flow rate, viscous sub-layer

Overfreezing of flow regulators causes pulsations of the rate of gas flow from the nozzle in the shielding carbon dioxide gas feeding system during welding operations, which leads to violation of the shielding gas curtain and deterioration of the weld quality [1]. In pauses during welding, a gas is often discharged from the safety valve, which is caused by seal failure in the reducing valve. The latter leads to an excessive consumption of gas and decrease in capacity, as it is necessary to shut off the gas bottle valve and ensure a time lag required for defrosting of the regulator. A cold gas (down to --20 °C) in feeding systems of the semi-automatic welding devices impairs work of the pneumatic valve. This leads to seal failure in the valve and losses of gas in pauses during welding. Frequent and high-amplitude gradients of temperature of the gas fed from the regulator cause a dramatic reduction in service life of the pneumatic valve and entire gas feeding system. Flow of the cold gas from the nozzle causes a dramatic increase in the probability of formation of micro vortexes in the gas curtain because of increase in gas viscosity. The «ragged» gas curtain leaking oxygen and deteriorating the weld quality is formed around the weld pool [2]. The intensive cooling effect by a cold carbon dioxide gas raises voltage of the arc, which decreases its stability and deteriorates the weld quality [3].

Table 1. Carbon dioxide quality indicators

Indicator	First class	Class I	Class II
Content of carbon dioxide, vol. %, not less than	99.8	99.5	98.8
Mass concentration of mineral oils and mechanical impurities, mg/kg, not more than	0.1	0.1	Acc. to tests
Mass concentration of water vapours at 20 °C and 101.3 kPa, $g/m^3$ , not more than	0.037	0.184	Not specified
Content of water, wt.%, not more than	Acc. to tests	Acc. to tests	0.1

© E.I. DENIKIN, Yu.D. NETESA and A.D. NETESA, 2005

The above problems can be solved by using a heater providing a positive gas temperature at the outlet of the flow regulator close to the ambient temperature over the entire gas flow rate range (up to 30 l/min) with minimal gas temperature gradients in transition processes.

Carbon dioxide supplied in liquid state in bottles is used for welding. Some of its quality indicators are specified in GOST 8050--85 (Table 1).

During the flow process, the gas pressure may vary from 50--60 atm to zero in the flow regulator reducing gap, which leads to overcooling of the gas, formation of liquid and crystalline (dry ice) carbon dioxide, as well as appearance of water crystals formed from moisture contained in the gas. The presence of liquid and pieces of ice disturbs operation of the reducing valve, which in turn leads to pulsation of the gas flow and violation of closing of the valve.

The following design types of the heaters are currently applied: continuous, of a direct action (type I); overlaid on the flow regulator casing (type II); continuous, of an indirect action, having a heat transfer channel (type III); continuous, of an indirect action, having no heat transfer channel (type IIIa); of indirect action, built into the regulator casing (IIIb); continuous, of an indirect action, having a swirler (type IV).

The continuous direct-action heater (type I) is a sealed vessel housing a ceramic insulator with an electric heater (nichrome spiral). This heater is no longer produced now because of low reliability.

The heater overlaid on the regulator casing (type II), which is produced now in Russia, is equipped with a device to apply heat through the flow regulator casing. It has a number of important drawbacks, such as low efficiency (the major part of thermal energy goes to the environment), strong dependence of the efficiency upon the ambient temperature and humidity, dependence upon the flow regulator design (heat-transfer resistance of the heat flow path), and low reliability because of considerable overheating of the spiral caused by insignificant removal of heat from it.

The continuous indirect-action heater equipped with a heat transfer channel (type III) is a casing with a built-in heating cell and elongated heat transfer channel for the gas flow. This heater uses a heating cell made from a special carbon material. A low efficiency of heat transfer is caused by a large size of the

**HIRNAL** 

gap in the heat-transfer channel (more than 2 mm). A more reliable closed-type thermostat is used as a temperature regulator. This heater is no longer produced because of large dimensions and high price of the heating cell.

The continuous indirect-action heater having no heat transfer channel (type IIIa), the manufacture of which was mastered at the beginning of 2004 in Russia, is a casing with a built-in heating cell and simple gas flow channels. The heater provides partial heating of the gas and heats the flow regulator through the inlet nozzle material. A reliable heating cell is used in this design of the heater, and a more reliable closedtype thermostat is employed as a temperature regulator. The heater has some drawbacks, such as low efficiency (the major part of thermal energy goes to the environment, low heat transfer to the gas flowing in it, and high resistance to the heat flow from the heater to flow regulator casing), and strong dependence of its efficiency upon the ambient temperature and humidity.

The indirect-action heater built into the flow regulator casing (IIIb). This design is characterised by an increased efficiency provided by a substantial decrease in resistance to heat transfer from the heating cell to the reducing valve. The regulator features a stable operation at high gas flow rates. However, because of a low heat transfer to the gas flowing though it, the gas temperature at the outlet of the regulator is insufficient for normal operation (below zero). In this case the problems are solved but partially, i.e. only for the reducing valve of the flow regulator. In addition, the combined design of the regulator and heater is not always convenient for operation.

The continuous indirect-action heater equipped with a gas flow swirler (turbulence generator) (type IV) presents an attempt to dramatically increase heat transfer from the heating cell to the gas flowing through it by raising the heat transfer intensity through detachment and destruction of a viscous sublayer as a result of the effect by roughness peaks and formation of vortex zones in the heated gas flow. However, efficiency of the vortex-type heat transfer turned out to be insufficient, which dramatically limited capacity of the heater (to 8 1/min).

As proved by the tests, all of the above types of the heaters fail to comply with the task. Even at a gas flow rate of 15 1/ min the gas temperature under the steady-state conditions falls more than twice, compared with the initial temperature (from +12 °C of the type II heaters to --2 °C of the type IIIa heaters). All the heaters have a negative gas temperature at the outlet of the flow regulator under the steady-state conditions at a gas flow rate of 30 1/ min (from -1 °C of the type II heater to --18 °C of the type IIIa heater).

The challenge in development of new heaters was to dramatically increase efficiency of heat transfer to the flowing gas and reduce weight through decreasing the thermal time constant. The latter increases response of a heater and decreases temperature gradient during transition processes.

When looking for the methods to increase efficiency of heat transfer, the starting point for the development was a patent [4] for a fluid medium electric heater. Its novelty was that increasing density and intensity of a turbulent flow of the medium provided increase in the intensity of heat transfer caused by detachment and destruction of the viscous sub-layer as a result of the effect exerted by roughness peaks and formation of vortex zones. This method was implemented in the continuous indirect-action heater with a gas flow swirler (type IV).

Analysis of the character of distribution of temperature in the boundary layer (according to the heating engineering course) allowed offering an idea to use this distribution to raise the efficiency of heat transfer in a carbon dioxide heater. To solve this problem, it was necessary to pump a carbon dioxide gas through the gap, the size of which should not exceed that of the viscous sub-layer. The smaller the size of the gap with respect to the viscous sub-layer, the higher the heat transfer efficiency.

As shown by calculations, size of the viscous sublayer in heating of the carbon dioxide gas flow at a rate of up to 50 1/ min is within a range of realistic values. Depending upon the cross section area of the gap, thermal contact area and temperature gradient, this value ranges from 0.05 to 0.5 mm. Increase in drag at a small gap is not an obstacle in this case, as there is a substantial margin of the gradient of pressure of a liquefied carbon dioxide gas (about 60 atm) and maximal working pressure of the flow regulator (up to 6 atm).

Structural diagram of a fluid medium heater with heat transfer in a viscous sub-layer was developed with allowance for the above factors (Figure 1). The heater comprises heating cell 1 in thermal contact with casing 2. Gap 6 is formed between casing 2 and jacket 5, radiating surface 3 and screening surface 4 are formed in the gap. Size of gap 6 is made smaller than that of the viscous sub-layer of the fluid medium, which allows increase in the efficiency of infra-red heat transfer through it and, as a result, leads to heating of screening surface 4 to temperature  $T_{sc}$ , this surface becoming radiating with respect to the fluid medium moving at velocity v. As a result, a wedge of two viscous sub-layers is formed in gap 6. In this wedge the gas heated from heat flow Q acquires temperature  $T_{sl}$  (temperature in slot), which is much higher than temperature of a turbulent core  $(T_t)$ . The latter characterises the mean temperature of gas in a case where the size of the gap is much larger than that of the viscous sub-layer,  $\delta$ .

This heat transfer intensification method allows dimensions of the gas heater to be decreased, design of the device as a whole to be simplified through using simple cylindrical surfaces that form the slot gap, and temperature of the heat transfer surface to be reduced, thus improving reliability and extending life of the heater.

Further increase in the heat transfer efficiency through decreasing the gap was limited by the capabilities and cost of its technical embodiment. It was found that the heat transfer efficiency could be increased through decreasing the heat transfer gap to a size much smaller than that of the viscous sub-layer as a result of using porous metallic and metal-ceramic materials. In addition, this offered the technological possibility of



**Figure 1.** Diagram of fluid medium heater with heat transfer in viscous sub-layer (see designations in the text)

reducing an efficient diameter of pores to 1  $\mu m$  with a substantial increase in the heat transfer area.

Technically, the nature of the heat transfer process is that grains of a metal-ceramic material adjoining the radiating surface form a through porous structure with channels smaller in size than the viscous layer. The total radiating surface of grains of the structure is by orders of magnitude larger than the radiating surface they adjoin, from which, because of their high conductivity, they intensively remove thermal energy to the heat carrier flowing via the channels in the porous structure. As a result, this makes it possible to substantially raise capacity of the heater or reduce its dimensions and decrease temperature of the heating cell.

One of the embodiments of this method is shown in Figure 2. It is intended for heating of a fluid (mainly gaseous) medium. It comprises heating cell 1 in thermal contact with casing 2, which has radiating surface 3. Screening surface 4 is on jacket 5. The surfaces are separated by gap 6, the size of which is not limited by size of the viscous sub-layer and can be larger than that dictated, primarily, by the heater capacity. Gap 7 is filled with grains 6, which should be made from a material characterised by high thermal conductivity (e.g. copper or its alloys). The porous structure can be formed of grains loosely pored into gap 7, or of grains consolidated into a module using a binder. Metal-ceramic gas filters may serve as an example. Heat

Figure 2. Diagram of heat transfer using porous metallic or metal-ceramic materials (see designations in the text) flow Q from heating cell 1 (see Figure 2) through casing 2 passes to grains 6 through a physical contact of the latter, pressed directly to radiating surface 3, and then to other grains located over the entire width of gap 7. Heat carrier v (in the case the gas under consideration) flows at a certain rate through the porous structure formed of grains 6. The grains form a porous space with channels, the sizes of which are smaller than size of the viscous sub-layer,  $\delta$  (Figure 3). Grains A and B have corresponding temperatures  $T_A$  and  $T_B$  ( $T_A$  is the radiating surface temperature, and  $T_B$  is the screening surface temperature).

