INCREASE IN STRENGTH PROPERTIES OF LOW-CARBON STEELS DUE TO STRUCTURAL TRANSFORMATIONS AT DEFORMATION BY ROTARY SWAGING

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Abstract: *Mechanical properties of low-carbon St.20 and 07G2MFB steels after rotary swaging (RS) were studied. It was established that an increase in strain ratio and decrease in temperature increase strength but decrease plasticity. The ultimate tensile strength of 867-927 MPa was obtained in both steels after deformation at temperature of 400 °C with a true strain ratio of 2.3 at good ductility of 15-17%.*

Keywords: LOW-CARBON STEEL, ROTARY SWAGING, ULTRAFINE-GRAINED (UFG) STRUCTURE, THERMAL STABILITY OF STRENGTHENING, MECHANICAL PROPERTIES

1. Introduction

It is well known that methods of severe plastic deformation (SPD) such as high-pressure torsion and equal-channel angular pressing lead to significantly refinement of structure and improve the strength and service properties of low-carbon steels [1,2]. But at the present time, SPD methods are difficult to embed into the industrial production. Therefore, it is important to obtain low-carbon alloys with ultrafine grained (UFG) structure by industrial deformation methods, such as rotary swaging [3].

The purpose of this research is to establish a possibility of producing ultrafine-grained (nano- and submicrocrystalline) structures of low-carbon steels by rotary swaging and to study of its mechanical behavior.

2. Materials and experiment

The deformation of St.20 (0.19%C, 0.49%Si, 0.21%Mn, 0.03%Ni, 0.25%Cr, 0.19%Cu, 0.05%As, and Fe as a balance in wt.%) and 07G2MFB (0.073%C, 0.252%Si, 1.58%Mn, 0.242%Ni, 0.007%P, 0.005%S, 0.151%Cu, 0.22%Cr, 0.037%Al, 0.018%V, 0.195%Mo, 0.015%Ti, 0.02%W, 0.08%Nb, 0.0029%N, and Fe as a balance in wt.%) low carbon steels was carried out by rotary swaging (Fig.1). St.20 was subjected to quenching in water from a temperature of 880°C (1 hour) and high-temperature tempering at 600°C (1 hour). The 07G2MFB steel was subjected to quenching in water from a temperature of 920°C (1 hour) and high-temperature tempering at 680°C (1 hour).

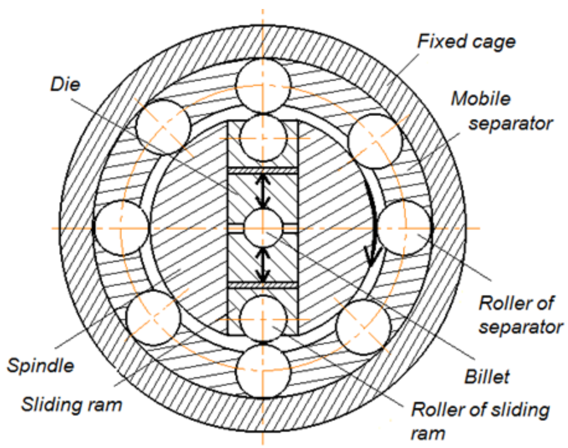

Fig. 1 *Schematic of the rotary swaging ($\mu = A_0 / A_f$, where A_0 and A_f are the initial and the final cross-sectional area of the billets, respectively)*

The initial structure of both steels was similar. It was a polyhedral (globular) ferrite with pearlitic colonies, and also oriented products of quenching (Fig. 2). Transmission electron microscopy (TEM) revealed that the quenching products are acicular ferrite and tempered martensite.

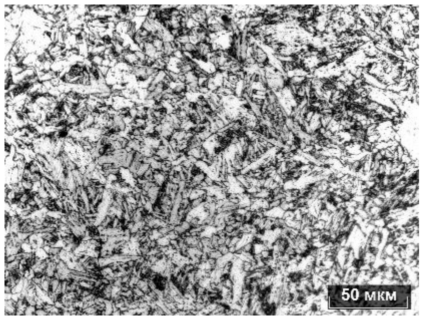

Fig. 2 *The structure of 07G2MFB steel after quenching and high-temperature tempering (optical microscopy)*

Rotary swaging of 07G2MFB steel was carried out in two modes with a decrease in the deformation temperature: 650°C (true strain ratio – 0,6) – 575°C (total true strain ratio –1,2) – 500°C (total true strain ratio –2,3) and 600°C – 500°C – 400°C with the same strain ratio. Rotary swaging of St.20 was carried out according to the second mode. The limited facilities of equipment and size of specimens did not allow an increase in the strain ratio during RS.

