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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH-STRENGTH STEEL WITH IMPROVED MACHINABILITY

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A structural steel (grade 40KhGM) with improved machinability was studied. The steel contains an increased amount of sulfur and was modified with calcium during metallurgical production stage. A qualitative analysis of the size of nonmetallic inclusions present in the studied steel was performed in comparison with conventional steel (40KhGMA) with low sulfur and calcium contents. A dilatometric study was carried out to compare the specifics of supercooled austenite transformation and hardenability of steel with improved machinability and standard steels. The corresponding continuous cooling transformation (CCT) diagrams of austenite transformations were plotted. The dependencies of the mechanical properties of the studied steels with various impurity contents on the tempering temperature have been established. According to the results, calcium-treated steel with improved machinability is characterized by a similar set of mechanical properties as conventional low-sulfur steels. This implies that the steel with improved machinability can be successfully used for the production of critical and high-strength parts using automated lines and machines.

Keywords: steel, calcium-modified, machinability, non-metallic inclusions, mechanical properties, continuous cooling transformation (CCT) diagram.

Introduction

Steel grades with improved machinability (free-cutting steels) are widely used in machine building to enable mass production of parts using automated flow lines [1, 2]. The main feature of such steels is reduced wear of the metal-cutting tools and increases performance of the metal-working machines. Currently, the following classes of steels with improved machinability are available: steel grades containing sulfur; sulfur and selenium; lead; bismuth; calcium; calcium and lead [1–4].

The principles used to create the above classes of steels with improved machinability are mainly based on the following phenomena that help reduce tool wear: increased brittleness of the shavings and lubricating effect of inclusions in steel [5, 6]. The increased brittleness of the steel shavings results from the presence of manganese sulfide inclusions, which is why almost all free-cutting steels contain a fairly high amount of sulfur: up to 0.2 wt.%. In addition, dispersed sulfide inclusions also cause a lubricating effect on the cutting edge of the tool, thus preventing it from overheating, while increasing resistance. The same effect is caused by lead, which is present in steel in the form of individual isolated inclusions, as well as calcium, which additionally prevents the adhesion of the metal from the machined part to the cutting edge of the tool. At certain cutting speeds, calcium deposits are formed on the cutting tool, which protects it from wear [7, 8].

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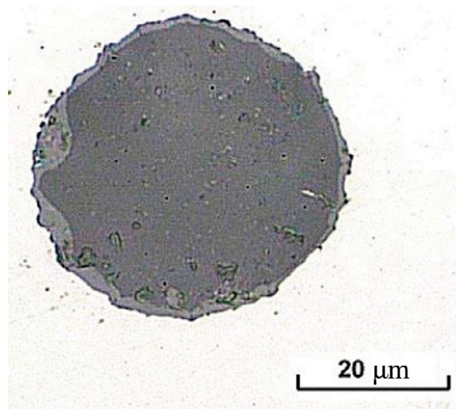


Fig. 1. Complex globular inclusion: calcium aluminate $CaO \cdot Al_2O_3$ coated with calcium and manganese sulfide [16].

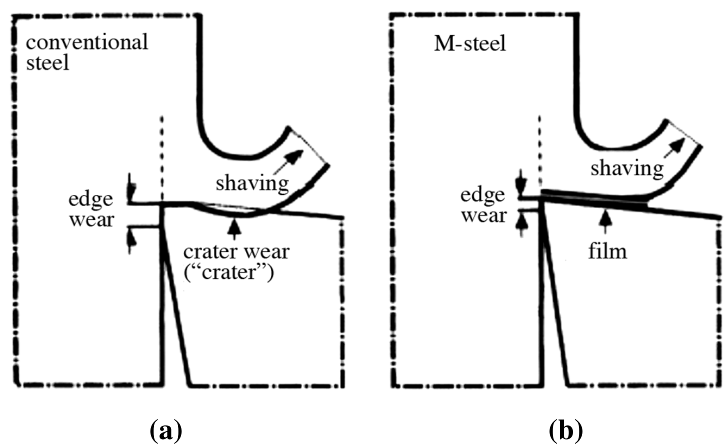


Fig. 2. Schematic diagram of shaving formation during machining of conventional steel (a) and M-Steel (b) [7].

Unfortunately, an increase in the sulfur content and the amount of foreign inclusions, especially of the string type, inevitably leads to a decrease in the level of mechanical properties of steel [9-11]. Therefore, free-cutting steels in most cases are represented by carbon or manganese low-alloy steels used for producing non-essential parts. Such steels either undergo no further heat treatment to achieve hardening, or are subjected to normalization or annealing only.

In the 1970–1990s, a new class of steel with improved machinability was developed by OVAKO: M-Steel ("M" stands for "Machinability") [12]. Conceptually, M-Steel is based on the formation of dispersed non-metallic inclusions of a special composition. Due to controlled contents of sulfur and calcium (up to 30-40 ppm), complex globular inclusions are formed in steel, representing calcium aluminates ($CaO \cdot Al_2O_3$) covered with a shell consisting of calcium and manganese sulfide (Ca, Mn)S (Fig. 1) [12–17]. Such inclusions cause a lubricating effect on the tool during machining and reduce the degree of wear of the cutting edge.

