

plasticity [4], reliability of fusion with the base metal as well as formation of hot and cold cracks in it. The hot cracks appearing in the process of sublayer hardfacing can provoke formation of failure of chip type during rollers' operation.

The wires containing REM are used for hardfacing of the sublayer of electrode materials with increased resistance to hot crack formation, however, their choice is limited by using of Sv-15GSTYuTsA and Sv-20GSTYuA ones.

Composite low-alloyed metal of 0.18–0.26 C, up to 1.5 Cr, 0.75–1.05 Mn, 0.55–0.75 Si, ≤ 0.025 S, ≤ 0.025 P and 0.020–0.058 wt.% of REM was investigated for evaluation of the possibility of its application as a sublayer obtained by hardfacing with flux-cored wire and flux. High technological strength and crack resistance of metal with 0.18–0.20 % C and 0.040–0.045 wt.% of REM allows recommending PP-Np-26Kh1G1S flux-cored wire for hardfacing of the sublayer during forming rolls repair.

Along with it, application of PP-26Kh1G1S flux-cored wire with 0.25–0.26 wt.% C and 0.047–0.052 % of REM for hardfacing with ceramic flux ZhSN-5 allows obtaining of wear-resistant layer with the structure more favorable in comparison with obtained with PP-Np-30KhGSA wire.

In both cases, the metal has martensite-ferrite structure with well-defined dendrite pattern (Fi-

gure 4). At the same time, crystals of the tempered martensite become more dispersed (Figure 4, *b*) due to REM addition, besides, the fraction of martensite component increases, that determines high hardness *HV* 450 and sufficient plasticity of deposited metal.

Such a metal differs by higher technological strength and resistance to thermal fatigue fracture: deposit of 35Kh8GSMF type has relative strength index 1.0 at average 230–380 number of thermal cycles up to crack appearance, and deposited 34Kh8GSMF metal with REM has, respectively, index 1.3–1.4 at 370–490 cycles at average.

Thus, addition of REM in the composition of Kh5MF and Kh12MF deposits applied for repair of forming rolls and rollers of machines for continuous billet casting increases its technological strength, impact toughness, resistance to thermal fatigue fracture and specific fracture work.

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EFFECT OF MANGANESE ON STRUCTURE AND WEAR RESISTANCE OF DEPOSITED METAL OF THE LOW-CARBON STEEL TYPE

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Investigation results are presented on structure and wear resistance of metal deposited by using flux-cored strips and having chemical composition of the low-carbon steel type with differing manganese content. The possibility of improving wear resistance of the deposited metal due to subsequent heat and thermochemical treatments is studied. It is shown that achievement of the optimal amount of meta-stable austenite in structure leads to improvement of wear resistance of the deposited metal.

Keywords: arc cladding, flux-cored strips, deposited metal, structure, martensite, austenite, bainite, strengthening, tempering, case-hardening

Peculiarities of commercial application of consumables providing formation of meta-stable austenite in the deposited metal and characterised by dynamic deformation martensitic transformation (DDMT) are described in study [1]. Also, it is noted in that study that inadequate attention is given now to development of such consumables. Known austenitic cladding consumables of the 110G13L steel type, containing an increased amount of manganese and carbon, as well

as chrome-manganese consumables of the PP-Np-25Kh10G10T type are insufficiently practicable, as metal deposited with them is hard to process by machining [2]. In a number of cases expensive alloying elements are used in such consumables. Therefore, the problem of development of sparsely alloyed cladding consumables is still topical. This problem can be addressed by providing the multi-phase structure in the deposited metal, where austenite is present along with other components (martensite, carbides, carbonitrides, etc.), rather than the austenitic one. For this it is important to have the meta-stable structure that is self-transformable under loading and characterised

Table 1. Chemical composition and properties of deposited metal

Content of alloying elements, wt.%				Hardness HRC	Presence of cracks
C	Mn	Si	Ti		
0.15	5.1	0.71	0.09	36	No
0.16	8.2	0.63	0.11	42	No
0.14	10.0	0.67	0.11	47	Yes
0.15	12.2	0.61	0.08	45	Yes
0.16	14.1	0.68	0.12	34	No

by occurrence of various structural and phase transformations leading not only to strengthening, but also to relaxation of microstresses. In particular, it is the meta-stable austenite experiencing DDMT that can serve as such a structure [3, 4]. The above transformations can be accompanied by the dynamic processes of twinning and ageing, changes in the dislocation density, dispersion of structure, etc.