The microstructure was investigated using an Olympus PME 3 optical microscope and a JEM- 1400 transmission electron microscope operated at 120 keV. Static tensile tests were performed using an INSTRON 3380 tensile testing machine with a load capacity of 100 kN. Measurements of microhardness were taken by means 402 MVD Wolpert Wilson with loading 1N.

3. Results and discussion

The structure of 07G2MFB steel after rotary swaging (RS) was studied in two modes with a decrease in the temperature of deformation: 650 ° C - 575 ° C - 500 ° C and 600 ° C - 500 ° C – 400 ° C. The structure after RS at 650 ° C with a true strain ratio of 0.6 does not practically differ from the structure of this steel after quenching and tempering (Fig.2, 3a). Decreasing the temperature of RS to 575 ° C and increasing the strain ratio to 1.2 led to the orientation of the initial grain structure (Fig. 3b). The final stage of the RS at 500 ° C with a total true strain ratio of 2.3 led to the formation of considerably oriented initial structure judging by the metallographic analysis (Fig. 3c). The TEM analysis revealed the formation of a submicrocrystalline structure with an average grain size of 343 nm inside this highly oriented initial structure. The metallographic analysis of 07G2MFB steel after RS by the mode of 600 ° C - 500 ° C - 400 ° C with a total true strain of 2.3 revealed an even more oriented structure due to a decrease in the strain temperature (Fig.4).

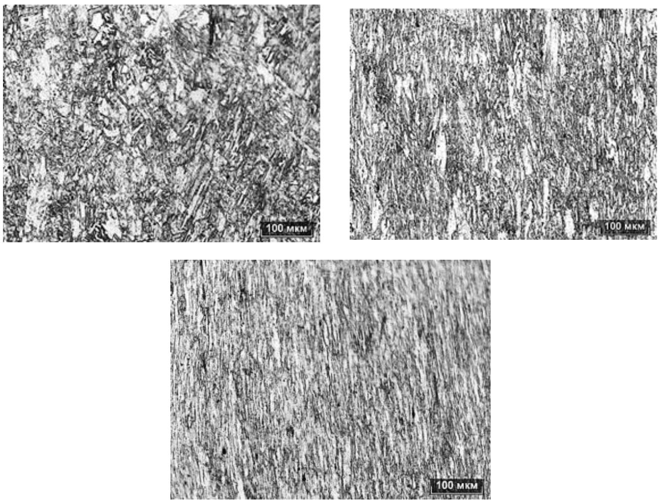

Fig. 3. The structure of 07G2MFB steel after rotary swaging with a decrease in temperature of deformation: 650 ° C (true strain ratio - 0.6) (a) - 575 ° C (1.2) (b) - 500 ° C (2.3) (c) (optical microscopy)

It can even metallographically observed the substructure inside highly elongated initial grains (Fig.4b). In this case, the TEM analysis revealed a submicrocrystalline structure with a smaller average grain size of 312 nm (Fig. 5).

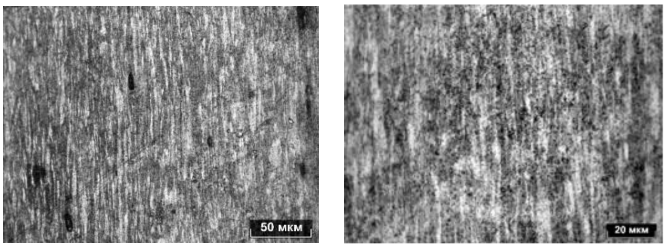

Fig. 4 The structure of 07G2MFB steel after rotary swaging with a decrease in temperature of deformation: 600 °C (true srainratio - 0.6) - 500 ° C (1.2) - 400 ° C (2.3) (optical microscopy).

The metallographic analysis of St.20 after RS by the 600 ° C - 500 ° C - 400 ° C mode (true strain ratio - 2.3) also revealed a highly oriented initial structure (Fig.6a). The TEM analysis revealed a submicrocrystalline structure with an average grain size of 285 nm (Fig.6b).