Calcium inclusions contained in M-Steel adhere to the cutting edge of the tool during machining and form a protective layer (Fig. 2). This layer reduces the adhesion of steel to the cutting tool and also prevents overheating of the tool during machining, since the significant amount of heat is removed with the shavings or remains on the surface of the part. In addition, high temperature results in better fragmentation of the shavings and their removal from the cutting zone. This significantly increases the service life of the cutting tool as well as machining productivity [7].

Table 1
Chemical Composition of Studied Steel Grades, wt.%

Steel	C	Cr	Mn	Si	Ni	Mo	S	P	Cu	Ca
M-Steel	0.44	1.02	0.82	0.25	0.24	0.15	0.046	0.016	0.22	0.045
40KhGMA	0.43	0.97	0.91	0.24	0.13	0.16	0.008	0.007	0.13	0.003
38KhGMA	0.37	0.81	0.64	0.24	0.09	0.15	0.004	0.011	0.24	0.002
40KhGMA-1	0.40	1.09	0.95	0.26	0.06	0.15	0.007	0.010	0.04	0.004
40KhGMA-2	0.42	1.10	1.05	0.22	0.31	0.55	0.007	0.007	0.04	0.004

Calcium treatment of the melt in order to produce M-Steel can be used in the production of any grade of steel. In this case, the most economical use of the tool and the best effect from improved machinability are achieved given the high-strength state of M-Steel. The tool durability when machining carbonized parts made of M-Steel with a surface hardness up to 59 *HRC* can be twice as high compared to conventional steel with the same microstructure and hardness [4, 5, 7, 15].

Since the inclusions of calcium aluminate formed in M-Steel are generally globular in shape and evenly distributed throughout the metal volume, they should not reduce the level of mechanical properties of such steel. Therefore, it becomes possible to produce M-Steels of various alloying systems for use in different industries (e.g., automotive, machine-building, etc.) to fabricate critical parts, including those subject to further thermal and thermochemical treatment.

The authors of this paper studied the possibility of replacing conventional structural steel (40KhGMA) with M-Steel of a similar alloying system with improved machinability in order to reduce the production costs, while providing the required level of mechanical properties. The parts have a hardness of 42–46 *HRC* and are used under complex operating conditions (e.g., abrasive wear, alternating loads).

Materials and Procedures

Studied steels included the following standard heat-treatable medium-carbon grades of the Cr-Mn-Mo alloying system: 40KhGMA, 38KhGMA, 40KhGMA-MOD1 and 40KhGMA-MOD2, as well as M-Steel with improved machinability. The chemical composition of the studied steel grades is shown in Table 1.

In order to compare the stability of supercooled austenite of M-Steel, as well as 40KhGMA and 38KhGMA steels, dilatometric studies were carried out using a LINSEIS L78 R.I.T.A. dilatometer. The heating temperature of the studied steel samples (diameter – 4 mm, length – 10 mm) was 850°C, and exposure time was 15 minutes. To prevent surface oxidation, the samples were heated in vacuum. Cooling of the samples to room temperature at constant rates ranging from 0.1 to 30°C/sec was done in vacuum or in helium. The temperature ranges of the phase and structural transformations were determined based on the dilatogram analysis: the starting and ending points of the transformations were the points, where the temperature dependence of the relative elongation deviated from the linear type [18, 19].

Heat treatment of the samples for mechanical testing was performed in the laboratory batch-type furnaces. The samples were heated for quenching to 850°C for 40 min with subsequent cooling in quenching oil. After quenching, the samples were tempered at 200–600°C for 3 hours.

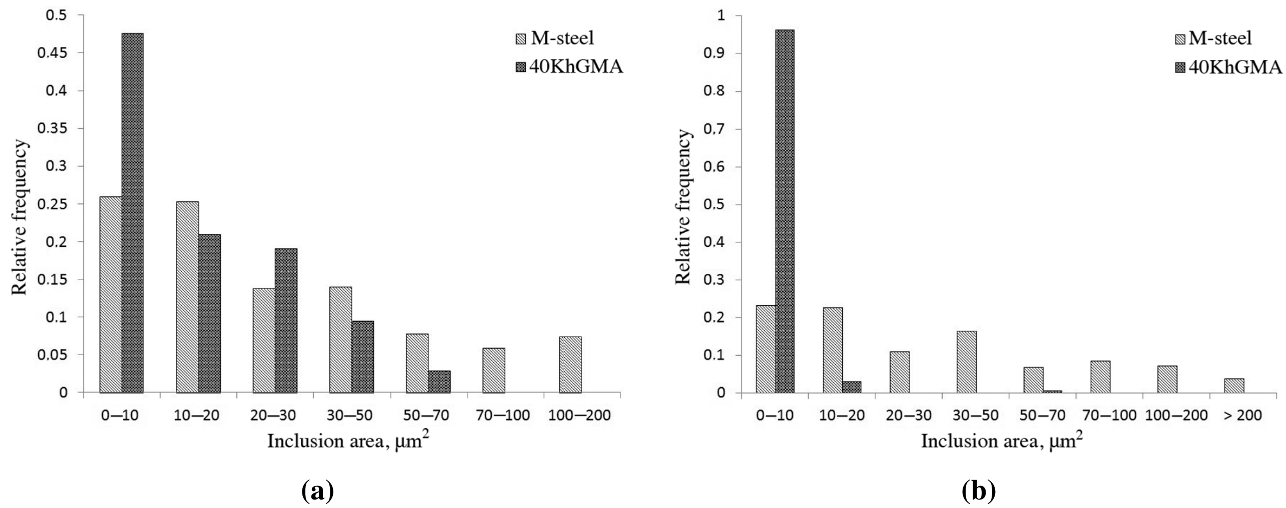


Fig. 3. Size distribution of non-metallic inclusions in M-Steel and standard 40KhGMA steel: (a) sulfide type; (b) globular type.

