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PECULIARITIES OF STRUCTURE OF Cu–Cu, NI–Cu AND STEEL–Cu JOINTS PRODUCED BY OVERLAP FRICTION STIR WELDING METHOD

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The work is dedicuted to investigation of overlap friction stir welded joints of sheet billets of homogeneous (Cu–Cu) and dissimilar metals with unlimited (Ni–Cu) and limited solubility (Cu–St.3, Kh18N10–Cu) of the components in solid state. The FSW process is performed due to plastic deformation of metal being heated to recrystallization temperature without melting. The leading role in this process plays mechanical stirring of metals in plastic state. The role of diffusion processes is insignificant. The quality joints are received at optimum welding modes. Plasticization and dynamic recrystallization in FSW of Cu–Cu plates promote for grain refinement (5–30 μm) in the stir zone and develop dense weld microstructure, comparable with the base metal. The weld microhardness reaches 80–107 % of the base metal microhardness. FSW of Cu and Ni resulted in the quality welded joint with mutual penetration of one metal into another at up to 3 mm depth. Interdiffusion of Cu and Ni along the grain boundaries takes place at up to 20 μm depth with formation of solid solution interlayers of these metals. Examination of Cu–St.3 and Kh18N10–Cu joints demonstrated significant grain refining in the recrystallization zone as well as in the HAZ. St.3 and Kh18N10 steels plung in copper at 1000 and 2000 μm depth in form of bands and strips. Large amount of Fe-based inclusions, embedded in form of separate bands and particles, is noted in the stir zone. Thus, applying the welds at specific distance from each other allows producing quality solid welding-up of upper thinner plate to massive lower plate (as in deposition) with overlapping of recrystallization zones at minimum heating and distortion of the parts. The carried investigations allow recommending this method for reconstruction of initial dimensions and development of protective layer (Ni, Kh18N10 steel) on copper plates of CCM mold. 11 Ref., 1 Table, 8 Figures.

Keywords: *friction stir welding, lap joint, mechanical stirring of metals, diffusion, solubility in solid phase, microstructure, X-ray spectrum microanalysis, chemical composition, microhardness*

FSW is the variation of pressure welding when a welded joint is formed as a result of mutual plastic deformation of parts being joined in solid phase [1–3]. From other types of pressure welding it differs by heating method, namely, by the method of heat input in the parts being welded. Kinetic energy in FSW is transformed into the heat energy, moreover, heat generation is strictly localized in the thin sub-surface layers of metal. Most of the researchers indicate the following advantages of FSW in comparison with other methods for production of permanent joints [4, 5]. This is, to a great degree, retaining of the properties of the base metal in the welding zone in comparison with fusion welding methods; possibility of producing defect-free welds on alloys which tend to formation of hot cracks and porosity in weld metal during fusion welding etc. Currently the possibility of FSW application for producing the dissimilar metal joints [6–9] is of large interest.

The FSW process involves the following: rotating tool in form of a rod, consisting of two main parts, i.e. shoulder and projecting from it pin, which plunges the material in such a way that the pin should enters to a depth below interface of two plates being joined. The shoulder presses the plates with significant force and serves as a main heat source. The tool is moved at determined rate and carries out welding of two plates (Figure 1). The FSW process generates sufficient amount of energy, necessary for plasticization, stirring and formation of quality joint. Deformation and stirring of the metal in solid phase develops denser, fine microstructure of the joint zone in comparison with the base metal [10, 11].

One of the main problems restraining wider application of FSW is resistance (life) of working tool, basic diagram of which and variants of manufacture are given in work [4].

