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ORIGINAL ARTICLE

Microstructure and Mechanical Properties of Calcium Treated 42CRMO4 Steel with Improved Machinability

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Abstract The steel 42CrMo4 with improved machinability was studied. The steel containing high amount of sulfur was calcium treated during metallurgical production stage. The size and area distribution of non-metallic inclusions present in the studied steel was analyzed and compared to the conventional Cr–Mn–Mo steels with low sulfur and calcium content. The dilatometric investigation was performed to reveal the features of the austenite transformations in studied Cr–Mn–Mo steels with various content of alloying elements. The mechanical properties of the high and low sulfur steels were analyzed in heat treated condition (oil quenching and tempering). The results proved that calcium treated 42CrMo4 steel with high sulfur content possessed almost the same characteristics of hardenability and mechanical behavior as the conventional low-sulfur steels. This implies that the steel with improved machinability can be successfully applied for the production of the heavy duty and high strength parts using automated lines and machines.

Keywords Calcium treated steel · Machinability steel · Non-metallic inclusions · CCT diagram · Mechanical properties

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1 Introduction

Steels with improved machinability are widely used in mechanical engineering for the mass production of parts using automated lines and lathes [1, 2]. The main feature of such steels is to increase the productivity of the metal-working machines through reduced wear of the cutting tools and improved chip control. There are the following main grades of steel with high machinability [1–4]: (1) sulfur containing steels; (2) sulfur and selenium containing steels; (3) lead steels; (4) bismuth steels; (5) calcium treated steels; (6) calcium and lead containing steels.

The development of the steels with improved machinability is based mainly on the following phenomena responsible for reducing the tool wear [5, 6]:

1. Increased chip brittleness, thereby facilitating the chip control.
2. Build-up of thin deposits from the steel inclusions onto the cutting tool. These thin deposits either reduce the heat generation or the heat transfer into the cutting tool or protect the cutting tool from chemical wear by the passing work piece material.

The increased brittleness of the chip is ensured by the presence of manganese sulfide inclusions in the steel. Therefore, almost all the free-cutting steels contain a sufficiently high amount of sulfur—up to 0.2 wt. %. In addition, dispersed manganese sulfide inclusions also provide a lubrication of the cutting edge of the tool, preventing its overheating and increasing the overall tool life. Lead provides the same effect, while it is found in steel as separate isolated precipitates. Calcium treatment, in addition to the aforementioned benefits, prevents the adhesion of the steel to the cutting edge, and, at certain cutting speeds, deposits on the cutting tool, protecting it from wear [7, 8].

Unfortunately, an increase in the sulfur content and the number of non-metallic inclusions, especially of the stringer type, inevitably leads to a decrease in the level of mechanical properties of steels [9–11]. Therefore, free-cutting steels in most cases are carbon or manganese low-alloy steels used for the manufacture of low-duty parts, which are either not heat treated at all or only normalized or annealed.

In the 1970–90 s, OVAKO (Imatra, Finland) developed a new class of steel with improved machinability: M Steel («M»—«Machinability») [12]. The concept of the M steel is the formation of dispersed non-metallic inclusions of a special composition. Due to the controlled sulfur content and the addition of calcium of 30–50 ppm, complex globular inclusions are formed in the steel. Typically, they are made up of a core of calcium aluminate $CaO \times Al_2O_3$ and a shell cover of calcium and manganese sulfide (Ca, Mn)S (Fig. 1) [12–17]. Such inclusions have a lubricating effect on the tool during cutting and reduce wear of the cutting edge.

A protective layer originating from the calcium inclusions in M steel is usually deposited on the cutting edge of a tool during machining (Fig. 2). This layer reduces the adhesion of steel on a cutting tool. It also prevents the tool from overheating during the turning operation: the significant amount of heat is removed with the chip or is left on the part's surface. Moreover, the high temperature of the chip leads to better chip breaking. This has an important effect on the life of the cutting tool and the productivity of machining operations [7].