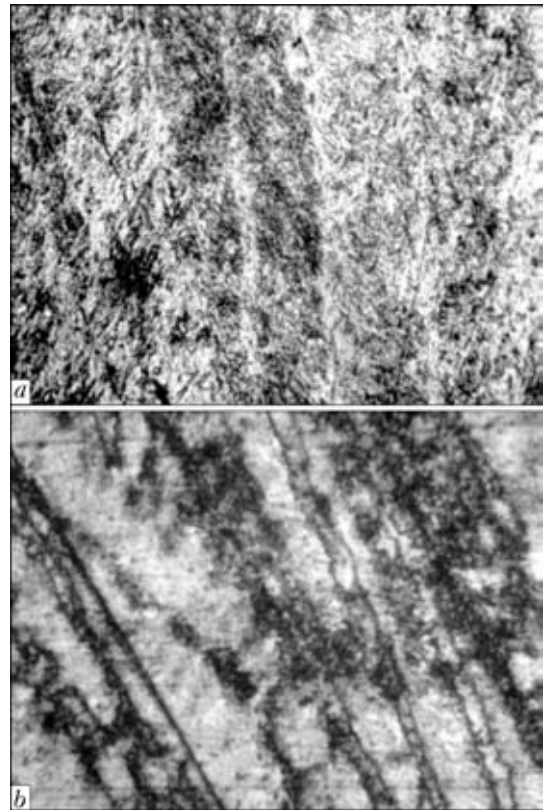
Cladding consumables providing the low-carbon Fe–Mn–C base deposited metal of the martensitic, martensitic-austenitic and austenitic-martensitic grades, as well as improvement of properties of the deposited metal as a result of heat and thermochemical treatments hold promise for manufacture of parts subjected to mechanical wear (various guides, shafts, rollers, sleeves, crane wheels, etc.).

Single-seam flux-cored strips 10 × 3 mm in size, with a fill factor of 48–50 %, were made from the charge containing a different amount of manganese metal and iron powder, as well as a small amount of ferrotitanium to refine grains in the deposited metal structure. A strip of cold-rolled steel 08kp (rimming) was used as a steel sheath. Cladding was performed in three layers on a 30 mm thick plate of steel VSt3sp (killed) by the submerged-arc method using flux AN-26 under the following conditions: current 450–500 A, voltage 30–32 V, cladding speed 25 m/h, no preheating. Subsequent beads were deposited after cooling to a temperature not higher than 250 °C.

Tempering of specimens cut out from the deposited metal was carried out at temperatures of 450, 550, 650 and 750 °C with holding for 1 h and subsequent cooling in air. The specimens were also subjected to case-hardening in solid carburiser at a temperature of 950 °C for 10 h. After that, part of the specimens was subjected to tempering at 650 °C. Chemical composition of the metal deposited with the experimental flux-cored strips is given in Table 1 (S, P ≤ 0.03 %).

Durometric and metallographic examinations were carried out. Phase composition was studied by the X-ray method using diffractometer DRON-4.

Microstructure of the deposited metal containing 5 and 8 % Mn (without heat treatment) was martensitic (Figure 1, *a*). No ferrite was detected in the deposited metal structure, this being in agreement with the data of study [5], which reports that diffu-

**Figure 1.** Microstructure (×500) of deposited metal with 5 (*a*) and 14 % Mn (*b*)

sionless martensitic $\gamma \rightarrow \alpha$ transformation in Fe–Mn steels containing more than 5 % Mn occurs at the usual rates of air cooling. The α -martensite region extended to 8 % Mn, and increase of the manganese content led to lowering of temperature ranges of the $\gamma \rightarrow \alpha$ transformations. The highest hardness of the deposited metal was fixed at 10 and 12 % Mn, this being caused by higher hardening of α -martensite, compared to 5 % Mn. As the manganese content was increased to 14 %, in addition to α -martensite, ϵ -martensite (about 20 %) and austenite (about 50 %) (Figure 1, *b*), having a much lower hardness, appeared in the deposited metal structure, thus causing decrease in hardness of the deposited metal.

No cracks were fixed in the deposited metal at a manganese content of 5, 8 and 14 %. Formation of cracks in the deposited metal containing 10–12 % Mn can be explained by the highest degree of hardening of α -martensite at a very low level of ductile properties. This is caused by intensive localisation of bond between the iron crystalline lattice atoms due to redistribution of external electrons from the iron to manganese atoms [6]. The absence of cracks at a manganese content increased to 14 % is explained by decrease in the degree of hardening of the deposited metal and increase of its ductility because of an increased amount of austenite formed in structure. The deposited metal containing 10–12 % Mn was not used in further investigations because of its low crack resistance.