The tool itself and, in particular, the working rod (pin) are subjected to high thermal-mechanical loadings. Torque moment and alternating cyclic bending force simultaneously effect the heated working rod. The material of surfacing tool shall be heat-resistant and high-temperature that allows operating in 800–1200 °C temperature range, at which plasticization of

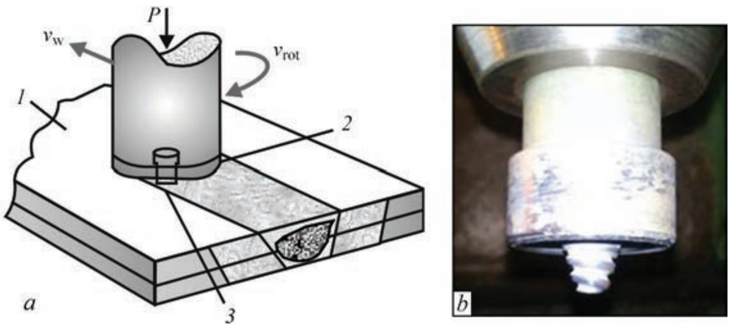

Figure 1. Scheme of FSW process (*a*), and working tool (*b*): *1* — part; *2* — shoulder; *3* — tool with special profile

copper, nickel, iron and their alloys takes place. An important requirement is also sufficiently high bending strength of the tool under these conditions.

For this work the V.N. Bakul Institute for Superhard Materials has developed and proposed the new materials based on vanadium carbides and boron nitrides. The technology was developed for sintering the tools from mixture of cubic boron nitride and aluminum with addition of refractory compounds of titanium and zirconium.

The tool's shape plays an important role in the FSW process. Thus, the best results were obtained at application of the tool with cone pin (Figure 1, *b*). In this case the bending loadings come along a tangent to main body of the tool, that is very important in use of tool of increased brittleness. Size and shape of the tools were developed based on number of experiments on surfacing of copper, nickel and other materials carried out between PWI, ISM and SPC «VISP».

Cu–Cu, Ni–Cu, Cu–St.3 and Kh18N10–Cu lap joints were examined for investigation of the processes taking place in FSW of homogeneous and dissimilar metals. Copper and nickel form continuous series of solid solutions, and copper with carbon and stainless steels have limited solubility of elements in solid state. FSW modes and characteristic of materials being welded are given in the Table. A complex procedure including optical metallography, X-ray spectrum microanalysis, scanning electron microscopy and durometry was used for examination of obtained joints.

Cu–Cu joint. Lap joints of copper plates were produced by FSW, the relationships were determined between structural changes, microhardness of samples and modes on which welding was carried out (see the Table). The copper plates were joined by single-pass (Figure 2, *a*) and multi-pass weld by overlaying of single-run parallel welds at specific distance from each other (Figure 2, *b*). As can be seen from Figure 2, the received joints are sound, without pore, defects and cracks.

In all the cases, tool passing provokes for a dynamic recrystallization in the upper plate, and fine-grain structure with equiaxed grains from 20 to 100 μm size (Figure 2, *c*) is registered. The depth of this zone makes 3–5 mm. A zone of oval-shape nucleus with insufficiently determined, interrupting growth rings of not less than 5 mm depth is formed under the recrystallized metal of upper layer. Size of grains in it is comparable with recrystallized grains of the upper plate.

Welding-up of copper plates between themselves is provided during their lap FSW at 16–19 mm distance between the welds (shoulder diameter 31 mm). The stirring zones of weld metals overlap each other. Sufficient amount of heat was generated at given modes of welding (v_w = 56–160 mm/min, v_{rot} = = 1400 rpm) which is necessary for plasticization and stirring of material of plates being welded and formation of quality joint as in deposition. FSW provides for high quality of welding. Denser microstructure of the joint zone comparable with the base metal is developed during metal deformation and stirring in solid phase. The weld microhardness achieves 80–90 % of the base metal microhardness and sometimes even more due to grain refinement. Thus, microhardness of the weld zones, i.e. the metal of upper plate and nucleus in relation to the base metal, makes 98 and 107 %, respectively (Figure 3) at v_w = 110 mm/min and v_{rot} = = 1400 rpm.