The mechanical properties (e.g., yield strength, tensile strength, relative elongation, and relative reduction) were determined at room temperature using INSTRON tester according to the procedure described in GOST 1497. Cylindrical samples (type III) with a working part measuring 6 mm in diameter and 30 mm in length were used. The impact bending tests were performed at room temperature using a pendulum impact method according to GOST 9454 with the use of standard samples with a V-shaped concentrator. The fatigue tests were performed in accordance with GOST 25.502 by using type II samples. The hardness measurements were done using a Rockwell instrument (scale C) according to GOST 9013.

The microstructure of the studied steels was analyzed by optical microscopy (MEIJI IM 7200). The polished surface of the samples was etched in a 4% nitric acid solution in ethyl alcohol.

Results and Discussion

A comparative analysis of the distribution of non-metallic sulfide and globular-type inclusions in M-Steel with improved machinability and higher sulfur content and in conventional 40KhGMA steel was performed. It was found that the amount of sulfide inclusions in M-Steel was expectedly higher (up to 13 pcs/mm^2) compared to standard 40KhGMA steel (up to 2 pcs/mm^2) due to the higher sulfur content. According to the results of the quantitative analysis, in addition to relatively small sulfide inclusions with an area measuring up to 70 μm^2 (typical for both M-Steel and standard 40KhGMA steel), there are large sulfide inclusions with an area measuring up to 200 μm^2 (Fig. 3a). However, their relative concentration in M-Steel is rather low and does not exceed 5–10% of the total number of detected inclusions.

The analysis has also shown a difference in the morphology of non-metallic inclusions of the globular type (Fig. 3b). In conventional steel, almost all detected inclusions (99%) of the globular shape (mainly oxides) have an area under 20 μm^2. M-Steel also contains very large globular non-metallic inclusions, the area of which reaches 200 μm^2 or more. The total amount of globular inclusions with the area exceeding 100 μm^2 constitutes 10–11% of all detected inclusions of this type. The majority of the globular-type inclusions (46%) have the area measuring up to 20 μm^2.