Figure 4 shows schematic diagram of the heater with a maximum possible efficiency, where the surface of each grain becomes radiating, and thermal energy is generated by eddy currents *i* in the granular metallic material using high-frequency alternating magnetic field *C*. This diagram can be used as a basis for making a small-size heater with an extremely high efficiency.

The fluid medium heater was developed, in which a contact in the form of a spiral was made between the radiating and screening surfaces forming the heat transfer channel. The spiral channel makes the path and time of contact of the fluid medium in the heating zone much longer, the size of the channel being not larger than that of the viscous sub-layer. The physical contact between the radiating and screening surfaces leads to a direct transfer of thermal energy from the first to the second region, thus transforming the latter into a radiating one. Therefore, the flow of the fluid medium interacts in fact only with the radiating surface, which encloses it on all sides.

Designs of the heaters shown in Figure 5 and 6 were developed on the basis of these solutions. A heating cell has a thermal contact with radiating surface 1 (Figure 5), which is in a physical contact through sites 2 with screening surface 3. Sites 2 have the form of a spiral. The simplest design of this structure is a conventional metric thread with a profile partially decreased in height on the shaft. Figure 6 shows a design with the screening surface formed of a spirally wrapped wire. In all the cases there is a spiral heat transfer channel 4 located between sites 2. The shape of the channel is determined by a design of the heater. This can be a triangular or rectangular section, or any other geometric configuration. The largest cross section size of the heat transfer channel should not exceed size of the viscous sub-layer of the



**Figure 3.** Diagram of flow of heat carrier in porous structure (see designations in the text)





Figure 4. Schematic diagram of heater with generation of eddy currents

fluid medium,  $\delta$ . Directions of heat flow Q from radiating surface 1 to screening surface 3, passing over contact sites 2, are indicated by arrows.

The above heat transfer designs and method are covered by Russian patent 2214696 «Fluid Medium Heater», and utility model certificate 21707 «Fluid Medium Electric Heater». In addition, two more applications were filed for the anticipated inventions.

In 2000 the Research & Production Company VRT completed development and mastered manufacture of carbon dioxide gas heater PUZ-70-50, based on the above design solutions. Figure 7 shows its design using the method of heat transfer with a gap smaller in size than the viscous sub-layer. Increase in the heat transfer intensity allowed dimensions of the gas heater to be reduced, design of the device as a whole to be simplified through using simple cylindrical surfaces, and temperature of the heating cell to be decreased, which made it possible to limit the temperature of heating of the casing to no more than 70 °C and provided a substantial improvement of reliability and extension of service life.

The characteristic feature of the heater PUZ-70-50 is that increase in the heat transfer intensity is provided by making the entire flow of a gas heated pass through the zone of the viscous sub-layer, which leads to reduction in heat-transfer resistance during the heat transfer process.

The fluid medium electric heater (Figure 7) comprises casing 3 with inlet and outlet nozzles 1 and 4, respectively. Tubular heating cell 5 is housed in casing 3, which is coaxial to gap 2. Control unit 6 with a



**Figure 5.** Diagram of heating cell with adjoining radiating and screening surfaces (see designations in the text)



**Figure 6.** Diagram of heating cell with screening surface formed of a wrapped wire (see designations in the text)

light indicator located inside it is mounted outside, coaxially to casing 3.

The fluid medium being heated passes through inlet nozzle 1 to gap 2 between tubular heating cell 5 and casing 3, where the heat transfer takes place. The fluid medium being heated decreases the temperature of casing 3 and heating cell 5 within the zone of inlet nozzle 1 and connection of control unit 6 by removing heat to outlet nozzle 4 with incoming masses of the fluid medium. Hence, mounting of control unit 6 on the outside allows the heat flow to it from heating cell 5 to be decreased. This improves reliability of the electric heater through decreasing overheating of control unit 6 and connecting contacts to heating cell 5.

When the heater is connected to the AC mains with a voltage ranging from  $36^{-15}$ % to  $42^{+10}$ % V, its casing is heated to a temperature not above 70 °C. The temperature is maintained automatically by the electronic control system. The control system is made in the form of symistor-based control unit  $\theta$ , the temperature being maintained using a temperature sensor. The symistor is switched over only when the supply voltage passes through zero, which provides a substantial decrease of the radio noise level. Only the «on» time of the heater changes with a change in the gas flow rate.

#### **Specifications of heater PUZ-70-50**



**Figure 7.** Appearance (*a*) and structural design (*b*) of heater PUZ-





**Figure 8.** Appearance (*a*) and structural design (*b*) of heater PUZ-70-30

Casing heating temperature (at ambient

temperature of30 - +50 °C), °C 60 <sup>+8</sup> <sub>-20</sub>	
Supply voltage (AC), V $\approx 36^{-15 \%} - 42^{+10 \%}$	
Maximum current consumption	
$(42^{+10 \%} V)$ , A, not more than	
Inlet and outlet mounting dimensions, thread G3/4"	
Weight, kg, not more than $\approx 0.5$	
Overall dimensions, mm, not more than $\dots D32 \times 66 \times 123$	

In 2004 the Research & Production Company VRT completed development and started mass production of the PUZ-70-30 heater (Figure 8). Increase in the heat transfer intensity allowed decrease in its dimensions, simplification of design of the device as a whole, and decrease in temperature of the radiating surface, which is made part of the casing, the temperature of which is not in excess of 80 °C according to the requirements of GOST 12.2.007.9--93, which provided a substantial improvement in reliability and extension of life of the heater. The gas flows through the channel formed between the thread of a hole in casing 3 and partially cut thread of insert 4, where the gas is heated. The flow regulator or reducer is connected to the heater outlet with thread G3/4". When the heater is connected to the AC or DC mains with a voltage ranging from  $36^{-15\,\%}$  to  $42^{+10\,\%}$ V via cable 1, its casing is heated to no more than 80 °C. The temperature is limited automatically by thermostat

2. Only the «on» time of the heater changes with a change in the gas flow rate.

#### **Specifications of heater PUZ-70-30**

Throughput capacity, $1/\min$ , not less than
Maximum gas pressure, MPa 20
Casing heating temperature, °C, not more than
Gas temperature at heater outlet (at ambient
temperature of 20 °C), °C:
at $U_{\rm s} \approx 36$ V and flow rate of up to 30 l/min 1821
at $U_s \approx 24$ V and flow rate of up to 15 l/min 1012
Supply voltage (AC or DC), V $\approx 36^{-15 \%} / 42^{+10 \%}$
Power consumption, W 100/136
Power consumption at $U_s \approx 24$ V, W, not more than 44
Inlet and outlet mounting dimensions, thread G3/4"
Cable length, m, not less than 2
Heater weight, kg, not more than:
with cable
without cable
Overall dimensions, mm, not more than $\dots$ D32 $\times$ 48 $\times$ 71

The accepted technical solutions for the heater allowed its weight and dimensions to be decreased almost twice.

To prove correctness of the accepted solutions, comparative tests of all the heaters produced currently in Russia (Table 2) were conducted.

The simplest testing method offered by a laboratory of the Russian Welding Institute (St.-Petersburg) was selected. This method can be easily understood by any welding operator working with semiautomatic  $CO_2$  welding devices. For this it is necessary to have a carbon dioxide gas bottle and heater, as well as thermometer and clock. The tests were conducted as follows: all the heaters were tested using one flow regulator of the U-30-2 type under laboratory conditions at a temperature of 22 °C.

The test procedure allows evaluation of both static characteristics of the heaters (steady-state temperature at the flow regulator outlet) and dynamic characteristics, such as time and decrease in temperature at the flow regulator outlet in transition processes.

Results of the tests of different Russian heaters are shown in Figure 9. It can be seen from analysis of the tests that characteristics of the heaters of types I, III and IV in the steady-state mode are within  $\pm$  5 °C both at 15 and at 30 l/min. It is obvious that the heater of type IIIa has worse characteristics. So, it was not considered in further analysis. The best results at a gas flow rate of 15 and 30 l/min were exhibited by the heater of type II. However, they were obtained at overheating of the heater casing by more than 80 °C. In our experiments the casing temperature was 110--120 °C, which did not comply with safety requirements (GOST 12.2.007-9--93) and could not be considered in comparative analysis. The heater of type III has much better characteristics than type IV. However, it is no longer produced. Therefore, we compared heaters PUZ-70-50 and PUZ-70-30 with heat transfer in the viscous sub-layer with a continuous indirect-action heater equipped with a swirler (type IV). Also, we compared temperature characteristics of the PUZ-70-50 and PUZ-70-30 heaters with heat transfer in the viscous sub-layer with those of the heater of type IV at a gas flow rate of 15 and 30 l/min.

Table 2. Main characteristics of tested heaters

Type of product	Characteristic of design of heater	Date of manufacture	Weight, kg	Power, W (U = 36 V)
Type II	Overlaid on regulator casing	2003	0.55	150
Type III	Continuous, indirect-action, with heat transfer channel	November 2003	1.13	150
Type IIIa	Continuous, indirect-action, without heat transfer channel	March 2004	0.70	160
Type IV	Continuous, indirect-action, with swirler	October 2003	0.45 without cable	130
PUZ-70-50, R&P Company VRT	Continuous, indirect-action, with heat transfer in viscous sub-layer	December 2003	0.55	90
PUZ-70-30, R&P Company VRT	Continuous, indirect-action, with heat transfer in viscous sub-layer, lightweight design	May 2004	0.35; 0.25 without cable	100

It was found that the gas temperature at 15 l/minwas +3 -- +4 °C (the heater of type IV), +23 -- +25 °C (PUZ-70-30) and +35 -- +36 °C (PUZ-70-50).