In practice, the FSW method is used for lap welding (as in deposition) by parallel welds of copper

Modes of FSW and characteristics of materials to be welded

Material of upper/ lower plate	Grade of material of upper/lower plate	Thickness of upper/ lower plate, mm	Depth of pin plunge, mm	Welding speed, mm/min	Rate of pin rolation, rpm	Microhardness of upper/lower plate, MPa
Cu/Cu	M0/M0	2.5–5.0/16–22	3.5–5.5	56–160	1200–1400	1145/1195
Ni/Cu	M1/M0	4/10	5.0	40	1250	2312/1160
Cu/St.3	M0/St.3	7/8	8.0	60	1250	1160/2160
Kh18N10/Cu	Kh18N10T/M1	3/18	4.5	56–160	1400	1430/470

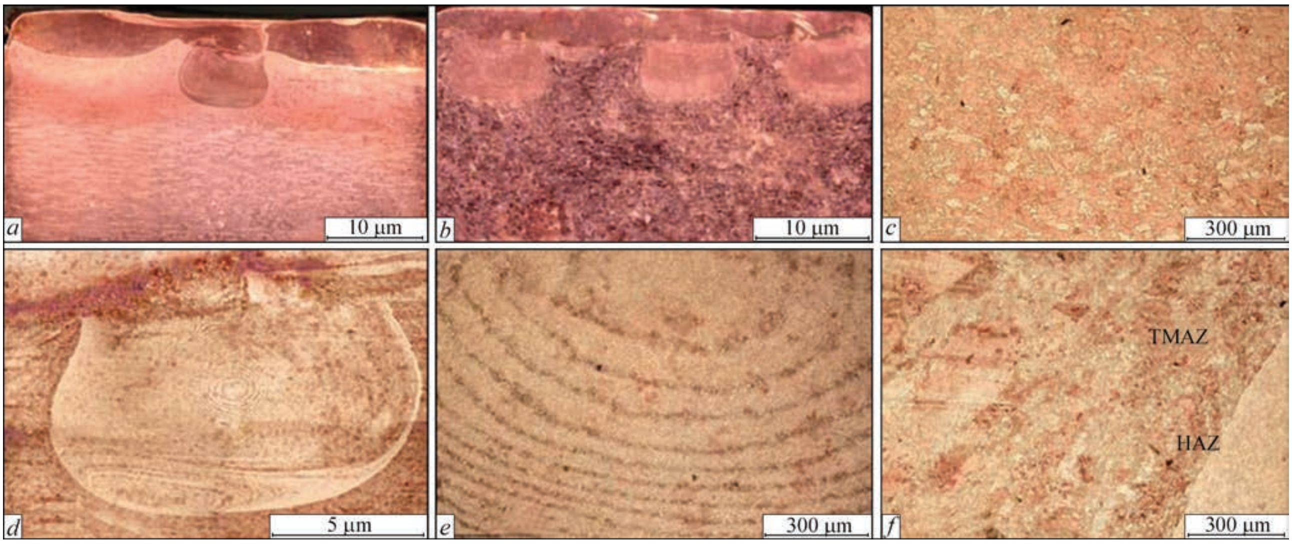

Figure 2. Structure of single- (*a*) and multipass (*b*) joints at lap FSW of copper plates; *c* — metal of upper plate; *d*, *e* — nucleus; *f* — HAZ and TMAZ

sheet to copper plate in CCM mold for the purpose of reconstruction of its initial size.

Ni–Cu joints. The joints of Ni–Cu dissimilar metals were produced by FSW using the modes indicated in the Table. Welding was carried out through nickel plate of 4 mm thickness. Longitudinal and cross metallographic sections of this joint (Figure 4) were investigated. The welded joint has no defects, i.e. lack of penetration, cracks and pores. A nucleus of rounded shape of 4×6 mm size located in copper and representing itself concentric deformation rings with nickel particles inclusions (nickel content makes approximately 10 vol.%) was formed in the joint zone cross-section. A region of nickel-to-copper mass transfer was formed in the nucleus upper part due to immersion of pin (Figure 4, *a*).