The flux-cored strips being developed are intended for repair and strengthening of parts subjected to wear

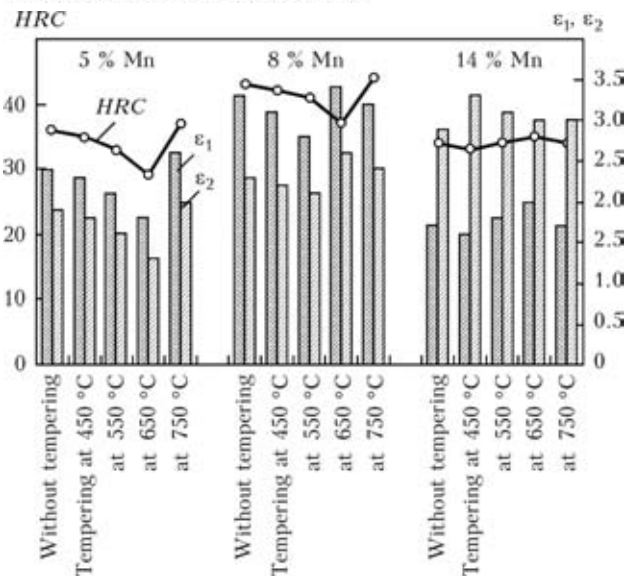


Figure 2. Hardness and relative wear resistance of deposited metal in dry friction, ϵ_1 , and without heat treatment and after tempering in grit flow tests, ϵ_2

in metal on metal friction. They are meant to be used instead of the widely applied cladding consumables providing the deposited metal of the low-carbon steel type, e.g. Np-30KhGSA and PP-Np-18Kh1G1M, and in a number of cases of the chrome-manganese austenitic steel type, e.g. PP-Np-14Kh12G12ST.

Wear resistance of parts is usually estimated by the results of the tests simulating interaction under the sliding and rolling friction conditions.

The tests under the sliding friction conditions were conducted by the block-roller scheme in dry friction (wear resistance ϵ_1). The speed of rotation of the 70 mm diameter roller of steel 55 with hardness HRC 56 was 200 rpm. Pressing of a flat specimen was provided by using the 8 kg load.

Comparative wear resistance tests of the deposited metal of different structural grades under the rolling friction conditions by the roller-roller scheme (pressure 320 MPa, speed of rotation of the rollers 0.98 m/s, slippage 0.09 m/s) and under the dynamic effect of a grit flow at different attack angles were carried out at a preliminary stage of the investigations. Manufacture of specimens for the second type of the tests was much less labour and material consuming. In this case, the surface of the flat specimen was affected by grits transported with a compressed air flow at a pressure of 5 atm in the system. The diameter of a nozzle at exit of the jet from a mixer was 16 mm. The time of testing of the specimens was determined by consumption of 20 kg of the grits.

The tests under the rolling friction conditions and under the effect of the grit flow resulted in fatigue fracture of the surface volumes of metal under the repeated force impact. Variations in the grit attack angle allowed the fracture conditions to be varied. Close values were obtained in the course of the investigations in tests by the roller-roller scheme and under

the effect of the grit flow at an attack angle of 60°. The latter scheme of wear was used for further investigations (ϵ_2). Results of the tests by the roller-roller and grit flow schemes were selectively rechecked on individual specimens of the deposited metal. The values of wear resistance were close in all the cases of the tests by the above schemes.

The metal deposited with a widely applied flux-cored strip PP-Np-18Kh1G1M, subjected to tempering at 600 °C to hardness of HB 280, was used as a reference for evaluation of a relative wear resistance.

The investigation results on wear resistance of the deposited metal containing 5, 8 and 14 % Mn without heat treatment and after tempering at different temperatures are shown in Figure 2.

Correlation of wear resistance of the deposited metal with its hardness was observed in dry friction. And on the contrary, when tested in the grit flow, the deposited metal with 14 % Mn exhibited the highest wear resistance together with the lowest hardness, this being caused, according to the X-ray analysis data, by transformation of retained austenite into martensite during wear. This transformation was not pronounced in dry friction, probably, because of heating of the surface above the martensitic transformation temperature [4].