The use of the viscous sub-layer allowed a substantial increase in the gas temperature at the flow regulator outlet (by 20  $^\circ C$  for PUZ-70-30 and more than 30 °C for PUZ-70-50), the design being simplified, weight of the heater and set power being decreased. Even at a gas flow rate of 15 l/min and ambient temperature of 20--22 °C the temperature at the flow regulator outlet in the heaters of types III and IV is not in excess of 10 °C.

An increased gas temperature at the flow regulator outlet for the PUZ-70-50 heater (36 °C), compared with the PUZ-70-30 heater (25 °C), is indicative of a higher temperature of its heat exchanger, which is almost completely insulated from the casing by the heat transfer gap. Temperature of the heat transfer surfaces for the PUZ-70-30 heater is less important, as these surfaces are made part of the casing, the temperature of which is limited to 80 °C according to GOST 12.2.007-9--93.

The steady-state gas temperature at a gas flow rate of 30 1/min is --8 -- --9 °C (type IV) and +22 -- +23 °C (PUZ-70-30 and PUZ-70-50). These experimental data prove advantages of the heaters with heat transfer in the viscous sub-layer. Almost all heaters of types III, IIIa and IV have a negative temperature at the flow regulator outlet. With a gas flow rate changed from 15 to 30 l/min, the «on» time of thermal regulators of these heaters increased by no more than 20--30 %. In this case, for the PUZ-70-50 and PUZ-70-30 heaters the «on» time of thermal regulators changed by a factor of 2--3. This difference in the «on» time of thermal regulators proves the efficiency of heat transfer provided by the PUZ-70-50 and PUZ-70-30 heaters.

A smaller dip in temperature at the second minute for the PUZ-70-30 heater (5 °C), compared with the PUZ-70-50 heater (--3 °C), is caused by the fact that weight of the latter is almost 2 times as large (0.45 compared with 0.25 kg), the power of the heater being a bit lower (90 compared with 100 W), and the heat transfer efficiency being higher with the PUZ-70-30 heater. The more efficient heat transfer with the PUZ-70-30 heater is confirmed by a insignificant fall of the steady-state gas temperature (from 25 to 22 °C) with a change in the gas flow rate from 15 to 30 l/min, compared with the PUZ-70-50 heater (from 36 to 22 °C). However, the efficiency of the PUZ-70-50



Figure 9. Time dependence of gas temperature at flow regulator outlet at a gas flow rate of 15 (a) and 30 (b)  $1/\min 1 - type$ II, overlaid on flow regulator casing; 2 ---- type III, continuous, indirect-action, which heat transfer channel; 3 - type IV, continuous, indirect-action, with swirler; 4 — type IIIa, continuous, indirect-action

heater is higher than that of the PUZ-70-30 heater, which is caused by a lower thermal power dissipated into the environment. This fact is proved by the temperature of the casing surface at a gas flow rate of 30 1/min. This temperature in the PUZ-70-50 heater is 46 °C, and in the PUZ-70-30 heater it is 72 °C.

It can be noted in conclusion that heaters with heat transfer in the viscous sub-layer meet to the fullest degree the main technology and consumer requirements, compared with heaters of other types, thus providing an increased capacity and improved weld quality in mechanised gas metal arc welding.

- Belfor, M.G., Paton, V.E. (1974) Equipment for arc and slag welding and surfacing. Manual for supervisors on im-plementation of advanced welding and surfacing methods in national economy. Moscow: Vysshaya Shkola.
   Fedko, V.T., Kiyanov, S.S. (2001) Optimisation of design of gas economizer. Svarochn. Proizvodstvo, 4, 27.
- (1998) Welding and materials to be welded. Vol. 2. Technology and equipment. Ed. by V.M. Yampolsky. Moscow: N.E. Bauman MGTU.
- Pavlovsky, V.G., Ganzha, N.G., Bykov, A.V. et al. Fluid medium electric heater. Author's cert. 1474870. Int. Cl. H05 B 3/50. Publ. 1989.

### FROM THE HISTORY OF BRAZING

### **ELECTRIC HEAT SOURCES FOR BRAZING**

#### A.M. ZHADKEVICH

E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

History of application of electric heat sources for brazing of different materials is described. Specifics and capabilities of the processes, performed using equipment based on electric heating, are analyzed. Contribution of individual specialists to the development of equipment and technologies of brazing is outlined.

**Keywords:** brazing, arc heating, resistance heating, vacuum, electric furnaces, electric contact heating, history of engineering

Electric power, being the most widely spread power source, is used for brazing. It began to be used for technological purposes since the time of invention of the first accumulators and devices for electric current generation.

The aim of the present work is to analyze the progress of electric heat sources for brazing, their relation with the first sources for metal treatment and discoveries in the field of electricity.

In the history of engineering the beginning of the XIX century was remarkable by the creation of DC power sources and discovery of physical and chemical phenomena in the field of electricity. Almost simultaneously, the search for methods of application of electric power began in different countries for the solution of industrial problems, first of all, technological problems directed to the improvement of methods of metal treatment.

V.V. Petrov, who discovered the phenomenon of arc discharge (1802), noted the feasibility of arc heat application for metal melting. Heat effect of current, passing in a platinum wire, was observed by L. Tener in 1881, and in 1807 G. Devi designed the first electric resistance furnaces with direct and indirect heating. Amount of heat Q, generated in a conductor at resistance R for time t in passing current I was stated in 1841 by J.P. Joule and confirmed in 1842 by precise experiment of E. Lentz:  $Q = \alpha I^2 Rt$ . In 1831 M. Faraday discovered the phenomenon of electromagnetic induction, and the eddy current in metallic masses began to be studied by L. Foucault. V. Felici (1853), H. Hertz (1880), E. Heaviside (1884) and other physicists were dealing with analytic calculation of this phenomenon. For the first time the method of induction heating of iron bar at the Edinburgh Fair was demonstrated by S. Thomson in 1891 [1].

Simultaneously with experimentally-theoretical investigations of these phenomena the attempts were made to use heat effect of current for different technological processes, including also for technologies of melting and joining of metals. In 1877--1884 E. Thomson developed a butt resistance welding, using the phenomenon of resistance heating, and in 1881 N.N. Benardos developed the first method of arc fusion welding [2].

At the end of the XIX ---- beginning of the XX centuries the optimum designs of metallurgical furnaces were invented in different countries of Europe and the USA. In Russia several different designs of unique furnaces were also developed by V.P. Izhevsky [1, 3]. Owing to these inventions it became possible to use electricity not only for welding, but also for related technologies, including brazing. Electric heat sources differ beneficially from other known heat sources by the feasibility to control temperature and heat rate quickly and precisely, to braze using refractory brazing alloys in any gas atmosphere or in vacuum. Since the last quarter of the XIX century the development of equipment and new technologies of brazing the increasing in nomenclature of materials and products has started. Since that time it is possible to start counting of the second period in the history of brazing characterized by the significant increase in amount of methods of joining, increase in efficiency of processes and quality of the products. By the middle of the XX century the technologies of brazing based on application of electric heat sources occupied the leading place forcing out the earlier-known technologies of brazing from many branches of industry and became to be used effectively in the solution of problems of the commencing scientific-technical revolution.

One of the first brazing methods was a furnace brazing. In 1912 M.N. Beketov brazed the molybdenum discs with steel bars in furnace in hydrogen atmosphere [4]. During the first years the brazing in gas media, using fluxes and brazing filler alloys, including refractory ones, was performed in furnaces for hardening, annealing, tempering and heating for forging, while at that time the industry of different countries has available arc, induction furnaces and furnaces with resistance heating [1]. By the end of the 1920s the more sophisticated furnaces were created for brazing. Among the first furnaces were electric resistance furnaces with a neutral or active gas medium, devices for preparation of active gas media, devices for assembly and transportation. By the principle of heating the electric resistance furnaces can be divided into two groups: furnaces with a convective heat transfer and furnaces with infrared heating (heat transfer by heating). Generators of increased (500--10000 Hz) and high (above 500000 Hz) frequency are used in installations for induction brazing as power sources [5]. The most optimum variant of heating is the direct heating of product. Induction muffle furnaces of industrial frequency with machine generators in which the heat is transferred from walls found also their application. In 1939 the installation for induction vacuum brazing of bodies of spark plugs of internal combustion engines was designed at the plant «Svetlana») (Leningrad city).

At the second half of the XX century titanium and aluminium alloys began to be used in ship and aircraft building, rocketry; zirconium, tungsten, nickel and other alloys ---- in nuclear power engineering, cryogenics, electronics and other developing branches. In manufacture and repair of these objects the brazing occurred to be most optimum in many cases and often indispensable technological process. And to provide the required service quality, the search for the new brazing alloys and heating technologies is carried out over the many years. Here, the properties of alloys joined and brazing filler alloys specify the precise maintaining of heating conditions and control of chemical-metallurgical reactions. Gas-flame heat sources did not satisfy these conditions. Therefore, the main attention was paid since the end of the 1940s to the development of new technologies, based on electric heating, in arrangement of products in furnaces and chambers, in open air and at a local protection, using fluxes, special coatings and others.

Over the next decades the furnaces of different designs have been developed: multi-channel, shaft, double-bell type furnaces and others [5]. Brazing capabilities were significantly widened owing to the creation of furnaces with high vacuum control and furnaces with devices for compression of parts being joined. The special furnaces for brazing were developed by VNIITVCh, VNIIETO, E.O. Paton Electric Welding Institute, K.E. Tsiolkovsky MATI and a number of other institutions. Brazing in electric furnaces makes it possible to use fluxes of almost any composition, to perform brazing in a wide temperature interval at simultaneous heating of the entire product. Except metals, the reliable joints of metals with ceramics and cermets can be produced in the furnaces [5]. In the 1960s a technology of brazing of metal-ceramic vacuum-compact products in furnaces was developed [6]. Technology of brazing in vacuum furnaces was developed in the 1970s in manufacture of devices for joining corundum ceramics with Fe--Ni alloys [6], in manufacture of aircraft structures from titanium alloys [7] and parts of gas turbine engines from heat-resistant alloys [8]. To improve the quality of brazing the process is performed in vapors of reactive metals in protection-reduction atmosphere in containers placed into furnace [9].