Examination of longitudinal section of the joint in Ni-to-Cu contact zone shows mutual penetration of these metals at up to 3 mm depth. Stirring of metals is observed in form of mutually penetrating alternating strips, directed to the side of pin movement (Figure 4, *b*). Structure refinement takes place due to recrystallization in these strips. Grain size in copper varies from 5 to 20 and that in nickel is from 5 to 40 μm. Microhardness of nickel bands makes 1270±40 and that

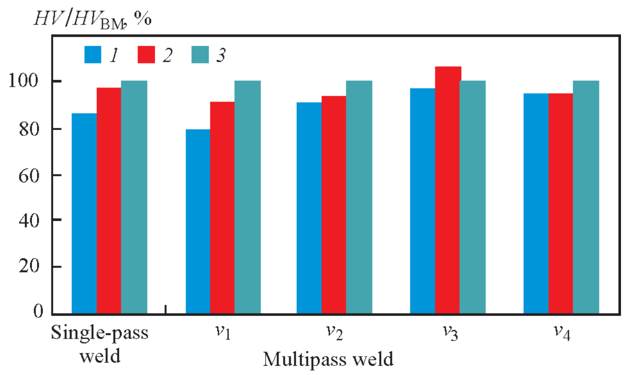

Figure 3. Relationship of microhardness of different weld regions to base metal microhardness HV_{BM} at different speeds of FSW: $v_1 = 56$; $v_2 = 80$; $v_3 = 110$; $v_4 = 160$ mm/min: *1* — region of upper place over nucleus; *2* — nucleus; *3* — BM

of copper is 1140±50 MPa. The thermomechanically affected zone (TMAZ) of up to 3 mm thickness with directed deformation strips and 20–70 μm grain size is registered in nickel over the area of metals stirring. The border region of nickel — HAZ located over the thermomechanically affect zone TMAZ — has coarser grains. The regions of thermal and thermomechanical effect of 0.6 and 0.1 mm width, respectively, are found in copper under nucleus zone. Edges of the strips and regions of nickel, in direct contact with cop-

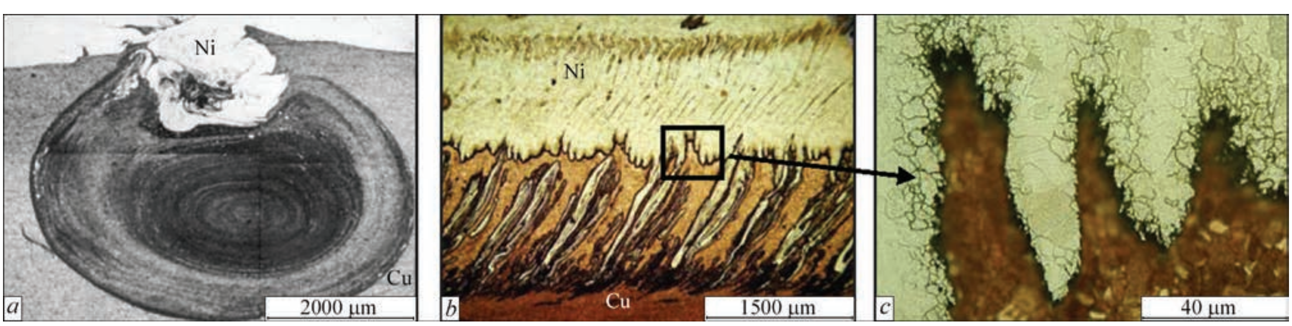

Figure 4. Microstructure of FS-welded Ni–Cu joint: *a* — cross section; *b* — longitudinal section; *c* — Ni and Cu mutual diffusion region