As the tempering temperature was increased from 450 °C to A_{c1} , wear resistance and hardness of the deposited metal containing 5 and 8 % Mn decreased due to weakening of martensite. The highest wear resistance of such a deposited metal at different types of wear was achieved in an intercritical temperature range (ICTR of $A_{c1} < t < A_{c3}$). This temperature corresponded to 750 °C for the deposited metal with 5 % Mn, and 650 °C — for the deposited metal with 8 % Mn. Redistribution of carbon and manganese between the α - and ϵ -phases and their enrichment with the latter took place in ICTR. As a result, in addition to martensite and a small amount of carbides, the deposited metal also contained austenite, i.e. 9 and 18 % at 5 and 8 % Mn, respectively. This austenite was meta-stable, and under loading it completely transformed into martensite. Figure 3, *a* and *b*, shows the data for the deposited metal with 8 % Mn. In addition, after heating and holding in ICTR, part of the austenite in cooling to room temperature transformed back to the martensite having a higher hardness due to its increased content of carbon and manganese. Along with the meta-stable austenite, that provided increase in wear resistance.

Heating of the deposited metal containing 14 % Mn in a temperature range of 450–750 °C had an unambiguous affect on wear resistance. In a case where stabilisation of austenite occurred with regard to DDMT (tempering at 450 °C), the wear resistance decreased in dry friction and increased in tests in the grit flow. And on the contrary, in destabilisation of

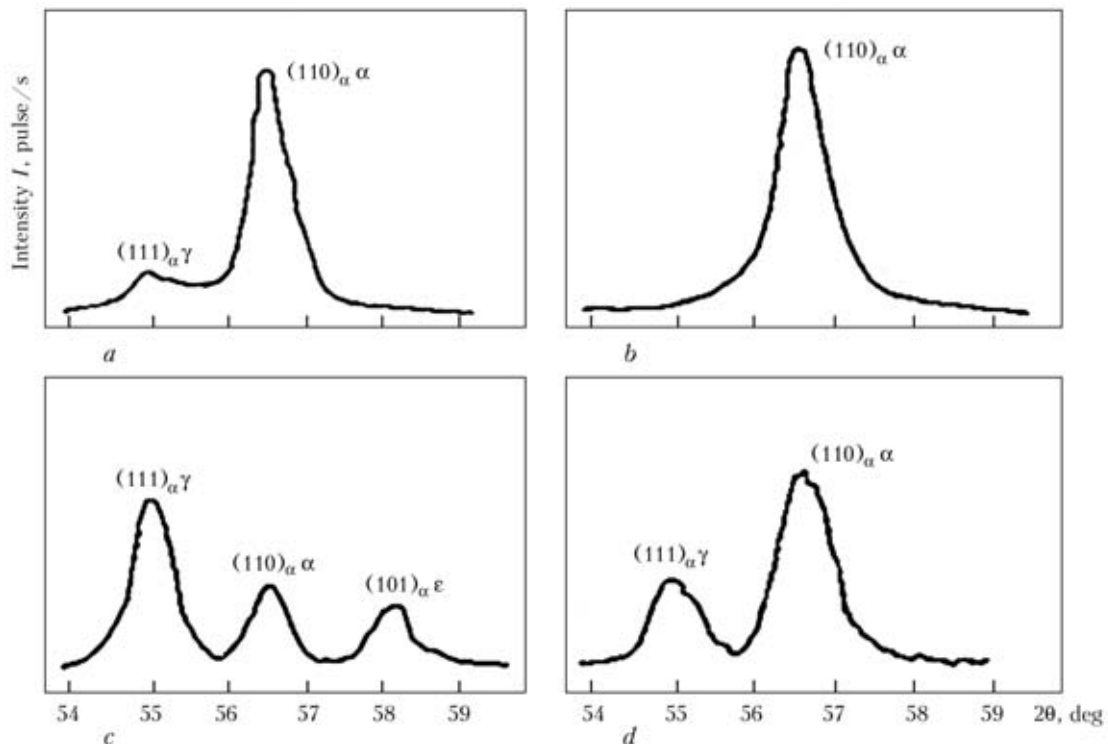


Figure 3. Diffraction patterns of deposited metal containing 8 (*a, b*) and 14 % Mn (*c, d*) after tempering at 650 °C before wear in grit flow (*a, c*) and after wear (*b, d*)

austenite because of precipitation of carbides (tempering at 550 °C and especially at 650 °C), wear resistance increased in dry friction and decreased in the grit flow tests. A change in phase composition of the deposited metal is confirmed by the diffraction patterns shown in Figure 3, *c* and *d*. Austenite prevailed in structure before wear, and martensite – after wear, the ϵ -phase being absent. After tempering at 750 °C, the structure and wear resistance were close to those in the as-clad condition.