An example of effective application of brazing in conventional furnaces for heat treatment can serve the equipment and technology of manufacture of aircraft and ship gas turbine engines, developed by specialists of NIID and «Salyut» (Moscow). To increase the service parameters of engines, in particular the operating temperatures of a hot path, it was necessary to use new dispersion-strengthened heat-resistant alloys of JS type referring to non-weldable and hardto-braze alloys. Brazing of nozzle components and combustion chamber, blades of turbines and compressors, and also other parts using the composite brazing alloys was suggested to be performed in containers in active gas medium from mixture of argon and products of decomposition of halogenides. Such technology allowed not only manufacturing of large-sized assemblies, but also reduction of expenses in preparation for brazing and post heat treatment [10].

Electric resistance furnaces occurred to be effective for realization of the flux-free brazing process in vapors of reactive metals, moreover, in gas atmospheres of lower purity and vacuum as compared with other processes. V.F. Khorunov, B.N. Perevezentsev and others have studied the physical-chemical processes and developed the technology of brazing using brazing filler alloys containing easily-evaporated components, which consists in adding of vapors of these elements into the furnace chamber, and proved the feasibility of alloying from a vapor phase. In addition, the studies were made in heating in argon, nitrogen,  $CO_2$  and closed air medium (Figure 1) [11].

Since the XX century the out-of-furnace electric resistance brazing began to be used in electric industry and instrument making. Brazing was realized for a long time for joining wires, plates, frames and other components using welding butt and spot machines, allowing maintaining the time and heat temperature at a high precision. At high heat content of parts  $P \cdot 10^{-4}$ , Pa







being joined it is possible to repeat the feeding of current pulses many times. As far back as by 1920 three schemes of heating were developed using direct passing of current through the brazed parts, current passing through one part with heating of the second part by heat transfer and heating of a special heater by current, at the expense of heat transfer from which the brazed parts are heated [4, 5].

In the 1960s at Toliatti Polytechnic Institute (S.V. Lashko, et al.) the investigations were carried out for the development of technologies eliminating such methods of removal of oxide films as application of degassing, reactive gaseous media, mechanical or ultrasonic action, fluxing. The feasibility of activation of surfaces being brazed by a local melting of metals and alloys at temperature below the temperature of their autonomous melting, contact-reactive brazing, was established [12]. This process was used in fluxfree brazing of aluminium alloys with some metals, having a good chemical affinity with aluminium [13], and also in brazing of corundum ceramics with niobium alloy using interlayers of a copper and titanium foil [14]. In K.E. Tsiolkovsky MATI (Yu.S. Dolgov, A.F. Nesterov et al.) the contact-reactive brazing with a negligible pressure between parts was used for manufacture of assemblies of aircraft engines made from nickel alloys of JS type.

An especially precise control of parameters of heating conditions and metallurgical processes was attained in contact-reactive brazing, in particular in manufacture of devices with parts made from molybdenum, tungsten and copper, coated with gold or silver (V.F. Khorunov, Yu.B. Malevsky, V.S. Nesmikh) [15, 16].

In many cases when selecting the technology of brazing and equipment, the definite requirements of service properties in combination with economy have the determinant importance. Thus, for example, it was managed to attain a significant saving of highspeed and structural steels due a electric contact heating at the Research Institute of Tool Manufacturing (Moscow). 12 modifications of specialized electric contact machines have been developed, whose application will 15--20 times save the electric power and 3--4 times save the area of equipment, as compared with machine TV4, and will allow using brazing alloys on Fe--Cu--Ni base instead of brazing alloys on silver base [17]. The effective method of electric contact heating at a single-side two-point supply of current has been developed at the Georgian Polytechnic Institute [18].

Many years the major solders both in electronic industry and also in jewelry were based on silver. Due to growing volume of manufacturing of instruments and other products with electronic elements, the problem of saving noble metals in soldering, and at the same time, of improvement of the reliability of joints, was faced. In a number of organizations the brazing alloys of Cu--P--Sn, Cu--Zn--P--Ni systems were developed for joining of parts made from copper and brass; Cu--Zn--Sn, Cu--Zn--Mn systems were developed for brazing of stainless steel, copper and steel. Electric contact flux-free brazing found the wide spreading [19].

In the 1960s the installations were developed at the E.O. Paton Electric Welding Institute for diffusion brazing in vacuum using induction and radiation heaters [20]. In the 1970s US companies General Dynamics and Boeing Airplane manufactured installations in which the products are heated directly by the passing current. In these and other installations the compression of parts being brazed is realized [21]. In the 1980s the vacuum installations for diffusion brazing were implemented in ship building industry, which were designed in Nikolaev Ship Building Institute (V.F. Kvasnitsky et al.) [22] and in some specialized research institutes.

At present the induction brazing, in spite of complexity of equipment and need in manufacture of specialized inductors, occupies one of the leading places by the volume of application and feasibility of manufacture of complex structures. The first specialized installations and technology of high-speed brazing in heating with high-frequency current were designed by V.P. Vologdin and M.G. Lozinsky at the second half of the 1930s. The induction brazing continued to be improved in the 1940--1950s in NIITMe, N.E. Zhukovsky VVIA and in other organizations (M.V. Poplavko, S.N. Lotsmanov, V.P. Frolov et al.) [23]. Such advantages of induction brazing as rapid heating of products, high efficiency and feasibility of mechanization and automation, attracted attention of many specialists in the developing branches of industry. The E.O. Paton Electric Welding Institute, branch research institutes of Minsudprom, Minsredmash and others also started the investigations of the process of induction heating and improvement of technology and equipment. It was stated that the induction brazing provides the high quality of joints using brazing filler alloys in which silver was replaced by less expensive components [24], uniform heating and quick penetration of the brazing alloy into thin-walled products of the intricate shape [25], producing composites in the form of an embedded element of a composite brazing alloy [26]. Induction heating has found application for melting of a large amount of flux and brazing filler alloy for the technologies of joining in melts of these materials [27], including also for brazing by a wave of the brazing alloy [28].

Induced current can serve not only for heating brazing alloy, flux and edges, but also is used in some installations as a force of interaction with natural magnetic field for movement of the brazing alloy [28]. Thus, it is used successfully for accelerating of fluxing [29].

At the beginning of the 1970s the work was intensified on brazing with applying of compressive loads. Thus, technology of braze welding was developed at the E.O. Paton Electric Welding Institute on the base of the high-frequency heating, in particular, the equipment for high-frequency brazing using pressure of such large-sized products as turbine rotors (V.K. Lebedev, L.G. Puzrin, G.A. Bojko) [29]; pipes (V.K. Lebedev, V.D. Tabelev, V.D. Pismenny) [30]. At a sufficient plastic deformation it is possible to attain the strength of joints equal to the strength of the parent metal [31--34].

The above-described methods of heating in brazing were developed almost simultaneously with the same methods of heating in welding and heat treatment. In the 1920s the arc discharge became the most widely spread heat source in welding, however, its use for brazing was limited. This was caused by a high concentration of heat energy in the zone of active spots, resulting in a high probability of pre-fusion of edges of the product, and in instable arc burning at decrease in current value to reduce the heat input. Nevertheless, in some cases the arc brazing finds application only due to a relatively high concentration of heat input. In the 1920–1940s the atomic-hydrogen process was used for brazing, besides the indirect arc between two electrodes.

Arc heating in brazing was used periodically in those cases when the brazing alloys with refractory components were used and a local heating was envisaged. Thus, at the end of the 1990s the technology of a repair brazing of blades of gas turbine engines from high-alloy nickel alloys using arc heating with tungsten electrode in argon and composite nickel brazing alloys with zirconium and hafnium was developed at the E.O. Paton Electric Welding Institute and NPO «Mashproekt» (V.F. Khorunov, S.V. Maksymova et al.) [35].

In 1964 microplasma welding was developed at the E.O. Paton Electric Welding Institute, including first in the world welding at variable-polarity pulses (B.E. Paton, V.S. Gvozdetsky et al.) [36]. This process, characterized by a local heating (Figure 2), found an application, simultaneously with welding, for brazing of thin-walled aluminium bellows, jewelry, parts of electronic devices. The advantage of application of the machine for microplasma treatment (Figure 3) is a good visibility of the brazing zone and minimum burning out and evaporation of brazing alloys in inert gases.

It should be noted that the thermal cycle in the point of a near-weld zone heated to temperature of brazing alloy melting (about 100 °C) in microplasma process is differed beneficially from the cycle of heating in argon arc process (Figure 2). These peculiarities of the microplasma process, as a rapid increment of temperature (I) and significant reduction in time of duration at maximum temperature (II) alloys using brazing filler alloys and fluxes with easily-evaporating comments for brazing, decreases HAZ. One more advantage is the possibility of supplying the reactive gas (for brazing alloy) through the external nozzle into the zone of melting.

In the 1970s at N.E. Bauman MVTU the process of welding and brazing with non-consumable hollow electrode in vacuum (with argon inleakage through a cavity of the tungsten electrode) was developed



Figure 2. Thermal cycles of microplasma (1) and argon-arc (2) welding (brazing)

[37]. The arc brazing in vacuum provides the high quality of dissimilar metal joints, including also in restoration of shape and sizes of gas turbine blades [38]. Unique equipment and technology of arc braze welding was developed at S. Ordzhonikidze Siberia Metallurgical Institute [39].

Another type of electric discharge, a glow discharge, began to be used for brazing since the 1960s [40]. It has a number of advantages as compared with other electric heat sources. Large volumes of investigations of technological features of this process were made in KPI (D.I. Kotelnikov), Nikolaev Ship Building Institute (V.S. Vanin), Perm Research Institute (V.F. Zinoviev et al.) and in other organizations [40– 42]. Glow discharge provides uniform heating of the



Figure 3. Versatile machine for microplasma treatment MPU-4



Figure 4. Vacuum installation for diffusion welding and brazing VUSP-28 (design of the E.O. Paton Electric Welding Institute)

entire product or its area, can exist in any atmosphere (for example, reduction), and is performed without fluxes in a closed chamber, high quality of the joints is guaranteed without a special cleaning of the surface [42].

Over many decades the most important problem of heat engineering was the creation of heat exchange devices. Since the 1960s a special attention was paid to the manufacture of plate-finned structures not only in power engineering, but also in aircraft and aerospace industries. The E.O. Paton Electric Welding Institute has developed the technological process in which the heating of product up to the temperature of melting of the brazing alloy is realized in a vacuum furnace by a pair of corrugated plates isolated from the product. As heaters, the graphite plates were also offered which in parallel with high heat conductivity and high electric resistance are not deformed at the brazing temperatures. These plate compress the product in the process of heating. Additionally, the product can be heated by a glow discharge [43, 44]. These combined installations make it possible to use brazing of heat exchange and lattice structures made from different materials (Figures 4 and 5).