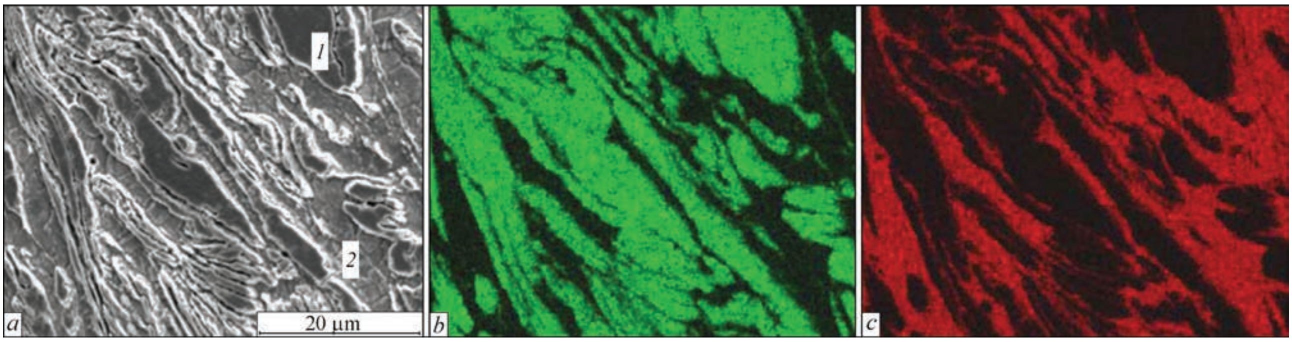

Figure 5. Image of Ni to Cu stir zone in secondary electrons (*a*), Ni (*b*) and Cu (*c*) in characteristic radiation (chemical composition of examined regions, wt./at.%: *1* — 99.23/99.29 Ni, 0.77/0.71 Cu; *2* — 4.03/4.35 Ni, 95.97/95.65 Cu)

per, have larger lamination and lower microhardness (1100±60 MPa). It can be explained by mutual diffusion of copper and nickel along grain boundaries with formation of solid solution interlayers of these metals at 10–20 μm depth (Figure 4, *c*).

The XSMA of the stir zone in characteristic radiation shows insignificant mutual diffusion of elements deep down the alternating strips of nickel and copper. Figure 5 represents the results of mapping of a zone of mechanical stirring of metals in Ni–Cu joint. The results of examination outline the fact that the mechanical stirring of metals in plastic state plays the leading role in FSW and to smaller extent their mutual diffusion.

Cu–St.3 joint. A copper-to-carbon steel joint was produced by FSW by means of action of the pin through a copper plate of 7 mm thickness. Examination of longitudinal and cross section of joint showed that it is dense and has no defects (Figure 6). Since the steel hardness is much more than the copper hardness, then formation of classical oval nucleus (Figure 6, *a*) in welded joint cross-section did not take place. The joint zone in the upper part consists of recrystallized copper, and lower one is a mixture of steel particles of different size in copper matrix. Wedge-like steel implantations in copper to 700–1000 μm depth limit the joint nucleus. These wedge-like implantations have ferrite-pearlite structure and virtually do not contain copper. The stir zone was formed in the copper-to-steel joint zone. Large number of iron inclusions, implanted in copper in form of the separate bands and particles (Figure 6, *b*) is noted.

Joint longitudinal section has a tooth nature. The wedge-like implantations inclined in welding direction are observed in copper (Figure 6, *c*). This region consists of implanted in wrought copper the finest steel particles of 1–10 μm size, microhardness of these regions is 2740–3020 MPa. Upper weld section, i.e. recrystallized copper of 7–30 μm size, is located above the wedge-like implantations. HAZ width in steel achieves 4.5 mm. Regions of complete and partial recrystallization are clearly observed. In the contact zone the size of steel grain is an order lower than in the base metal, its microhardness makes 2290±120, when that of ferrite-pearlite steel is 2160±100 MPa.

Figure 7 shows the results of mapping of the stir zone in Cu–St.3 joint, which represents itself mechanical mixture of copper (base) and steel particles of different size. The disperse inclusions of copper are observed in the largest steel particles. The examination of copper and iron in characteristic radiation does not show mutual diffusion of elements, however, can not be excluded in the near-boundary regions. It is also determined that FSW of these metals provokes for significant grain refinement in the stir zone as well as in HAZ metal. It follows from carried investigations that stirring of metals in plastic state plays the leading role in production of copper-to-steel welded joint using FSW, and role of diffusion processes is insignificant.