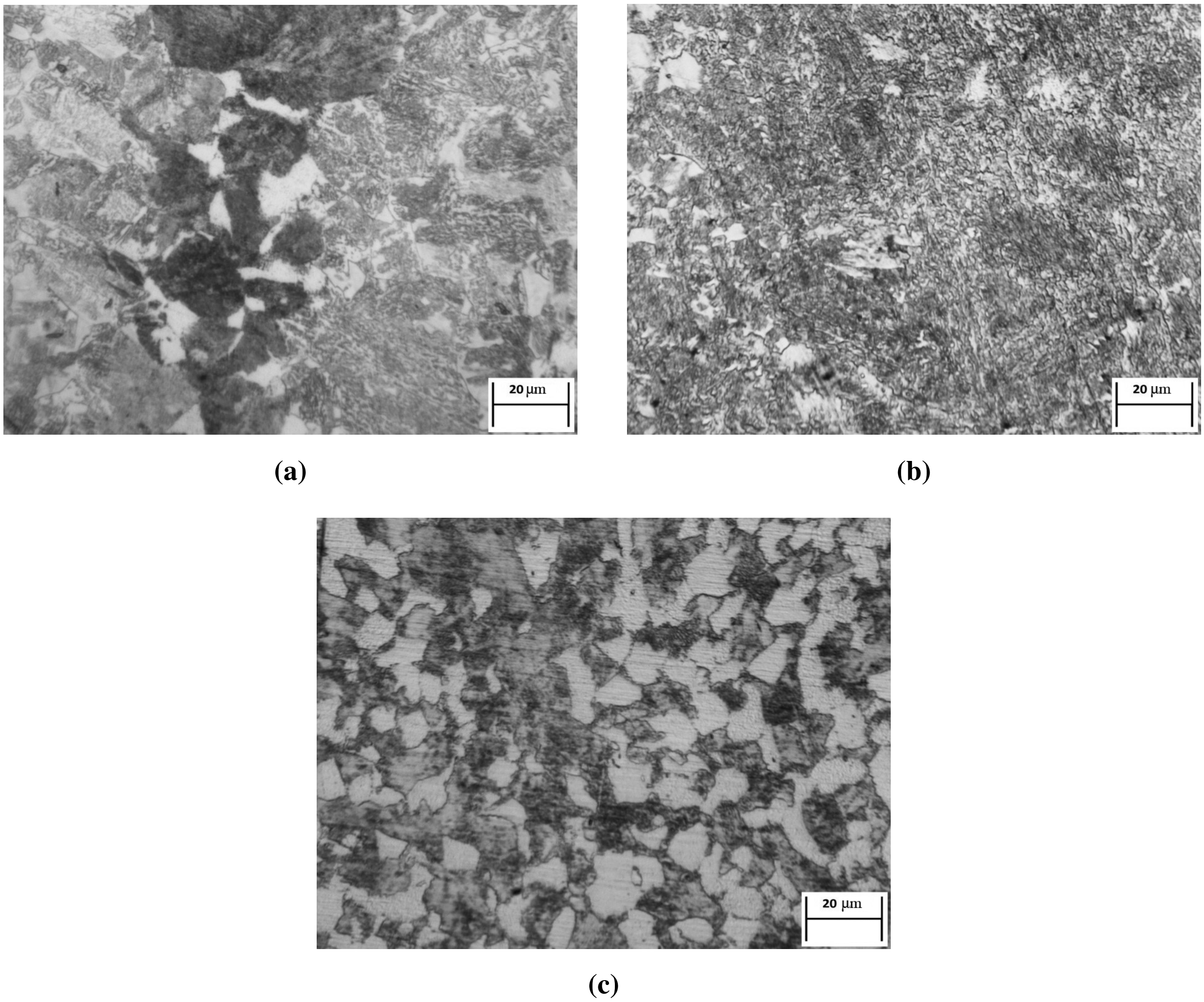


Fig. 4. Microstructure of the studied steel samples after cooling from 850°C at a rate of 0.3°C/sec: (a) M-Steel; (b) 40KhGMA; (c) 38KhGMA.

Thus, M-Steel contains a large number of non-metallic inclusions with a wide range of sizes, which is typical for steels with improved machinability. The increased number of globular-type inclusions in M-Steel compared to standard steel (40KhGMA) is due to the presence of modified calcium aluminate inclusions having a globular shape, same as oxide-type inclusions.

A dilatometric analysis of M-Steel with improved machinability was performed to establish the characteristics of transformation and stability of supercooled austenite compared to standard 40KhGMA and 38KhGMA steels. The critical temperatures of austenite formation during heating of the studied steels were as follows: Ac_1 = 765°C, Ac_3 = 810°C (M-Steel); Ac_1 = 730°C, Ac_3 = 780°C (40KhGMA); Ac_1 = 730°C, Ac_3 = 770°C (38KhGMA). The higher austenite formation temperatures observed in M-Steel during heating are likely caused by the increased content of sulfur and calcium impurities.

When cooling from the austenitizing temperature (850°C) at a rate of 0.1–0.3°C/sec, dilatometric and metallographic signs of the bainite formation are observed in the microstructure of M-Steel and 40KhGMA steel along with the ferrite-pearlite mixture (Fig. 4a, b). In 38KhGMA steel, only diffusion transformation of supercooled austenite takes place at such cooling rates (Fig. 4c).