The unique method of manufacture of semiconductor instruments was developed at the E.O. Paton Electric Welding Institute (A.A. Rossoshinsky, V.A. Lebiga, V.M. Kislitsyn et al.), based on heating of brazing site with Joule heating, here a semi-conductor structure used as a heating element, through which the electric current is passed in a direction to *p*--*n* transition [45]. Except the above-mentioned technologies of brazing, based on heat action of electricity, the other types of brazing are known (using a wave of brazing alloy, autovacuum, in molten flux, electric



Figure 5. Scheme of heating of multi-layer structures at current passing through graphite plates and with use of a glow discharge: - frame connected to a positive pole of the second power source for creation of a glow discharge; 2 - current supply to a graphite plate and first power source; 3 ---- graphite plate with electricallyisolated layers; 4 — product being brazed

solder irons) in which the heat energy, generated in current passing, is used [27, 46--48].

#### CONCLUSIONS

1. Application of electric heat sources widened greatly the capabilities of brazing since the end of the XIX century to the middle of the XX century. During the second stage of the brazing development such technologies were developed which make it possible to control the condition parameters: temperature and rate heating, heat input and others at a high precision.

2. Versatile and special equipment with electric heaters and devices to provide pressure on the product, with a feasibility of degassing and creation of a controllable atmosphere has been developed.

3. Development of new methods of brazing provided the manufacture of products made from new materials, such as complex-alloyed metallic alloys, cermet and ceramics, operating under extreme conditions meeting the requirements of high electro- and magnetic conductivity, corrosion resistance, strength and reliability in service.

- Shevtsov, M.S., Borodachyov, A.S. (1983) Development of electrothermal engineering. Moscow: Energoatomizdat.
- Khrenov, K.K., Kornienko, A.N. (1982) Welding of metals 2. in Russia before the October Revolution. In: Welding in the USSR. Moscow: Nauka.
- 3. Zhadkevich, A.M., Izhevsky, V.P. (2004) At the origin of electrometallurgy. Advances in Electrometallurgy, 4, 50--54.
- 4. Lashko, N.F., Lashko-Avakyan, S.V. (1959) Brazing of metals. Moscow: Mashgiz.
- (1975) Reference book on brazing. Ed. by S.N. Lotsmanov, I.E. Petrunin, V.P. Frolov. Moscow: Mashinostroenie. 5.
- 6. Metyolkin, I.I., Shmelyov, A.E. (1972) About brazing of ceramics with active metals. Fizika i Khimiya Obrab. Materialov, 4, 123-128.
- 7. Kozlov, V.V., Gorchakov, R.K., Gruzdev, B.L. et al. (1978) Brazing of pieces of VT9 alloy. Avtomatich. Svarka, 7. 53–55.
- 8. Dolgov, Yu.S., Nesterov, A.F., Tkachenko, A.G. et al. (1986) Technological features of brazing of high-resistant
- (1986) Technological features of brazing of ingeresistant nickel alloys. *Ibid.*, **12**, 44-47.
  9. Perevezentsev, B.N., Krasnopevtsev, A.Yu., Ryabov, V.N. (1985) Variation of gas medium composition in brazing in the presence of zinc vapors. *Ibid.*, **11**, 73-74.
- Klyuchnikov, I.P., Gejkin, V.A., Kryukov, M.A. (2000) Development of permanent brazed joints in aircraft engines. In: Proc. of Int. Math. Sci.-Techn. Conf. on Brazing-2000, Toliatti, 2000.
- 11. Perevezentsev, B.N., Tyunin, Yu.N., Krasnopeev, A.Yu. (1980) Application of active metal vapors in brazing of steels. In: *Brazing in mechanical engineering*. Omsk: OPI.





- 12. Lashko, S.V., Upolovnikova, G.N., Lashko, N.F. (1975) Lashko, S.V., Upolovnikova, G.N., Lashko, N.F. (1973) Contact solid-liquid activation of surface of aluminium al-loys in fluxless air brazing. *Avtomatich. Svarka*, **7**, 27–30. Lashko, S.V., Upolovnikova, G.N., Lashko, N.F. (1975) Contact-reactive activation of aluminium alloys during braz-
- 13.
- Kostina, L.A., Chastikov, S.M., Yudin, V.M. (1976) Braz-ing of niobium alloy with corundum ceramics. *Svarochn. Proizvodstvo*, **10**, 43-44. 14.
- Khorunov, V.F., Malevsky, Yu.B., Nesmikh, V.S. et al. (1968) Effect of some technological parameters on welding-brazing process. *Avtomatich. Svarka*, **11**, 22–25. 15.
- Nesmikh, V.S., Malevsky, Yu.B., Gubenko, B.G. et al. (1970) Contact-reactive brazing of copper with refractory 16. metals. Ibid., 8, 59-61.
- Ivanov, I.N., Kuznetsova, G.P. (2000) Current brazing al-17. loys and equipment in tool production. In: Proc. of Int. Math. Sci. Techn. Conf. on Brazing-2000, Toliatti, 2000.
- Yakobashvili, S.B., Mogilner, I.Yu. (1980) Resistance braz-18. ing of copper connection terminals with elements of Fe–Al heaters. Avtomatich. Svarka, **12**, 57–59.
- Krivoshej, A.V., Beltsev, A.N. (1974) Soldering and weld-ing in manufacturing of electronics. Moscow: Energiya. 19.
- (1968) Welding equipment. Catalogue-Refer. book. Part 2. Kiev: Naukova Dumka. 20.
- Petruchuk, L.N., Karakozov, E.S., Grigorievsky, V.I. (1976) Heater for pressure welding, brazing and heat treatment of multi-layer panels. *Avtomatich. Svarka*, **12**, 50–51. 21.
- Romanovsky, G.F., Kvasnitsky, V.F., Safonov, A.I. et al. (1999) The 40th anniversary of Welding Chair at UMGTU. Zbirnyk Nauk. Prats UDMTU, **6**, 3–19. 22.
- Frolov, V.P., Markova, I.Yu., Eroshev, V.K. et al. (2001) Development in brazing in the XX century. In: *Current ma-terials, technologies, structures.* Moscow: TsRDZ. 23.
- Tabelev, V.D., Kareta, N.L., Rossoshinsky, A.A. et al. (1986) Brazing of low-alloy steel by copper-phosphorus brazing alloy. Avtomatich. Svarka, 2, 73-74.
   Pirozhkov, N.G. (1989) Induction brazing of relay bodies. *Ibid.*, 4, 73.
- Lebedev, V.K., Pismenny, A.S., Martynova, T.I. (1992) Experience of application of composite brazing alloy for pressure welding-brazing. *Ibid.*, **9/10**, 42-43. 26.
- Pashchenko, M.A., Frumin, E.I., Bazilsky, S.V. (1987) In-duction brazing of geological drilling bits in flux melt. 27. Ibid., 5, 71-72.
- Buslovich, S.L., Kotsynsh, I.A., Kalkut, L.E. et al. (1976) Automation of soldering of circuit boards. Moscow: Energiya.
   Storchaj, E.I. (1975) Kinetics and mechanism of fluxing process in brazing of aluminium and its alloys in melts of chloride-fluoride salts. Avtomatich. Svarka, 1, 36-39.
- *Protocols of technical meetings*. Archives of the E.O. Paton Electric Welding Institute. Doc. 2440. 30.

- 31. Protocols of technical meetings. Archives of the E.O. Paton
- Lebedev, V.K., Tabelev, V.D., Pismenny, A.S. (1983) Butt pressure welding of steel pipelines. Avtomatich. Svarka, 9, 25-27. 32.

- 23-27.
   Pismenny, A.S., Shinlov, M.E., Safronov, E.A. (1998) Some peculiarities of induction butt welding-brazing of tubes enameled inside. *Ibid.*, 10, 32-37.
   Pismenny, A.S. (1998) New in application of induction heat-ing in welding and related technologies. *Ibid.*, 11, 54-60.
   Khorunov, V.F., Maksymova, S.V., Zvolinsky, I.V. et al. (1999) Brazing of heat-resistant nickel alloys using the arc heating. *Zbirnyk Nauk. Prats UDMTU*, 6, 114-116.
   Curadataku, V.S., Dudko, D.A. et al. (1970)
- 36.
- Paton, B.E., Gvozdetsky, V.S., Dudko, D.A. et al. (1979) *Microplasma welding.* Kiev: Naukova Dumka. Popov, Yu.V., Yampolsky, V.M., Magnitov, V.S. et al. (1972) Excitation of arc discharge with hollow cathode and methods of control of discharge. *Izvestiya Vuzov. Mashi*-37. nostroenie, 10, 188-190.
- Yampolsky, V.M., Nerovny, V.M. (1981) Strengthening and repair of rotor blades of gas turbine engines by vacuum brazing. *Trudy MVTU*, **363**, 72--78. 38.
- Terentiev, V.A., Shapenkov, V.G., Zubkov, N.S. (1990) Improvement of technology of arc welding-brazing. Avto-39. matich. Svarka, 7, 58-62
- Vanin, V.S. (1962) Welding and brazing of metals in glow discharge. *Ibid.*, **4**, 23–25. Kotelnikov, D.I. (1981) Technological features and prob-40.
- 41. lems of brazing in glow discharge plasma of pieces of indivi-dual and mass production. In: *New developments in field of brazing*. Kiev: PWI.
- Zinovieva, V.F., Galtseva, S.M., Emelianov, S.V. et al. (1990) Glow discharge brazing of dissimilar materials and 42
- hard alloys. Avtomatich. Svarka, **11**, 71–73. Kuzhel, A.V., Khorunov, V.F., Malevsky, Yu.B. (1979) Technology of brazing of lamellar structures. In: Inform. letter of AS of Ukr. SSR, 9. Kiev: PWI. 43.
- 44. Kuzhel, A.V., Khorunov, V.F., Malevsky, Yu.B. et al. (1979) Pilot-production installation for brazing of lamellarfinned heat exchangers. In: Inform. letter of AS of Ukr. SSR, 28. Kiev: PWĬ.
- 45. Kislitsyn, V.M. (1982) Brazing of semiconductor devices with electric resistance heating. In: Current methods of brazing. Kiev: PWI.
- Khryakin, V.E., Lakedemansky, A.V. (1974) Refer. book of brazing operator. Moscow: Mashinostroenie. **46**.
- Kuchuk-Yatsenko, V.S., Shvets, V.I., Gordan, G.N. (1992) Formation of transition zones in joint of stainless steel Kh18N9T with alloy AD1 during brazing by P425 brazing alloy. In: New developments in brazing. Kiev: PWI. 47.
- Puzrin, L.G., Bojko, G.A., Atroshenko, M.G. (1975) Auto-vacuum brazing. Kiev: Znanie. 48

45

The Paton

## WELDING ABROAD

How to melt a welder's heart when the mercury plummets way below zero...