Kh18N10–Cu joint. Joining of Kh18N10 stainless steel with copper was produced by FSW at modes, given in the Table. This experiment was carried out

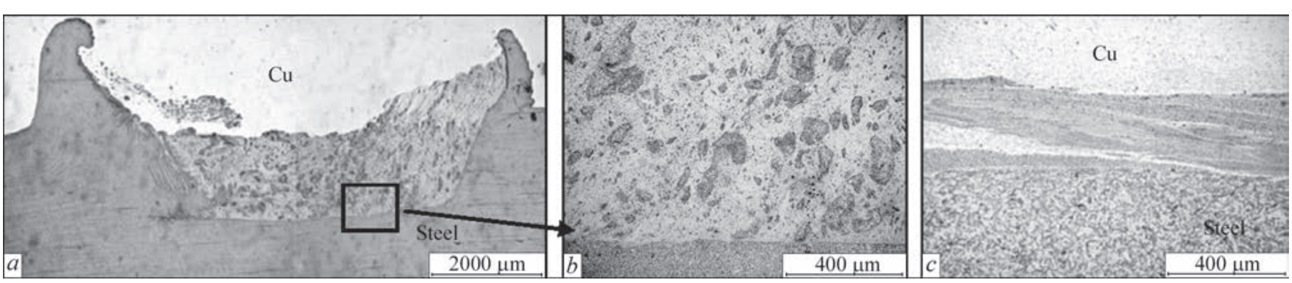

Figure 6. Microstructure of FS-welded Cu–St.3 joint: *a* — cross section; *b* — stir zone; *c* — longitudinal section

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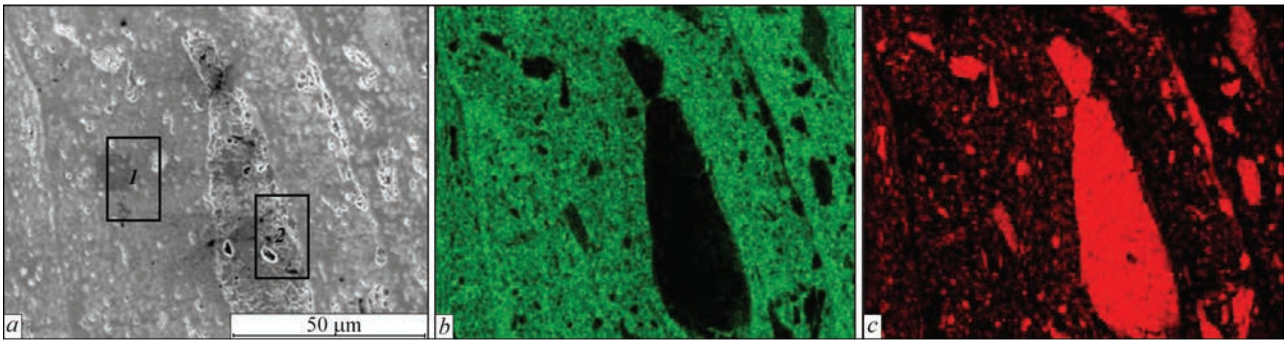

Figure 7. Image of Cu to St.3 stir zone in secondary electrons (*a*), Cu (*b*) and Fe (*c*) in characteristic radiation (chemical composition of examined regions, wt./at.%: *1* — 21.47/23.72 Fe, 78.27/75.99 Cu, 0.26/0.29 Mn; *2* — 97.60/97.44 Fe, 0.99/0.87 Cu, 1.14/1.16 Mn)

for creation of protective layer of stainless steel (as in deposition) on copper plate of CCM mold.

The steels of this class have pronounced tendency to air quenching and formation of cracks in welding. The heat conductance and expansion coefficient of this steel is considerably lower than carbon one.