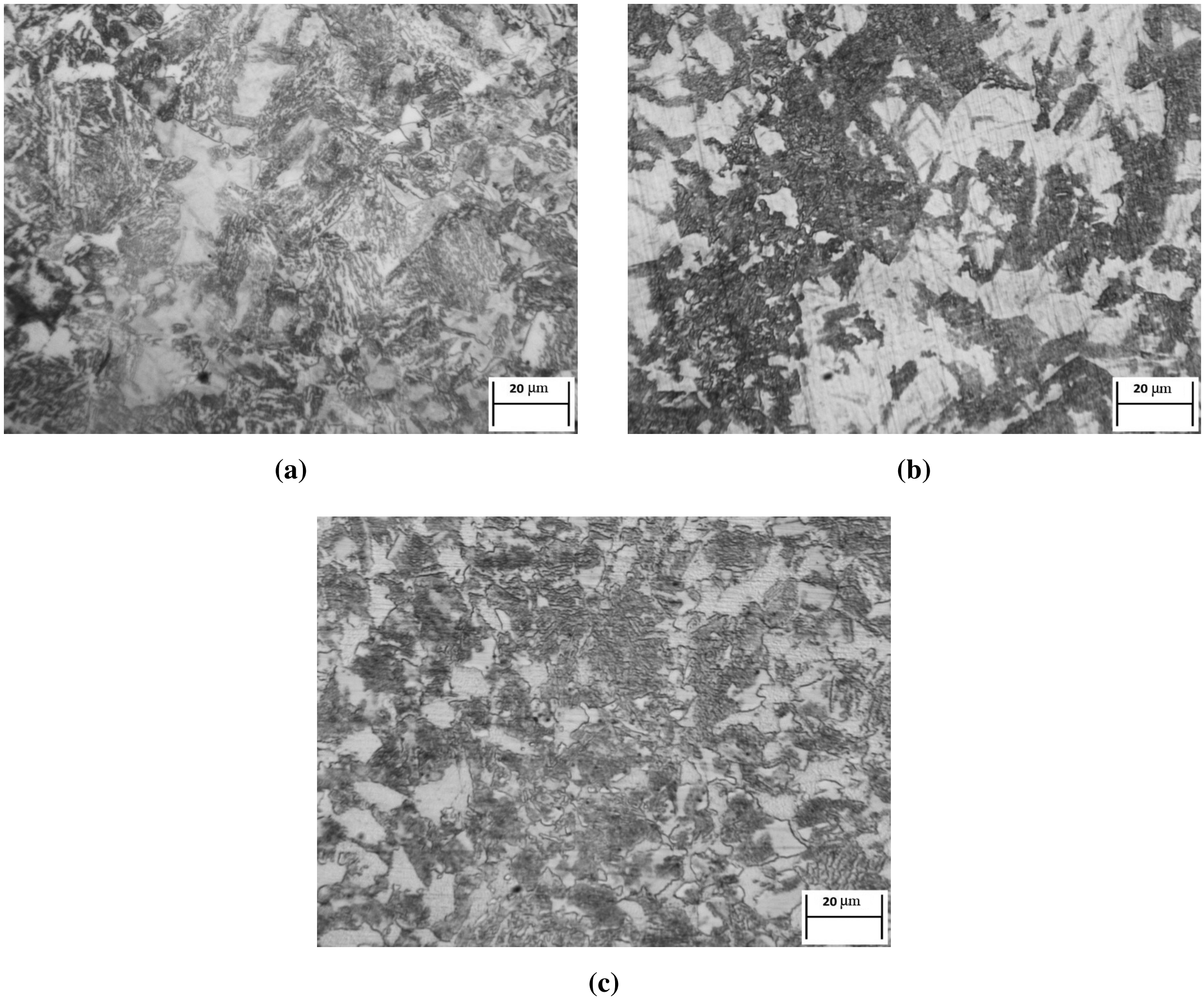


Fig. 5. Microstructure of the studied steel samples after cooling from 850°C at a rate of 1.0°C/sec: (a) M-Steel; (b) 40KhGMA; (c) 38KhGMA.

When the cooling rate is increased to 1°C/sec, low-temperature structural components (e.g., bainite, martensite) are formed in M-Steel along with a certain amount of products of diffusion conversion of supercooled austenite (Fig. 5a). In 40KhGMA steel, the formation of ferrite and perlite at this cooling rate is completely suppressed, and the steel microstructure consists of a mixture of bainite and martensite (Fig. 5b). After cooling at a rate of 1°C/sec, 38KhGMA steel contains a significant amount of ferrite-pearlite mixture (Fig. 5c), and therefore has the lowest hardness (24 *HRC*) compared to M-Steel (35 *HRC*) and 40KhGMA steel (38 *HRC*).

As the cooling rate increases further, the amount of bainite in the structure of the studied steels decreases, while the amount of martensite increases. The latter is accompanied by an increase in hardness. A predominantly martensitic microstructure with the maximum hardness levels of 54–56 *HRC* (M-Steel) and 55–56 *HRC* (40KhGMA steel) is formed at a cooling rate of 10°C/sec and higher (Fig. 6a, b). In this case, a significant amount of bainite is still observed in the structure of 38KhGMA steel (Fig. 6c), which causes a reduction in hardness (48 *HRC*).

Based on the performed dilatometric, metallographic, and durometric studies, the corresponding continuous cooling transformation (CCT) diagrams of supercooled austenite transformations in the studied steels were

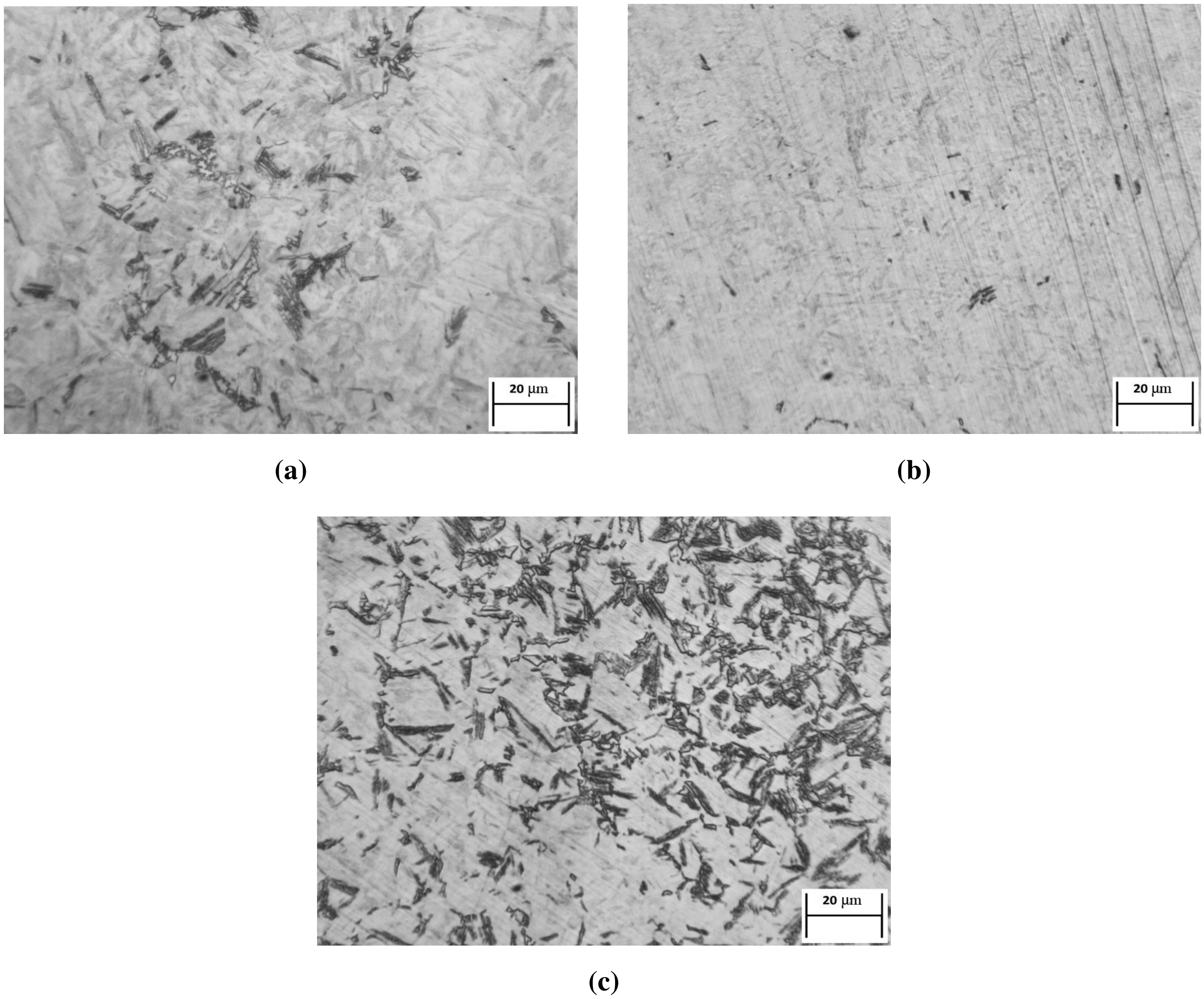
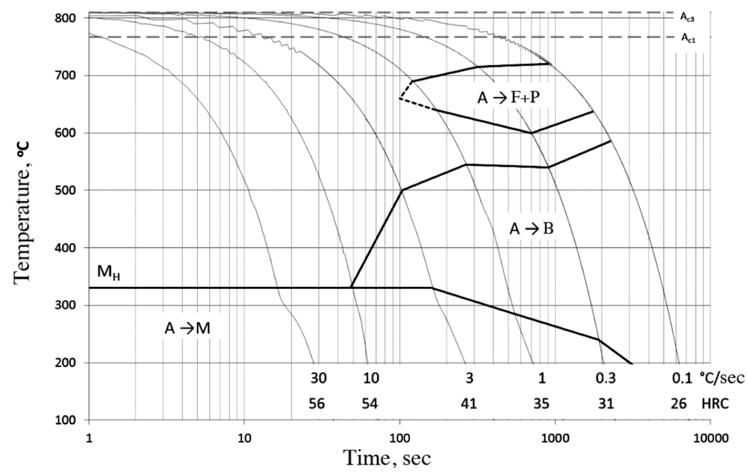