### **AUTOMATED PIPELINE WELDING**

Cranfield automated pipewelding system (CAPS) is a special GMA welding process based on tandem technology and developed specifically for pipeline construction by Cranfield University. CAPS is intended to make pipeline welding faster and more economical while coping with harsh environmental conditions and temperatures which can often become bitterly cold.

Stephen Blackman, Director of Welding Engineering at Cranfield University's Welding Engineering Research Centre in England, has been using Fronius Tandem GMAW equipment since 1997. In 2001, British Petroleum were looking for a welding process that could significantly reduce the cost of pipeline construction. Laser welding and one-shot welding had failed to deliver and BP consulted a group of industry experts for guidance. As an acknowledged expert in the field, Stephen Blackman, had the answer in tandem GMAW. BP liked his ideas and set Cranfield a challenging target ---- to develop and field test a mechanised tandem GMAW pipeline welding system within 18 months. BP had one other requirement, the field trials had to be performed in winter under Arctic conditions.

This latter requirement was based upon the target pipeline project. The new process had to be suitable for use on the proposed large-diameter, long-distance gas pipeline known as the Alaskan Gas Pipeline. This is a 5700 km long pipeline between Alaska and Chicago and at a predicted cost of USS 16 bln this will be the largest private financed project in North America. Due to environmental considerations, most of the construction work in the Arctic will have to be carried out in winter, at temperatures of down to --50 °C.

Cranfield University realised that they would only be able to deliver BP's project objectives if they worked closely with industrial partners. They approached a number of potential partners but only Fronius and RMS Welding Systems of Alberta, Canada, were able to provide the necessary expertise and technology. Fronius accelerated their TimeTwin Digital development programme and provided this welding system to the project. RMS Welding Systems provided automatic pipeline welding equipment to carry the welding torch around the pipe and conducted the field trials.

The welding engineering requirements for the Alaskan Gas Pipeline are very stringent:

• the pipes can only be laid (and thus welded) in winter, when the ground is solid enough to hold the weight of the construction equipment, and the snow and ice protects the tundra from permanent damage by the vehicles;

• the 24 m long pipes must be welded inside a special shelter. This protective enclosure is transported from «weld-seam to weld-seam» suspended from a side-boom tractor. Each welding shelter needs to be self-sufficient, carrying all equipment and consumables for the welding operation and powering the welding power sources from a diesel generator;

• to get the highest welding speeds, welding is performed vertically downwards with one machine on each side of the pipe;

• each welding machine carries two tandem welding torches spaced 70 mm apart, so that two weld passes are deposited simultaneously. This dual-tandem welding process with two pairs of arcs allows high deposition rates to be maintained at the 130 cm/min travel speeds used;

• the Alaskan Gas Pipeline is being designed using X100 linepipe. This high strength material allows high operating pressures at reduced wall thicknesses, and significant cost savings are obtained compared with conventional linepipe. However, X100 has never been used in a long-distance pipeline before, and the 690 MPa of the pipe must be overmatched by the strength of the weld metal. BP requires a minimum weld metal strength of 810 MPa for X100. The pipe-line will be 1321 mm diameter with a 22.9 mm wall thickness.

The field tests were intended to simulate these requirements, although the X80 pipe of 1016 mm diameter and 19.1 mm wall thickness was used.

Cranfield University had two TimeTwin welding systems but purchased another two to perform the initial dual-tandem welding trials. The original machines worked well, but a smaller system was required for the field application, and the Fronius TimeTwin Digital welding systems were selected. Cranfield purchased 8 power sources. These were tested at Cranfield and then shipped to RMS for the field trials, where they were tested outdoors at temperatures down to --42 °C.



Figure 1. System configuration for real-life conditions crane, welding tent, thermobox, truck

Fronius developed special pipeline versions of its equipment to cope with the specific requirements needed for pipeline construction and the extremely low temperatures:

- power sources: TPS 4000R MV Thermo;
- welding database with special programs;
- software: Weld Process, JobExplorer;
- interface: Ethernet, Can Open;
- wirefeeder: VR 1500 Thermo;
- interconnecting cable 20 m;
- cooling unit: FK 9000 Thermo;
- coolant functional down to --50 °C;
- welding torch: TWIN Pipe Torch;
- remote-control units: RCU 5000i, RCU 4000.

Commercial tandem torches are generally designed for robotic applications, and these were too bulky for pipeline applications and do not allow access into the narrow bevel preparation  $(3-6^{\circ})$  normally used for mechanized pipeline girth welds (Figure 2). In order to apply tandem GMAW for pipeline girth welding, it was first necessary to design a lightweight welding torch. Long narrow contact tips are used to gain access to narrow bevel preparations in thick section materials, and this considerably reduces the weld volume. Fronius produced a new tandem torch which followed the initial Cranfield specification and performed extremely well due to the forced wire contact and the lightweight aluminium construction that minimised the weight carried by the welding machines.

From 3--13<sup>th</sup> March 2003, the CAPS equipment was field tested in Edmonton, Alberta, Canada. Cran-

field worked with Fronius and RMS Welding Systems to complete the field trials. These were performed on  $40" \times 19.1$  mm X80 linepipe. Table 1 shows mechanical test results for the dual-tandem GMAW weld procedure. The procedures was qualified with a 1 % Ni, 0.3 % Mo welding consumable to meet overmatching criteria. Despite the high strength levels, excellent Charpy impact and CTOD properties were obtained.

During the trials, 5 sample welds were used for mechanical testing. The results are shown in Tables 2--4 and confirm that weld procedure properties could be replicated under field conditions.

For metallurgical reasons, the pipe is first preheated to 100 °C before an internal weld pass is made using the RMS Internal Welding Machine. This



Figure 2. Bevel preparation

Table 1.	Mechanical	test	data	for	CAPS	field	trial	weld	procedure
----------	------------	------	------	-----	------	-------	-------	------	-----------

$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$				in the proton					
$\begin{array}{c cccc} Charpy impact, & Weld metal cap & Fusion line cap & Weld metal root & Fusion line root \\ 10 \times 10 \ \text{mm}, & 210, 197, 210 & 243, 244, 244 & 317, 298, 202 & 250, 250, 228 \\ (206) & (244) & (272) & (243) \end{array}$	All weld tensile test	σ <sub>0.2</sub> , MPa 753		σ <sub>t</sub> , MPa 810		$\sigma_{0.2}/\sigma_t$ , MPa 0,93		À, % 23	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Charpy impact,	Weld metal cap		Fusion line cap		Weld metal root		Fusion line root	
CTOD         Weld $B \times 2B$ HAZ - 50 % $B \times 2B$ HAZ - 15 % $B \times 2B$ Weld root $B \times B$ -10 ${}^{1}\tilde{N}$ , mm         0.555 ( $\delta_{m}$ )         0.624 ( $\delta_{m}$ )         0.336 ( $\delta_{u}$ )         1.756 ( $\delta_{m}$ )	10 × 10 mm, 20 °C, J	210, 197, 210 (206)		243, 244, 244 (244)		317, 298, 202 (272)		250, 250, 228 (243)	
10 <sup>î</sup> $\tilde{N}$ , mm 0.555 ( $\delta_m$ ) 0.624 ( $\delta_m$ ) 0.336 ( $\delta_u$ ) 1.756 ( $\delta_m$ )	CTOD	Weld B×2B		HAZ — 50 % B×2B		HAZ — 15 % <i>B</i> ×2 <i>B</i>		Weld root <i>B</i> × <i>B</i>	
	10 <sup>î</sup> Ñ, mm	0.555 (δ <sub>m</sub> )		<b>0.624</b> (δ <sub>m</sub> )		<b>0.336</b> (δ <sub>u</sub> )		1.756 (δ <sub>m</sub> )	
$0.571 \ (\delta_{\rm m}) \qquad 0.629 \ (\delta_{\rm u}) \qquad 0.546 \ (\delta_{\rm u}) \qquad 1.784 \ (\delta_{\rm m})$		0.571 (δ <sub>m</sub> )		<b>0.629</b> (δ <sub>u</sub> )		<b>0.546</b> (δ <sub>u</sub> )		1.784 (δ <sub>m</sub> )	
0.615 ( $\delta_m$ ) 0.107 ( $\delta_c$ ) 0.677 ( $\delta_m$ ) 1.268 ( $\delta_m$ )		0.615 (δ <sub>m</sub> )		0.107 (δ <sub>c</sub> )		0.677 (δ <sub>m</sub> )		1.26	<b>8</b> (δ <sub>m</sub> )
Cross weld tensile613 MPa621 MPa617 MPa618 MPatestsParent metal fractureParent metal fractureParent metal fractureParent metal fracture	Cross weld tensile tests	613 MPa Parent metal fracture		621 MPa Parent metal fracture		617 MPa Parent metal fracture		618 MPa Parent metal fracture	
Nick break tests Pass Pass Pass Pass	Nick break tests	Pa	SS	Pass		Pass		Pass	
Side bend tests Pass Pass Pass Pass Pass Pass Pass P	Side bend tests	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Maximum hard- Parent cap FL cap Weld cap FL mid Weld mid Parent root FL root Weld root	Maximum hard-	Parent cap	FL cap	Weld cap	FL mid	Weld mid	Parent root	FL root	Weld root
ness HV <sub>0.5</sub> 235 288 334 259 307 232 279 255	ness $HV_{0.5}$	235	288	334	259	307	232	279	255