Longitudinal and cross sections of steel-to-copper lap joints (Figure 8) were investigated. Stainless steel plunges into copper at up to 2 mm depth in form of strips and bands at pin height 4.5 mm. Simultaneously, dragging and stirring of the small regions of copper into stainless steel take place. Weld consists of two parts, i.e. one is located in steel, and another is in copper (Figure 8, *a*). In the weld steel part the pin promotes for deformation of metal with 20–30 % reduction of its thickness, appearance of deformation bands and structure recrystallization with formation of equiaxial grain of 5–25 μm size. Microhardness of this zone makes 1450–1700 MPa. Part of the weld located in copper is virtually a stir zone. Recrystallization of the both metals with fine grain formation, namely 10 μm (Figure 8, *b*) takes place in this region. HAZ with fine grain of 200–300 μm width is located around the stir zone in copper. Behind it the TMAZ with coarse, somewhat wrought grain, is located, along the boundaries of which incomplete recrystallization with formation of fine (20–30 μm) grain took place (Figure 8, *c*).

Examination of the weld cross-section showed that metal stirring takes place with steel implantation into copper in form of alternating bands and inclined strips at 4.4–5.2 mm gap (Figure 8, *d*). Their high and extension increases with welding speed rise. The maximum depth of steel implantation into copper makes 2 mm, and thickness of bands is varied from 30 to 100 μm at welding speed increase from 10 to 110 mm/min.

Macrostructure of the examined specimens, produced at different speeds of welding (see the Table) have common peculiarities. Investigation of cross and longitudinal section of the joints showed that the mass transfer of steel into copper takes place in form of bands, separate strips and particles (Figure 8, *e*, *f*). It is