Fig. 6. Microstructure of the studied steel samples after cooling from 850°C at a rate of 10.0°C/sec: (a) M-Steel; (b) 40KhGMA; (c) 38KhGMA.

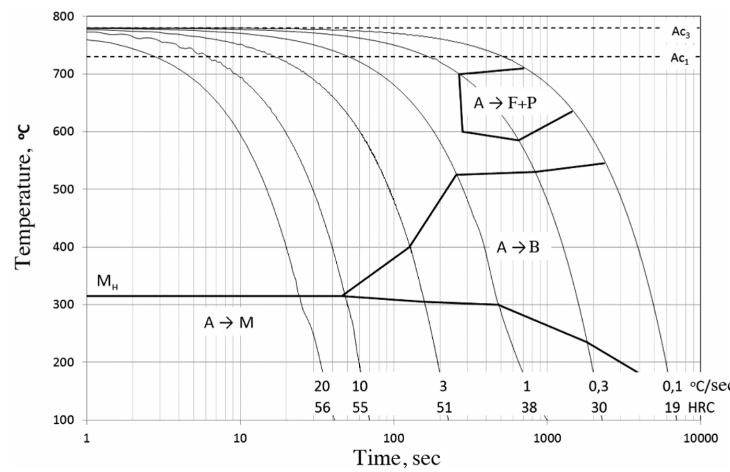
plotted (Fig. 7). As can be seen, the stability of supercooled austenite in M-Steel with improved machinability (Fig. 7a) is comparable to that in the standard steel (40KhGMA) (Fig. 7b), while the hardenability of M-Steel is significantly higher than that of the lower-allowed 38KhGMA steel (Fig. 7c). Thus, in terms of ensuring the required hardenability of the parts during heat treatment, M-Steel is comparable to the standard used steels of similar composition.

It is generally believed that the increased content of impurities and non-metallic inclusions in steel, especially sulfide ones, significantly reduces the set of mechanical properties, such as ductility and viscosity [9–11]. In this regard, a comparative study of mechanical properties of medium-carbon steels of Cr–Mn–Mo alloying system was performed out.