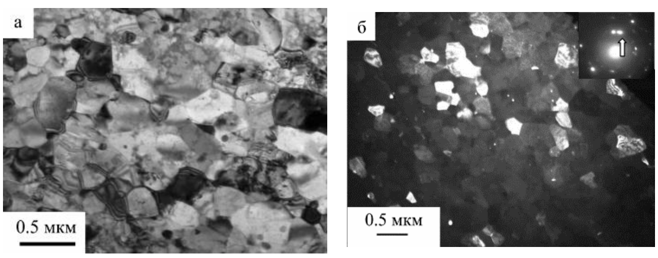

Fig. 5 The structure of 07G2MFB steel after rotary swaging with a decrease in the temperature of deformation: 600 ° C - 500 ° C - 400 ° C (true strain ratio - 2.3):(a) bright-field; (b) dark-field image obtained in [110] $_{\alpha\text{-Fe}}$.

Thus, the selected modes of rotary swaging of St.20 and 07G2MFB steels made it possible to obtain a predominantly submicrocrystalline structure with grain sizes ranging from 285 to 375 nm in these steels.

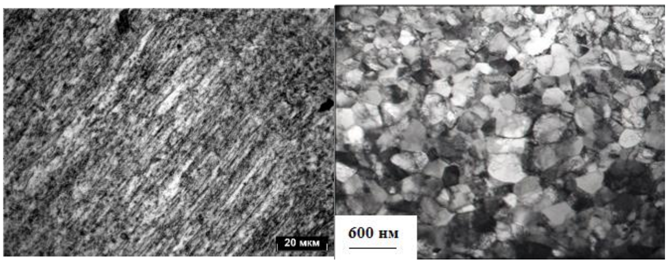

Fig. 6 The structure of St.20 after rotary swaging with a decrease in deformation temperature: 600 °C - 500 °C - 400 °C (true degree of deformation - 2.3): (a) - optical microscopy, (b) - TEM

The thermal stability of strengthening of St.20 and 07G2MFB steels after RS was studied according to the microhardness vs annealing temperature. The values of microhardness increase with decreasing temperature of RS and increasing strain ratio (Fig.7 and 8). After RS, the microhardness of 07G2MFB steel as compared with St.20 steel is higher (Fig.8).

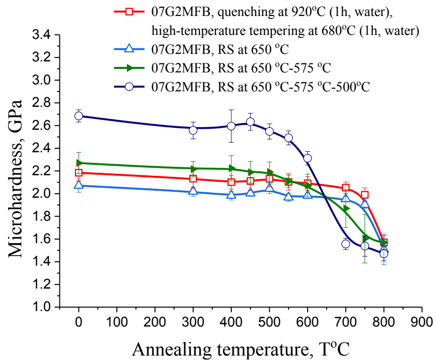

Fig. 7 The thermal stability of strengthening of 07G2MFB steel after quenching and tempering and RS by mode of 650 ° C - 575 ° C – 500 °C

The thermal stability for these steels of both treatments is about the same, but lower than that after quenching and tempering, despite a significantly higher level of strengthening.

For example, the thermal stability of the strengthening of 07G2MFB steel after the final stage of the RS at 400 °C is 400-450 °C, and after quenching and tempering it is 700 °C, but the microhardness level is 2.9 and 2.2 GPa, respectively (Fig.8a).

The mechanical properties of low-carbon St.20 and 07G2MFB steels after rotary swaging were studied. With a decrease in temperature and an increase in the strain ratio, the strength properties increased, and plasticity declined only slightly, which is observed both on 07G2MFB steel (Fig. 9 a, b, Table 1), and on St.20 (Fig. 9c, Table 1).

Acknowledgements

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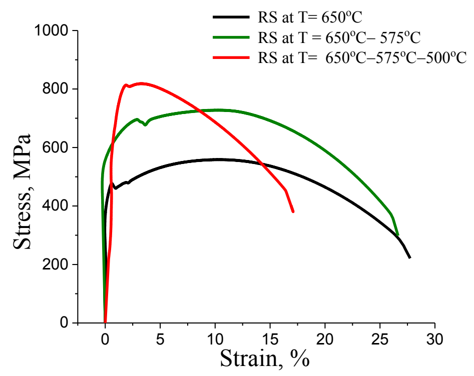
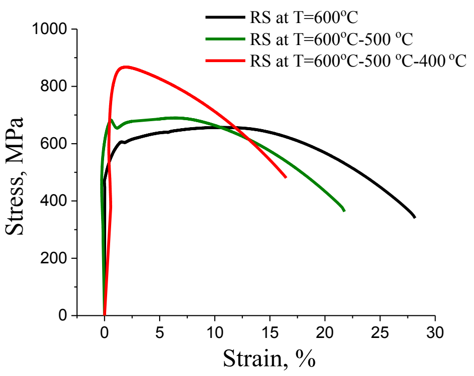


a



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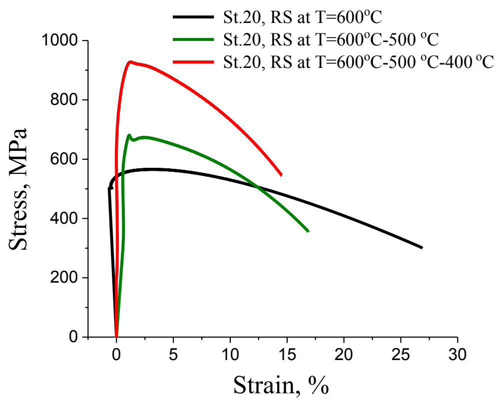