It is a known fact that increase in the carbon content of steels leads to improvement of their wear resistance. However, the high-carbon deposited metal is difficult to machine, and is susceptible to cracking. An efficient technological approach is cladding with low-carbon steels followed by their case-hardening [7]. The data on the effect of case-hardening and tem-

pering at 650 °C on structure and properties of the deposited metal are given in Table 2.

The highest wear resistance after case-hardening under the dry friction conditions was exhibited by the deposited metal containing 5 % Mn. In this case, the structure contained 35–40 % of meta-stable austenite, along with martensite and carbides. With increase in the manganese content to 8 and 14 %, the wear resistance of the deposited metal in dry friction decreased due to an increased content of austenite in its structure.

Because of weakening of martensite and decomposition of retained austenite, tempering of the deposited metal containing 5 % Mn at 650 °C led to decrease of its wear resistance under the dry friction conditions. And on the contrary, wear resistance of the deposited metal containing 8 and 14 % Mn increased after tem-

Table 2. Properties of deposited metal after case-hardening and subsequent tempering

Mn content, %	Treatment	Phase content*	Hardness <i>HRC</i>	Wear resistance	
				ϵ_1	ϵ_2
5	Case-hardening	35–40 % A + (M + C)	48	7.2	3.7
	Same + tempering at 650 °C	20–25 % A + (M _t + M + C)	36	5.5	2.9
8	Case-hardening	75–80 % A + (M + C)	39	6.4	5.8
	Same + tempering at 650 °C	50–55 % A + (M _t + M + C)	41	6.9	5.3
14	Case-hardening	95–97 % (A + C)	26	3.7	4.1
	Same + tempering at 650 °C	85–90 % A + (M + C)	35	4.8	4.6

* A – austenite; C – carbides; M – martensite; M_t – tempered martensite.

pering at 650 °C due to activation of DDMT as a result of precipitation of carbides from austenite.

In grit flow tests, the highest wear resistance was fixed after case-hardening of the deposited metal with 8 % Mn and containing 75–80 % of retained austenite in its structure.

As established, tempering may have a different effect on wear resistance of the deposited metal when tested in the grit flow, depending on its manganese content. At the 5 and 8 % Mn content, it decreased after tempering at 650 °C, whereas at the 14 % Mn content it increased. This can be explained as follows. Tempering at 650 °C is accompanied by weakening of martensite and excessive activation of DDMT at the 5 and 8 % Mn content, when stability of austenite is low, this leading to decrease in wear resistance. At a manganese content of 14 %, when stability of austenite is increased, activation of DDMT, on the contrary, increases wear resistance.

In all the cases, the method proposed for improvement of wear resistance by subjecting the low-carbon deposited metal alloyed with manganese to case-hardening provides for formation of retained meta-stable austenite in its structure, in addition to martensite and carbides. This is its characteristic feature, as traditional methods are aimed at providing the martensite-carbide structure after case-hardening and subsequent heat treatment, whereas retained austenite is considered to be an undesirable structural component that decreases hardness and wear resistance. At the same time, it is important to take into account that the highest wear resistance can be achieved at the optimal stability of austenite with regard to DDMT for a specific type of loading or testing.

High stability of overcooled austenite in the deposited metal containing no more than 5 % Mn to formation of the ferrite-cementite mixture allows using no special hardening environments, as self-hardening takes place during the process of air cooling. Important advantages in this case are the absence of cracks, increase in wear resistance, simplification of

the technology, as well as the cost-effective and environment-friendly technological process.

CONCLUSIONS

1. It is shown that development of sparsely alloyed cladding low-carbon manganese-containing consumables, which provide formation of the martensitic or martensitic-austenitic structure in the deposited metal, holds high promise.

2. High tempering conducted to relieve stresses in the deposited metal with the martensitic structure should provide formation of a certain amount of meta-stable austenite, which transforms into martensite during wear. For this, the temperature of heating and holding of the clad parts should ensure fitting the intercritical temperature range.

In a case of the primarily austenitic structure of the deposited metal, tempering should regulate stability of austenite with regard to deformation transformation of martensite allowing for the loading conditions.

3. It is suggested that deposited metal of the low-carbon steel type containing no more than 5 % Mn should be subjected to case-hardening to improve its wear resistance.

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