M steel treatment can be applied during the production of steel of any grade. The main assumption of this class of steel is the harder the machined steel, the more benefit M steel offers. The tool life during the turning operation of the carburized parts of M steel grade with the surface hardness up to 59 HRC can be twice as long as for the conventional steel with the same microstructure and hardness [4, 5, 7, 15]

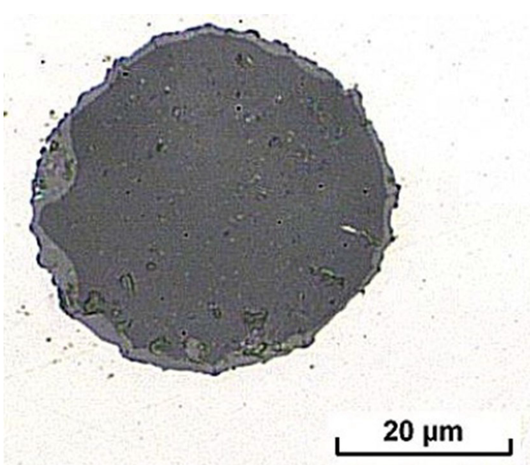

Fig. 1 Complex globular calcium aluminate inclusion $CaO \times Al_2O_3$ covered with a shell of calcium and manganese sulfide [16]

Owing to the globular shape of the calcium aluminate inclusions and their uniform distribution over the volume of the metal, these inclusions should not reduce the level of mechanical properties of steel. Therefore, it becomes possible to produce alloyed M-steels intended to be used in various industries—automotive, mechanical engineering, etc.—for the production of heavy duty and critical parts subjected to the heat treatment and thermochemical treatment.

The aim of this work is to investigate the possibility of replacing the conventional low-sulfur 42CrMo4-type steel with the calcium modified M steel providing the manufacturing costs reduction and assuring the specification and load demands of the final product. The component targeted is high strength shaft for mining application. The product is used in the quench and tempered condition of 42–46 HRC (420–470 HV). The steel properties are assessed with this particular application in mind.

2 Experimental

The investigated material is the low-sulfur heat-treatable Cr-Mn-Mo medium-carbon steels (42CrMo4, 38CrMnMo, 42CrMo4-MOD1 and 42CrMo4-MOD2) and 42CrMo4-M steel with improved machinability. The chemical composition of the studied steels is given in Table 1.

A comparative study of the hardenability of steels 42CrMo4-M, 42CrMo4 and 38CrMnMo was carried out using a LINSEIS L78 R.I.T.A. dilatometer. The samples of the studied steels (diameter 4 mm, length 10 mm) were heated to the austenitization temperature of 850 °C and held for 15 min. The samples were heated in a vacuum to exclude surface oxidation. The cooling of the samples from the austenitization temperature to the room temperature was carried out at constant rates 0.1–30 °C/s using vacuum or helium atmosphere. The temperature ranges of phase transformations were determined from the analysis of the dilatometer data: the points at which the temperature dependence of the sample elongation deviated from the linear form were taken as the onset or suspension of the austenite transformations [18, 19].

Heat treatment of steel samples for mechanical tests was carried out using laboratory chamber furnaces. The samples were quenched in oil (850 °C, 40 min) and tempered at 200–600 °C for 3 h. Uniaxial tensile tests were performed at the room temperature according to ASTM E8 standard using «Instron» machine. Charpy impact strength tests were carried out according to ASTM E23 standard.

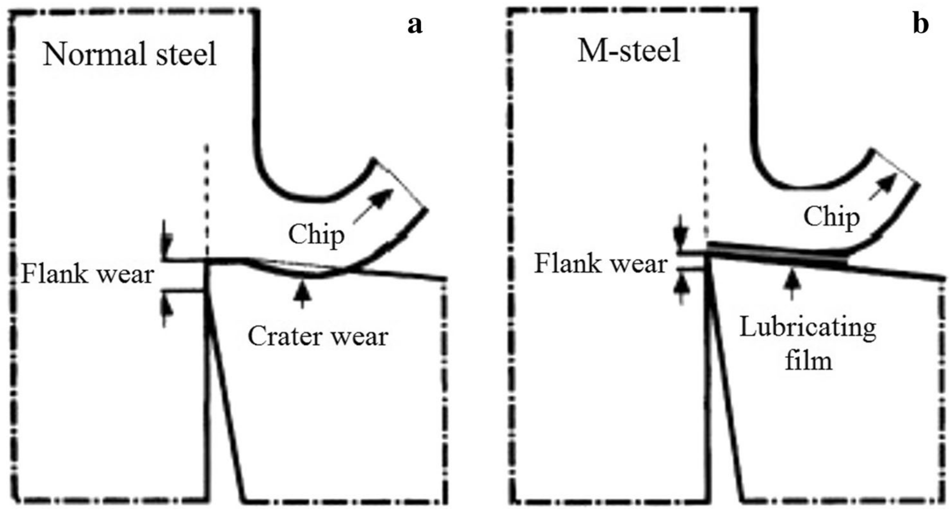

Fig. 2 Illustration of the difference between the chip formation during hard turning of normal steel (**a**) and M steel (**b**) [7]