Table 2. Charpy impact data, J, at --20 °C,  $10 \times 10$  mm specimens

Weld No.	Weld metal cap	Fusion line cap	Weld metal root	Fusion line root
20	168, 134, 174 (159)	245, 270, 262 (259)	236, 194, 268 (232)	252, 209, 248 (236)
27	159, 164, 145 (156)	255, 244, 233 (244)	258, >325, 260 (>281)	194, 125, 239 (186)
34	180, 239, 228 (216)	245, 243, 250 (246)	292, 262, 290 (281)	237, 241, 182 (220)
39	160, 116, 172 (149)	245, 231, 248 (241)	214, 283, 264 (254)	235, 235, 243 (238)
41	201, 178, 256 (212)	220, 214, 241 (225)	>325, >325, 315 (>322)	220, 220, 226 (222)

Table 3. Maximum hardness  $HV_{0.5}$ 

Weld No.	Parent cap	FL cap	Weld cap	FL mid	Weld mid	Parent root	FL root	Weld root
20	228	279	304	245	293	222	250	265
27	231	267	341	241	282	232	240	269
34	228	280	343	235	287	227	247	256
39	231	253	326	257	319	227	242	256
41	222	251	317	253	354	223	262	340

equipment acts as an internal alignment clamp for the pipe to align the pipe bevels, and incorporates four GMAW welding heads that travel around the inside four of the pipe at a speed of 762 mm/min. Once the root is completed the welding shelter is set over the



Figure 3. Bead sequence: cap (1), fills (2), hot pass (3), root (4)

weld, and the external passes are completed using the CAPS dual-tandem process. Three weld runs were performed with dual-tandem GMAW before the final capping pass was made with single-tandem GMAW. All fill passes were welded at a travel speed of 1300 mm/min, which is more than twice the speed of the current welding technology used for pipeline construction (Figure 3).

The results of this joint development work are truly astounding, and extremely satisfactory for all involved: a conventional GMAW welding process

Table 4. Cross weld tensile strength, MF
--

Weld No.	20	27	34	39	41
Ò1	621	626	631	617	620
Ò2	613	615	635	613	617

All failures in parent material.



Table 5							
Weld run			Fills			Cap	(split)
Weld pass	Root (internal)	Lead (2 wires)	Trail (2 wires)	Lead (2 wires)	Trail (2 wires)	Lead (2 wires)	Trail (2 wires)
Electrode diameter, mm	0.9	1.0	1.0	1.0	1.0	1.0	1.0
Electrode type	ER480S-6	ER690S-G	ER690S-G	ER690S-G	ER690S-G	ER690S-G	ER690S-G
Amperage range, A	185210	200220	140-170	190-210	140-160	110-140	110140
Voltage range, V	2022	2023	19-22	10-22	18-21	18-20	1820
Wire feed speed, mm∕min	9652	12200	9200	11500	8500	7000	7000
Travel speed range, mm∕min	760	1270	1270	$1270\pm10~\%$	$1270\pm10~\%$	$1270\pm20~\%$	$1270\pm20~\%$
Heat input range, kJ∕mm	0.320.38	0.300.40	0.30-0.40	0.30-0.40	0.30-0.40	0.20-0.30	0.200.30
CTWD, mm	9.011.0	13.014.0	15.5-16.5	13.0-14.0	15.5 - 16.5	14.5-15.5	16.517.5
Head oscillation width, mm	No	2.03.0	2.5-3.5	3.0-4.0	3.5-4.0	1.5-2.5	1.52.5
Oscillation speed, cpm	No	350	350	350	350	300	300
Welding head angle, deg	57 (leading)	2 +2	2 +2	2 +2	-2 - +2	2 +2	2 +2

used for pipeline construction would require many welding stations to complete each weld at the required productivity. Up to 19 welding stations may be required for the Alaskan Gas Pipeline, whereas CAPS would require only 4. This results in major savings in equipment and labour as well as easier logistics in the Arctic environment. The lower personnel number working in these environments also reduces the safety risk. BP has therefore estimated that the use of CAPS on the Alaskan Gas Project could save more than US\$ 150 mln.

Following the success of the field trials, 12 more power sources have been purchased, and CAPS is currently being tested by three pipeline welding contractors in preparation for its first production use. Early next January, work will then begin in earnest in Canada using single-tandem for a 610 mm diameter X80 pipeline and dual-tandem for a 914 mm diameter X100 pipeline. These are expected to be the first of many.

Whilst most industrial applications involve high deposition downhand welding, work at Cranfield has shown that the use of appropriate pulse parameters makes it possible to obtain increased productivity in positional welding for pipeline construction and other challenging applications. The Fronius welding systems has been shown to deliver excellent and consistent welding parameters under very demanding conditions.

#### The welding technology in detail

- Parameters:
- base metal: X80 and X100
- pipeline diameter: over 610 mm
- wall thickness: up to 23 mm

- weld filler metal: G3NMMo, 1.0 mm
- length of pipe: 24 m

• weld passes: root from inside: 1 wire with 4 heads; filler and top passes on outside ---- tandem with 4 heads.

#### Typical welding procedure sheet

- process: CAPS
- polarity: DCSP
- position: 5G/ vertical down
- preheat: min 100 °C
- interpass temperature: min 100 °C/max 150 °C

• time interval between passes: root/second ---max 5 min; second/fill(s) ---- max 60 min; to completion ---- max 24 h

• line-up method: IWM

• removal of line-up clamp: 100 % root bead complete

• welding consumable: GSNMMo

• gas shielding: all passes ---- Ar + (5 % He, 12.5 % CO<sub>2</sub>)

• number of welders: internal ---- 4 to 8 welding heads; external ---- two dual-tandem heads (2  $\times$  4 wires).

Welding parameters are show in Table 5.

Contact details: Stephen Blackman: welding@cranfield.ac.uk +44 1234754693

Martin Kepplinger: kepplinger.martin@fronius.com +43(0)7242/241-396



### ESTIMATION OF IMPACT STRENGTH OF LOW-ALLOY WELD METAL

**O.G. KASATKIN** 

E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Dependence of impact strength of low-alloy weld metal on its composition and mechanical properties in tensile tests is considered. It is shown that, along with the content of main alloying elements, specific fracture energy and yield strength are the informative factors for estimation of impact strength of the weld metal.

**Keywords:** arc welding, low-alloy steels, weld metal, impact strength, calculation, alloying of weld metal, mechanical properties, specific energy of fracture

One of the most widely spread and simple methods of estimation of brittle fracture resistance is the bend impact test of Charpy specimens with a sharp notch [1, 2]. As the energy of formation of weld surface is low, a main part of energy in metal fracture is spent for a plastic deformation. Energy consumption for the plastic deformation depends on the composition and structure of the metal.

At present there is a number of regression models, describing the dependence of impact strength on composition of metal, thermal cycle of welding and test temperature. These models are not completely adequate. They take into account only main alloying elements and impurities, while the rate or duration of cooling in a definite interval of temperatures (usually 850--500 °C) is also a sufficiently rough estimate of the welding thermal cycle. It is important to note that the mentioned models allow estimation of impact strength of welded metal directly after welding and do not account for its possible change in the process of the welded joint service. For example, the welded joints in power engineering equipment at temperature about 300 °C can manifest the susceptibility to temper brittleness.

To construct the more adequate and precise model it is necessary to add the additional factors into it, taking into account the change of structure and other properties of the weld metal. In this connection it seems interesting to estimate the feasibility to use the results of tensile tests of weld metal specimens, including those of a small size. These tests are simplest and accessible and carried out in the first turn in study of properties of weld metal, however, their results are not usually used for the estimation of the impact strength.

In the present work the weld metal was examined containing the following alloying elements, wt.%:  $C \le \le 0.2$ ;  $Mn \le 2.0$ ;  $Si \le 0.8$ ;  $Cr \le 2.0$ ;  $Mo \le 2.0$ ;  $Ni \le \le 2.0$ ;  $V \le 0.6$ . Content of impurities (sulphur, phosphorus, nitrogen and oxygen) was limited in the following ranges, wt.%:  $S \le 0.03$ ;  $P \le 0.03$ ;  $N \le 0.02$ ;  $O \le 0.06$ . Except chemical composition, the following

© O.G. KASATKIN, 2005

values of tensile tests of specimens at 20 °C temperature were used as factors: limits of proportionality  $\sigma_p$ and yield  $\sigma_{0.2}$ ; ultimate strength  $\sigma_t$ ; proportional and relative elongation, respectively,  $\delta_p$  and  $\delta_5$ ; relative reduction in area  $\psi$ ; real rupture strength  $S_{\text{fin}}$ ; specific energy of fracture  $W_f$ . Thermal cycle of welding was evaluated by the time of weld metal cooling from 850 to 500 °C, which varied from 7 up to 40 s. Welding was performed into groove with coated electrodes under flux in CO<sub>2</sub> and inert gases.

Experimental material for statistic analysis contained the results of investigations of 220 specimens of different welds, and also data, given in work [3]. The following models were obtained as a result of processing of experimental data by the methods of multi-dimensional regression analysis with subsequent omitting of factors, negligible at the level  $\alpha$ = 0.02:

Impact strength at 20 °C:

$$\begin{aligned} &\ln(KCV \ [MJ/m^2]) = 1.06 - 0.157 \ C - \\ &- 0.483 \ Si - 0.126 \ Mo - 0.868 \ V - 18.2 \ P - \\ &- 9.25 \ N - 0.0012 \ \sigma_{0.2} + 0.0074 \ \psi + \\ &+ 0.225 \ \cdot 10^{-6} \ W_f^2 \ , \end{aligned}$$

multiple factor of correlation R = 0.92; residual deviation  $\sigma_{0.2} = 0.35$ .

Specific energy of fracture  $W_{\rm f}$  can be estimated from the results of tensile tests [4]:

$$W_{\rm f} \,[{\rm MJ}/{\rm m}^2] = (\sigma_{0.2} + S_{\rm fin}) \ln(d_{\rm in}/d_{\rm fin}),$$

where  $d_{in}$  is the initial diameter of specimen;  $d_{fin}$  is the final diameter of specimen in the zone of neck after its fracture.