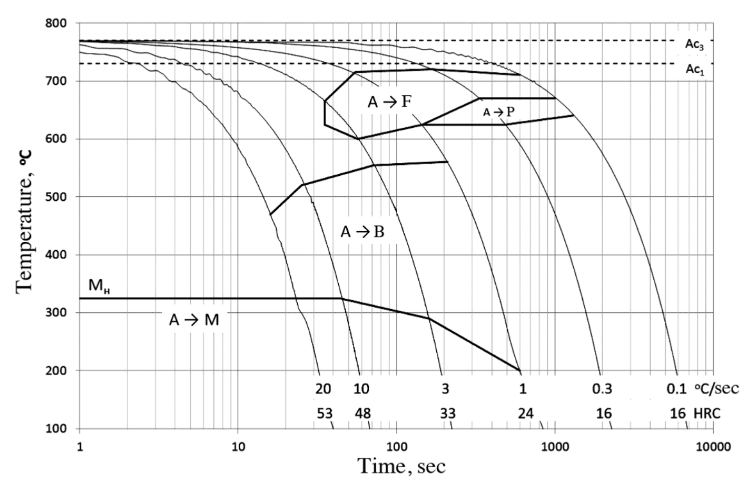
It was established (Fig. 8) that when the tempering temperature increases from 200 to 600°C, M-Steel exhibits a smooth decrease in the strength properties (yield strength – from 1,590 to 930 MPa) and an increase in viscosity and ductility characteristics (relative elongation – from 9 to 16%; relative reduction – from 35 to 57%; impact strength *KC*V – from 0.2 to 0.9 J/cm^2). Similar dependencies of mechanical properties as a function of tempering temperature were obtained for standard 40KhGMA steel.



(a)



(b)



(c)

Fig. 7. CCT diagrams of supercooled austenite transformations in the studied steel samples (austenitizing temperature – 850°C, exposure – 15 min): (a) M-Steel; (b) 40KhGMA; (c) 38KhGMA.

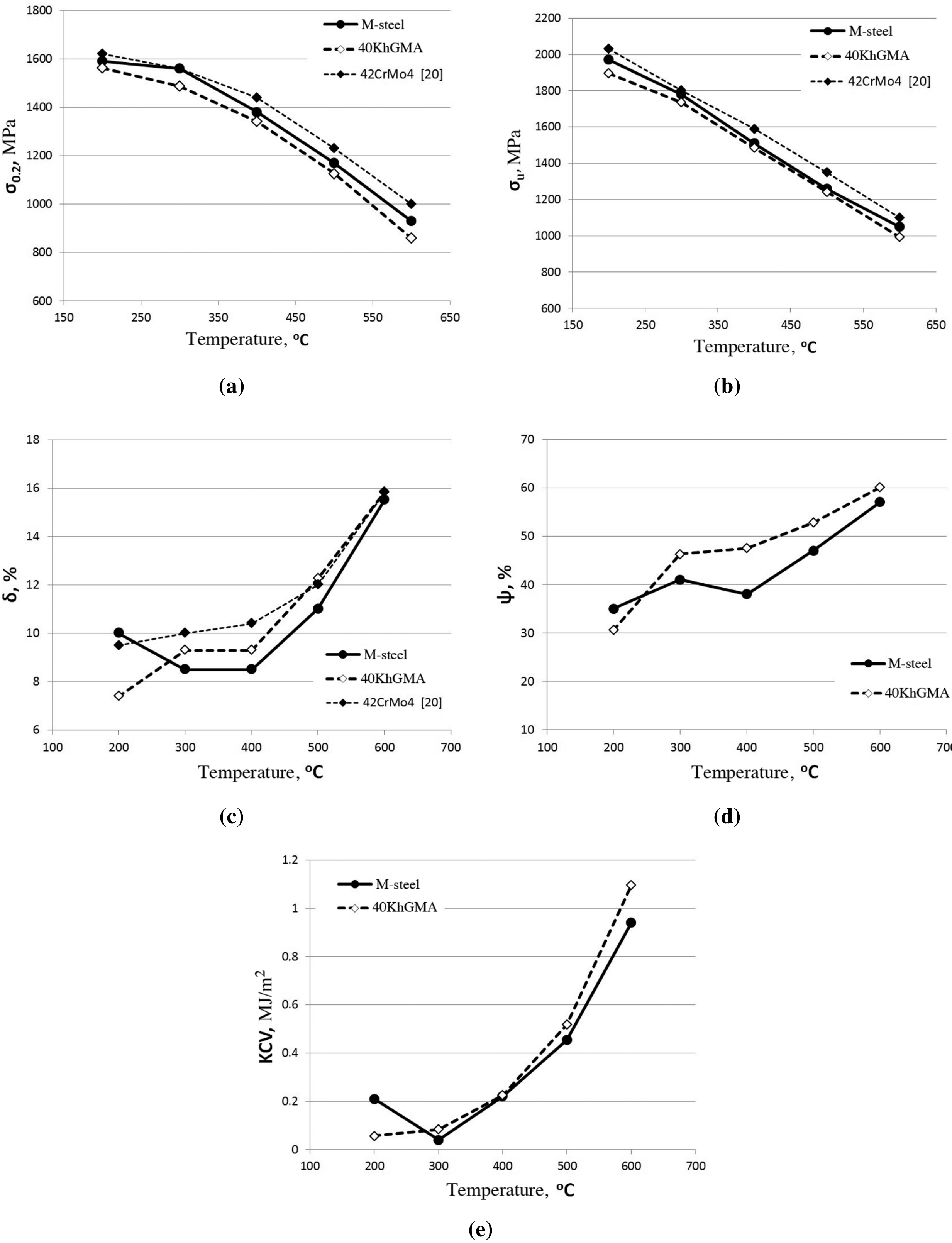


Fig. 8. Mechanical properties vs. tempering temperature for M-Steel compared to standard 40KhGMA steel and reference data for 42CrMo4 steel [20].