Table 1 The chemical composition of the studied steels, as assessed by spark spectrometry [wt. %]

Steel	C	Cr	Mn	Si	Ni	Mo	S	P	Cu	Ca*
42CrMo4-M	0.44	1.02	0.82	0.25	0.24	0.15	0.046	0.016	0.22	45
42CrMo4	0.43	0.97	0.91	0.24	0.13	0.16	0.008	0.007	0.13	3
38CrMnMo	0.37	0.81	0.64	0.24	0.09	0.15	0.004	0.011	0.24	2
42CrMo4-MOD1	0.40	1.09	0.95	0.26	0.06	0.15	0.007	0.010	0.04	4
42CrMo4-MOD2	0.42	1.10	1.05	0.22	0.31	0.55	0.007	0.007	0.04	4

*Ca in [ppm]

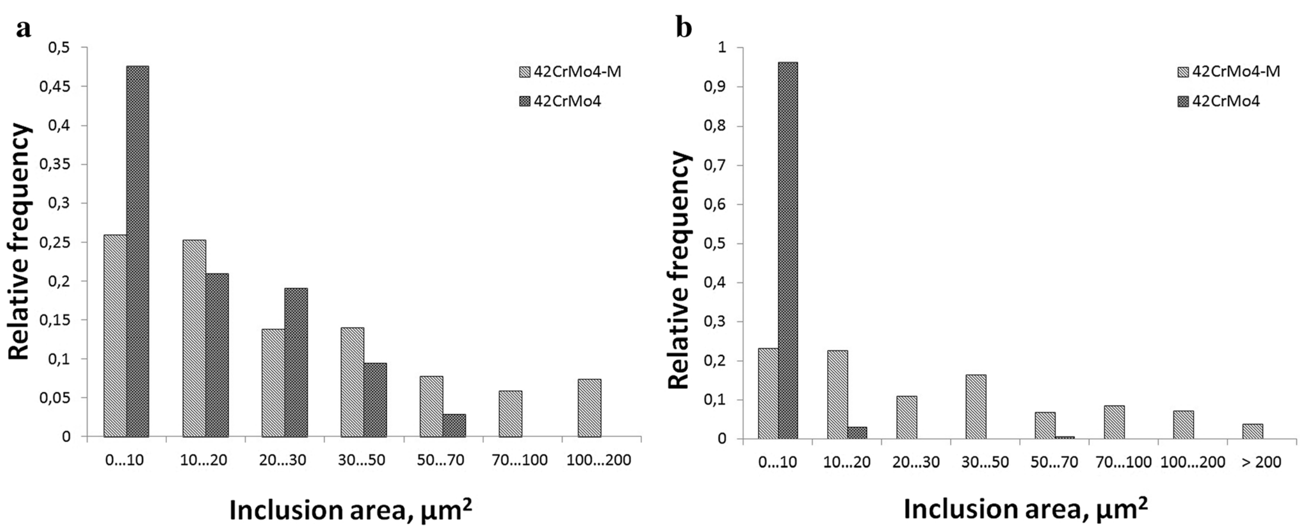

Fig. 3 Distribution of non-metallic inclusions in 42CrMo4-M steel and low-sulfur 42CrMo4 steel by an area: **a** stringer sulfide type; **b** globular oxide type