Impact strength at increased (T = 95 °C) and decreased (T = -20 °C) temperatures:

$$\ln(KCV [MJ/m^{2}]) = 1.53 - 0.266 \text{ C} -$$

$$- 0.074 \text{ Mn} - 13.5 \text{ P} - 12.7 \text{ N} - 0.00159 \sigma_{0.2} + (2)$$

$$+ 0.000497 W_{f}; R = 0.91; \sigma_{0} = 0.28;$$

$$\ln(KCV [MJ/m^{2}]) = 0.63 + 2.70 \text{ C} -$$

$$- 0.49 \text{ Si} - 0.178 \text{ Mo} - 1.43 \text{ V} - 9.80 \text{ N} -$$

$$- 0.00136 \sigma_{0.2} + 0.374 \cdot 10^{-6} W_{f}^{2};$$

$$R = 0.84; \sigma_{0} = 0.57.$$
(3)



Temperature corresponding to preset value of impact strength  $KCV_0$ . For critical structures the critical temperature  $T_{\rm cr}$  is estimated from condition  $KCV_0 = 0.6 \text{ MJ/m}^2$ . Then

$$T_{\rm fin} \ [^{\circ}\tilde{\rm N}] = -71 + 41.6 \ {\rm Si} + 13.4 \ {\rm Mo} + \\ + \ 60 \ {\rm V} + 810 \ {\rm N} + 0.061 \ \sigma_{0.2} - 0.048 \ W_{\rm f};$$

(4)

R = 0.81;  $\sigma_0 = 32$ . Level of upper shelf of impact strength curve:

$$\ln(KCV_m \,[\text{MJ/m}^2]) = 1.24 - 1.32 \text{ C} -$$

$$- 0.042 \text{ Mo} - 18.6 \text{ P} - 9.44 \text{ N} - 0.00128 \sigma_{0.2} + (5) + 0.000567 W_{\text{f}}; R = 0.86; \sigma_0 = 0.35.$$

Region of transition temperatures  $\Delta T_s$ . In this region with increase in temperature the impact strength is increased from 0.16 to 0.84 with respect to the level of the upper shelf:

$$\ln(\Delta T_s \ [^{\circ}\tilde{N}]) = 3.17 + 2.31 \ C + 0.154 \ Mn + + 0.099 \ Cr + 0.083 \ Ni + 6.38 \ N + 0.000412 \ \sigma_{0.2}; \quad (6) R = 0.57; \ \sigma_0 = 0.42.$$

Analysis of obtained models showed that the statistically important is the effect of only two characteristics at tensile test on impact strength: specific energy of fracture and yield strength. It should be noted that in these models the value of the specific energy of fracture is higher than all other factors. Unlike the earlier published models of impact strength the given relationships do not include in a clear form the factor, reflecting the thermal cycle of welding, and also the content of some alloying elements. This is explained by the fact that the effect of some alloying elements and rate of cooling are accounted for to some extent using values  $\sigma_{0.2}$  and  $W_{\rm f}$ . The given models include in a clear form those alloying elements whose nature of effect on impact strength and values  $\sigma_{0,2}$ and  $W_{\rm f}$  are greatly differed. The above-noted statistic importance of effect of  $\sigma_{0,2}$  and  $W_{\rm f}$  on impact strength is correlated with existing interrelation between the values of strength and ductility of weld metal at tensile tests. Below, the correlation matrix of these values is given:

	$\sigma_{p}$	σ <sub>0.2</sub>	$\sigma_{t}$	$S_{ m fin}$	$\delta_{p}$	$\delta_5$	ψ
$W_{ m f}$	0.19	0.19	0.12	0.80	0.08	0.54	0.88
ψ	-0.26	0.30	0.46	0.46	0.36	0.83	
$\delta_5$	-0.56	0.63	0.66	0.07	0.78		
$\delta_{p}$	-0.81	0.85	0.84	0.58			
$S_{ m fin}$	0.66	0.69	0.71		-		
$\sigma_{p}$	0.94	0.96		-			
$\sigma_{0,2}$	0.98		-				

Analysis of obtained coefficients of a pair correlation showed that the closest link is observed between the values  $\sigma_p$ ,  $\sigma_{0.2}$  and  $\sigma_t$ . This proves that the mentioned characteristics contain almost the same information. Among them, the yield strength  $\sigma_{0,2}$  can be considered as most informative, whose value is most closely connected both with  $\sigma_t$  and also with  $\sigma_p$ . The next group of characteristics  $\delta_p,\,\delta_5$  and  $\psi$  characterize the ductility of weld metal. In this group the link between  $\delta_p$  and  $\delta_5$ , and also between  $\delta_5$  and  $\psi$  is not so close. Characteristics  $\delta_p$  and  $\psi$  are not interrelated in principle. The most informative representative of this group is characteristic  $\psi$ . The specific energy of fracture is closely connected with values  $S_{\text{fin}}$  and  $\psi$ , but do not almost correlate with  $\sigma_{0.2}$ . Therefore, among the above-described characteristics the yield strength and specific energy of fracture reflect most completely the properties of weld metal, which are determined in tensile tests of specimens.

BRIEF INFORMATION

Models (1)--(5) can be used for approximate estimation of change of impact strength from the tensile tests of specimens. Model (6) has a low coefficient of correlation *R*, and it can be used only for evaluation of the nature of effect of yield strength on the values of range of transition temperatures. Models (5) and (6) show with static importance that with increase in metal yield strength the upper shelf and angle of inclination of impact strength curve are lowered. This proves a certain non-correctness of Master-curve method [5], based on assumption about the fact that in degradation of metal properties, the curve of the impact strength is not changed, but only shifted into the region of the higher temperatures.

The obtained relationships indicate the informativity of specific energy of fracture  $W_f$  in evaluation of changes in impact strength. In addition, this characteristic can be used for evaluation of metal resistance to the growth of fatigue crack [6].

- 1. Dolby, R.E. (1981) Charpy V and COD correlation between test data for ferritic weld metals. *Metal Constructi*on, 13(1), 43-51.
- Kiuchi, A., Aoki, M. (1983) Statistical estimation of critical COD from Charpy-V impact transition temperature. Q. J. JWS, 1(2), 261–266.
- 3. Marshall, J.A., Heuschkel, J. (1977) Statistical analysis of dependence of weld metal properties on composition. *Welding Res. Council Bull.*, **228**, 34.
- 4. Romvari, P., Tot, L., Nad, D. (1980) Analysis of principles of fatigue crack propagation in metals. *Problemy Prochnosti*, **12**, 18–28.
- 5. (1998) ASTM E 1921–97. Standard test method for determination of reference temperature  $T_0$  for ferritic steels in the transition range. Annual book of ASTM standards. Vol. 03.01, 1068--1084.
- 6. Kasatkin, O.G. (1985) Calculated evaluation of weld metal resistance to fatigue cracks. *Avtomatich. Svarka*, **12**, 1-4.

## INFORMATION FOR CONTRIBUTORS TO THE PATON WELDING JOURNAL

THE PATON WELDING JOURNAL is a scientific **Manuscripts should be supplemented with** journal publishing fundamental and applied papers and short notes in the area of

- weldability of structural materials welding different types of steels and cast irons welding non-ferrous metals, including aluminium,
- titanium, etc. joining dissimilar and composite materials
- welding refractory metals and alloys
- welding cryogenic materials
- joining polymers arc welding

- flash-butt welding electron beam and laser welding
- explosion welding and cutting
- friction welding electroslag welding soldering and brazing
- advanced structural materials
- surfacing and coating
- cutting
- computer technologies in welding strength of welded joints and structures

- welding stresses and strains calculation and design of welded joints and structures
- automation of welding fabrication estimation of residual life of welded structures
- welding for fabrication of unique structures welding and repair in thermal and nuclear power engineering
- advances in underwater welding, cutting and repair
- welding in Space

The journal accepts also advertisements and announcements of conferences and publications on related topics.

THE PATON WELDING JOURNAL is published monthly. Subscription requests should be sent to the Editorial Office.

Manuscripts should be submitted in duplicate in English, and supplemented with a text file and figures on a diskette. An electronic copy may be submitted by e-mail.

The rules for submission of electronic copies are as follows:

- an electronic copy should be submitted on a diskette or by e-mail simultaneously with sending a hard copy of the manuscript;
- acceptable formats: **MultiEdit** text (txt), MS Word'97 (rtf, doc);
- acceptable graphic formats for figures: EPS, TIFF, CDR. Figures created using software for mathematical and statistical calculations should be converted to one of these formats.

#### Manuscripts should be sent to

Aleksander T. Zelnichenko **Executive Director of Project** «The Paton Welding Journal», 11, Bozhenko Str., 03680, Kyiv, Ukraine PWI, International Association «Welding» Tel.: (38044) 227 67 57, Fax: 268 04 86 E-mail: journal@paton.kiev.ua E-mail: tomik@mac.relc.com

- official letter signed by a chief manager of the institution where the work was performed. This rule does not apply to papers submitted by international groups of authors;
- publication permission: conclusion of a commission authorized to permit open publication of the paper (only for authors from Ukraine).

#### **Title Page:**

- title of the paper and name(s) of the author(s);
- name of affiliated institution, full address, telephone and fax numbers, e-mail addresses (if available) for each author.

Abstract: up to 100 words, must be presented in English. Before the abstract text one should indicate in the same language: the paper title, surnames and initials of all authors.

Key words: their amount must not exceed eight word units. In the specific cases it is acceptible to use two- or three-word terms. These words must be placed under the abstract and written in the same language.

*Text* should be printed double-spaced on white paper (A4 format) with a 12-point font. Titles of the paper and sections should be typed with bold capitals.

Tables should be submitted on separate pages in the format of appropriate text processors, or in the text format (with columns separated by periods, commas, semicolons, or tabulation characters). Use of pseudographic characters is not allowed.

List of references should be double-spaced, with references numbered in order of their appearance in the text.

Captions for figures and tables should be printed in the manuscript double-spaced after the list of references.

**Pictures** will be scanned for digital reproduction. Only high-quality pictures can be accepted. Inscriptions and symbols should be printed inside. Negatives, slides and transparencies are accepted.

*Figures:* each figure should be printed on a separate page of the manuscript and have a size not exceeding  $160 \times 200$  mm. For text in figures, use 10-point fonts. All figures are to be numbered in order of their appearance in the text, with sections denoted as (a), (b), etc. Placing figure numbers and captions inside figures is not allowed. On the back side, write with a pencil the paper title, author(s) name(s) and figure number, and mark the top side with an arrow.

**Photographs** should be submitted as original prints.

Color printing is possible if its cost is covered by the authors or their sponsors. For information about the rules and costs, contact the Executive Director.

No author's fee is provided for. Publication in TPWJ is free of charge.