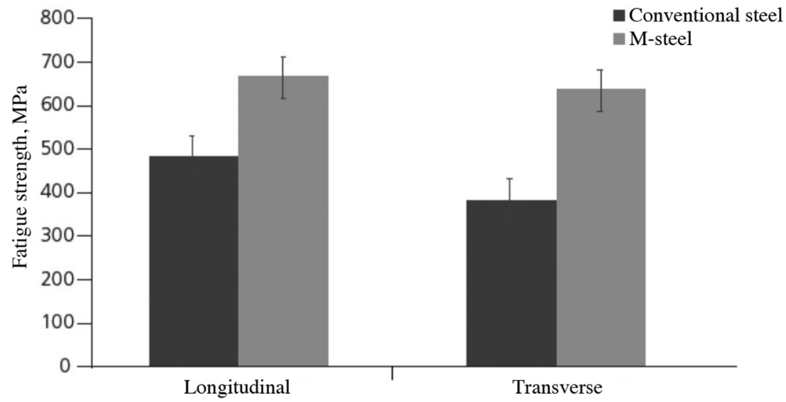


Fig. 9. Comparison of fatigue strength of quenched and tempered conventional and M-Steel.

Table 2
Mechanical Properties of Medium-Carbon Cr–Mn–Mo Steels after Quenching and Tempering to Obtain the Same Level of Hardness (42–46 *HRC*)

Steel	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	ψ, %	*KC*V, MJ/m^2
M-Steel	1260	1370	10.0	43	0.35
40KhGMA	1300	1365	10.5	49	0.43
38KhGMA	1245	1325	9.5	48	0.38
40KhGMA-1	1235	1365	11.0	50	0.38
40KhGMA-2	1260	1360	8.0	31	0.31

Table 2 shows the results of mechanical tests of M-Steel with improved machinability after quenching in oil and tempering to obtain a hardness of 42–46 HRC compared to a number of similar steels with the same level of strength after heat treatment. As can be seen, M-Steel can provide the same level of impact toughness (0.30–0.50 MJ/m^2) and ductility (relative elongation 8–11%) after heat treatment as standard steels.

The obtained data indicate that despite the high content of impurities and non-metallic sulfide-type inclusions, the strength and viscous-ductile properties of M-Steel are only slightly lower (by 10–15%) than the corresponding characteristics of the standard steels with reduced sulfur content, and are generally consistent with the reference data for mechanical properties of 40KhGMA steel [20] (Fig. 8).

Along with providing a sufficiently high set of mechanical properties during static tension, one of the advantages of M-Steel is the improved fatigue strength compared to standard steels, especially in the transverse direction (Fig. 9). This is especially important for parts operating under cyclic load conditions. The main factor responsible for the improved fatigue characteristics of M-Steel, is the spheroidal form of inclusions uniformly distributed within the metal volume. Conventional steels contain predominantly long and thin inclusions of manganese sulfide, acting as stress concentrators, which results in a satisfactory level of fatigue strength in the longitudinal direction (i.e., parallel to the length of inclusions), and a reduced level in the transverse direction. M-Steel, which contains a sufficient amount of uniformly distributed spheroidal inclusions in addition to string-type inclusions, has good fatigue strength both in the longitudinal and transverse directions.

Thus, alloyed M-Steel with improved machinability can be successfully used instead of the standard steels in the production of machine parts, including the critical ones, since it is capable of providing similar hardenability and a close set of mechanical properties. In addition, due to the presence of special modified non-metallic inclusions containing calcium and sulfur, high resistance of the metal-working tools will be provided, even in case of machining high-strength parts. This makes it possible to use M-Steel for the production of critical high-strength steel parts using automated flow lines. For example, the studied M-Steel was compared to three different smelts of standard steel (40KhGMA) used to manufacture high-strength shafts subject to quenching and tempering (final hardness – 42–46 *HRC*). When machining shafts made of M-Steel, there were much fewer problems with straightness, vibration, and fragmentation of steel shavings. Therefore, the service life of the tool was increased by five times, while the cost savings with respect to shaft production reached 24%.

CONCLUSIONS

1. A quantitative analysis of non-metallic inclusions in M-Steel with improved machinability and conventional 40KhGMA steel with low-sulfur content was performed. The amount of inclusions in M-Steel is significantly larger (by about 6 times) compared to clean steel with low sulfur and calcium contents. The size range of the detected inclusions in M-Steel is also larger: the maximum area of string-type sulfide inclusions and globular inclusions of calcium oxide and calcium aluminate is 200 μm^2 in M-Steel and 70 μm^2 in 40KhGMA steel.

2. The stability of supercooled austenite in M-Steel with improved machinability is consistent with that of conventional 40KhGMA steel, and is much higher compared to 38KhGMA steel with lower content of the main alloying elements. The microstructure formed in M-Steel after continuous cooling at different cooling rates (0.1–30°C/sec) is similar to that of 40KhGMA steel with low-sulfur content.

3. The mechanical properties of M-Steel with improved machinability are comparable to those of 40KhGMA and similar steel grades after quenching in oil and tempering in the temperature range of 200–600°C. The ductility and impact strength of M-Steel, containing significantly more non-metallic inclusions, is only slightly lower (by 10–20%) compared to low-impurity steel.

4. Considering a good level of basic mechanical properties of M-Steel (e.g., static and fatigue strength, ductility, impact strength), such steel can be used for commercial production of critical steel parts such as high-strength shafts, body components operating under complex conditions, etc.

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