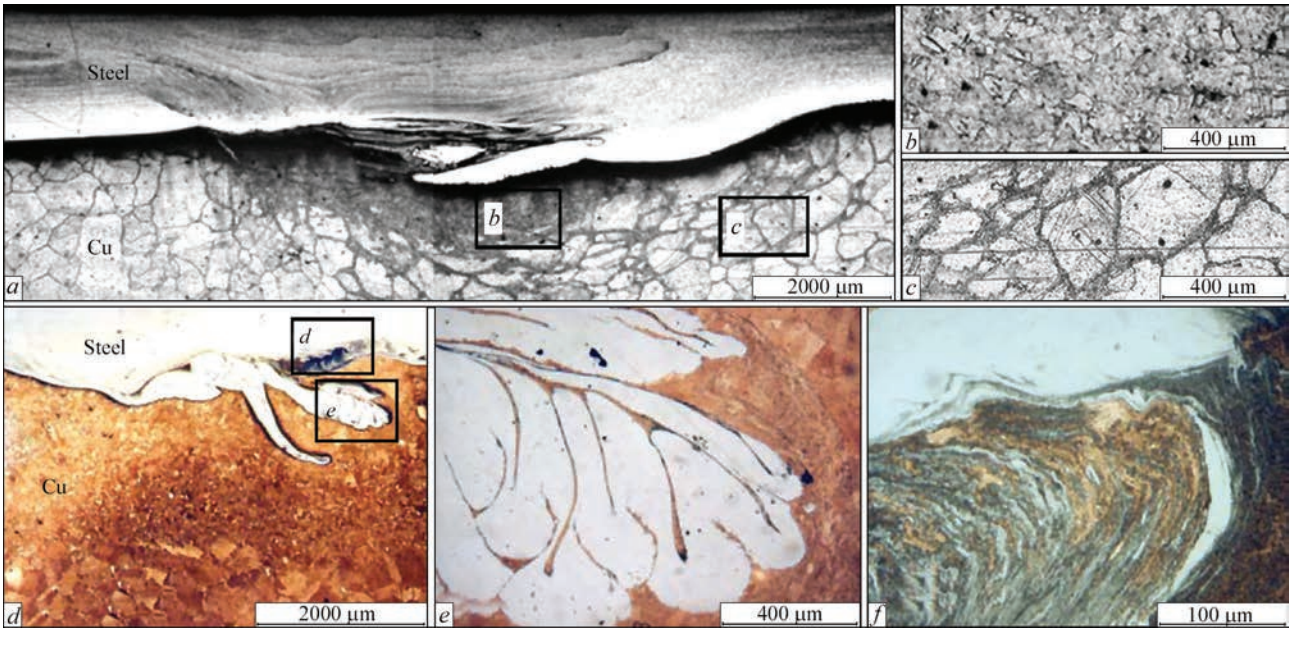

Figure 8. Microstructure of FS-welded Kh18N10–Cu joint: *a* – cross section; *b* — HAZ; *c* — TMAZ, *d* — longitudinal section; *e*, *f* — stir regions

found that formation of such stir regions occurs with certain sequence, and distance between them increases with welding speed rise. The most often defects of the joints are pores and cracks which are formed in stainless steel. The cracks are observed from the side of tool advancing in zone of copper-to-steel contact at small welding speeds (to 20 mm/min). Welded joints of the highest quality are produced at v_w = 20–50 mm/min.

Conclusions

1. FSW process, which is performed without base metal melting due to plastic deformation of metal heated to recrystallization temperature at optimum modes of welding, allows producing high-quality lap welded joint of homogeneous (Cu–Cu) as well as dissimilar (Ni–Cu, steel–Cu) metals.

2. Mechanical stirring of metals in plastic state plays the leading role in FSW. The role of diffusion processes is insignificant. Processes of recrystallization in the zones of metal plastic stirring promote for grain refinement and development of dense microstructure of weld comparable with base metal.

3. Carried investigations allow recommending this method for lap welding of dissimilar metals, having different solubility in solid state. Weld deposition at specific distance from each other helps to receive quality solid welding-up of upper (thinner) plate to massive lower one (by deposition type) with overlapping of recrystallization zones at minimum heating and distortion of the parts.

1. Thomas, W.M. *Friction stir butt welding*. Pat. 9125978.8 G.B. Int. Cl. PCTrGB92. Publ. 01.12.91.
2. Lebedev, V.K., Chernenko, I.A., Mikhalsky, R. et al. (1987) *Friction welding*: Refer. Book. Leningrad: Mashinostroenie.
3. Ericsson, L.G., Larsson, R. (2003) Rotational friction welding: Researches and new fields of application. *Tekhnologiya Mashinostroeniya*, **6**, 81–84.
4. Mishraa, R.S., Ma, Z.Y. (2005) Friction stir welding and processing. *Materials Sci. and Eng.*, **50**, 1–78.
5. Arbegast, W.J. (2006) Friction stir welding. After a decade of development. *Welding J.*, 85(**3**), 28–35.
6. Grigorenko, G.M., Adeeva, L.I., Tunik, A.Yu. et al. (2014) Structural features of FSW joints of metals with different element solubility in the solid phase. *The Paton Welding J.*, **4**, 6–16.
7. Xue, P., Ni, D.R., Wang, D. et al. (2011) Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu joints. *Materials Sci. and Eng.*, **528**, 4683–4689.
8. Saeida, T., Abdollah-Zadehb, A., Sazgarib, B. (2010) Weldability and mechanical properties of dissimilar aluminum-copper lap joints made by friction stir welding. *J. Alloys and Compounds*, **490**, 652–655.
9. Kosta, A., Coelho, R.S., dos Santos, J. et al. (2000) Microstructure of friction stir welding of aluminium alloy to magnesium alloy. *Ibid.*, **66**, 953–956.
10. Karmanov, V.V., Kameneva, A.L. (2013) *Friction stir welding of aluminium alloys: Matter and specifics of process*. Kiev: Naukova Dumka.
11. Graf, E.V., Shevchuk, M.V. (2008) Friction stir welding of nonferrous metals and their alloys. In: *Proc. of 12th Regional Sci.-Pract. Conf. of Students on Advanced Technologies and Economy in Machine-Building*, 17–19. Yurga: TPU.

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