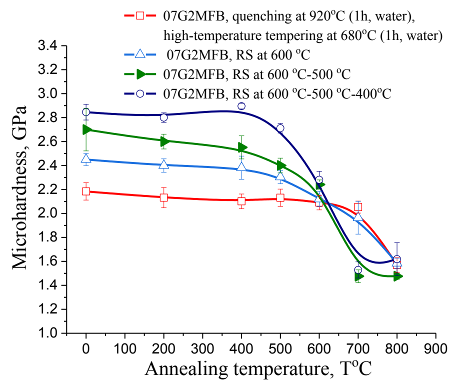
c

***Fig.** 9 Mechanical properties of low-carbon 07G2MFB (a, b) and St.20 (c) steels*

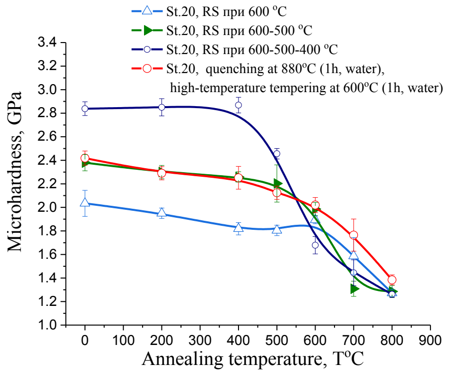
Comparing the ultimate tensile strength both of steels, deformed by the second mode of 600 °C – 500 °C – 400 °C, it can be seen that swaging at 600 °C with a true strain ratio of 0.6 leads to a slightly greater tensile strength in 07G2MFB steel, and swaging at 400 °C with a true strain ratio of 2, 3 - in St.20 (Fig. 9b, c, Table 1). But it should be noted in this case rather close values of the ultimate tensile strength. Therefore, it can be argued that the ultimate tensile strength of 867-927 MPa was obtained for both steels at the final stage of the RS at 400 ° C and with a true strain ratio of 2.3 at good ductility of EL = 16-17%.

***Table 1:** Mechanical properties of low-carbon 07G2MFB and St.20 steels*

	Treatment /T_{def}°C,	Ultimate Tensile Strength σ_{UTS}, MPa	Yield Stress σ_{YS}, MPa	EL, %
07G2MFB	Quenching at 920°C (1h) → high-temperature tempering at 680°C (1h)	594	481	27
	RS / T=600°C	654	604	28
	RS / T=600°C→500 °C	690	654	22
	RS/T=600°C→500 °C→400 °C	867	846	17
	RS / T=650°C	558	460	28
	RS / T=650°C→575 °C	728	678	27
	RS / T=650°C→575 °C→500 °C	819	808	17
St.20	Quenching at 880°C (1h) → high-temperature tempering at 600°C (1h)	600	460	21
	RS / T=600°C	565	505	27
	RS / T=600°C→500 °C	673	664	17
	RS / T=600°C→500 °C→400 °C	927	923	15



a



b

***Fig. 8** The thermal stability of strengthening of steels after quenching and tempering and subsequent RS by mode of 600°C – 500°C – 400°C: (a)- 07G2MFB steel;(b)- St.20*

4. Conclusions

1. Rotary swaging of 07G2MFB steel was carried out by two modes with a decrease in the deformation temperature: 650 ° C (true strain ratio - 0.6) - 575 ° C (1.2) - 500 ° C (2.3) and 600 ° C - 500 ° C – 400 °C with the same strain ratio. Rotary swaging of St.20 was carried out according to the second mode.
2. Rotary swaging of low-carbon St.20 and 07G2MFB steels at the final stage of the RS at 400 ° C with a true strain ratio of 2.3 leads to the formation of an ultrafine-grained (UFG) structure with a size of structural elements 285-312 nm.
3. The ultimate tensile strength in the range from 867 to 927 MPa with a true strain ratio of 2.3 and with good ductility EL = 16-17% was obtained in both steels at the final stage of the RS at 400 ° C.

5. References

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