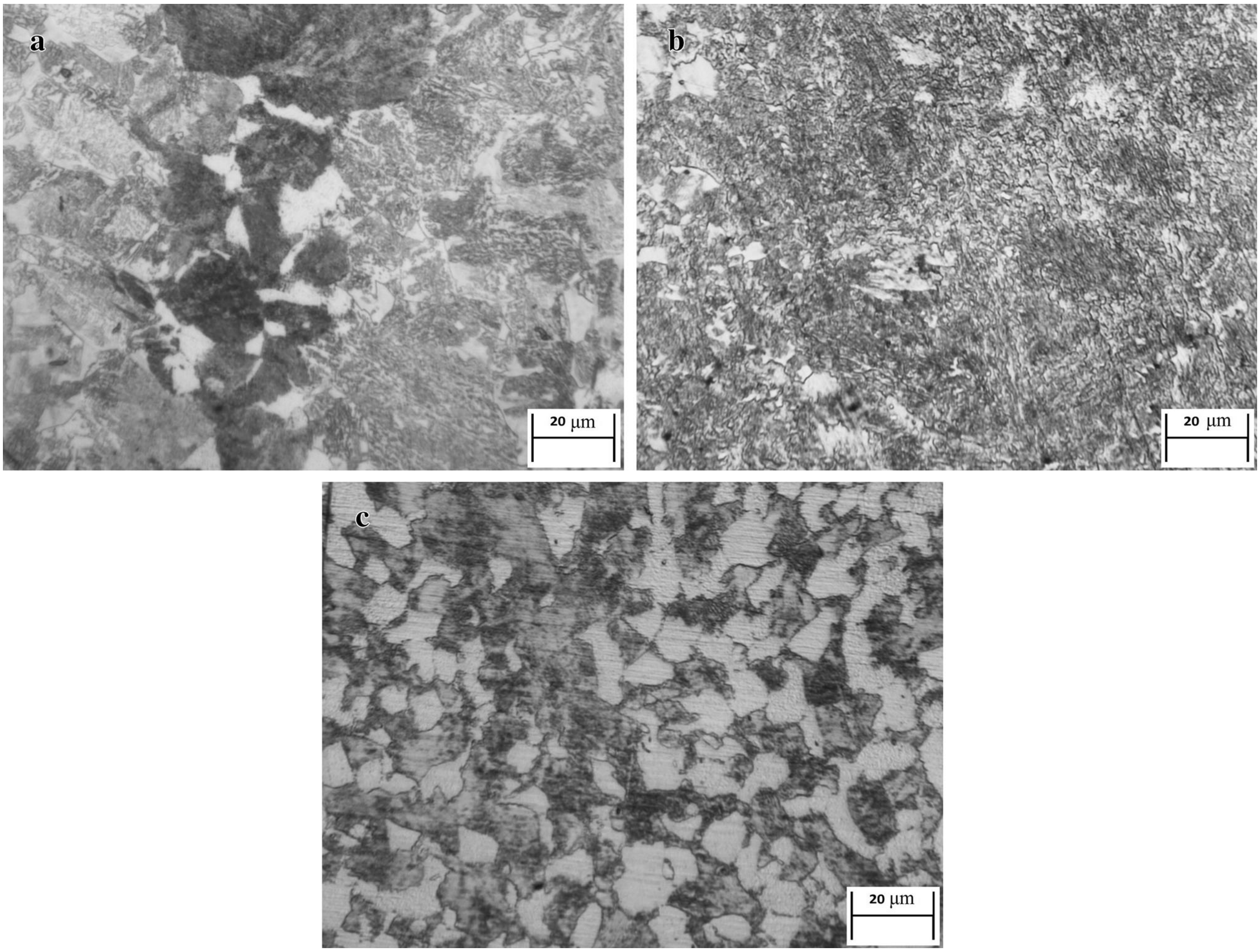

Fig. 4 Microstructure of the studied steels after cooling from 850 °C at a rate 0.3 °C/s: **a** 42CrMo4-M; **b** 42CrMo4; **c** 38CrMnMo

The hardness of the samples after dilatometer tests and laboratory heat treatment was measured using a Rockwell hardness tester according to ASTM E18 standard.

The microstructure of the studied steels was studied by optical microscopy (MEIJI IM 7200). The polished surface of the samples was etched using a 4% Nital solution.

3 Results and Discussion

A comparative study of the distribution of stringer sulfide and globular non-metallic inclusions has been carried out for the steel 42CrMo4-M with improved machinability and low-sulfur 42CrMo4 steel. The amount of stringer sulfide inclusions in 42CrMo4-M steel is higher (up to 13 pcs/mm^2) than in low-sulfur 42CrMo4 steel (up to 2 pcs/mm^2), which is due to the higher sulfur content in 42CrMo4-M steel. A quantitative analysis has shown that in 42CrMo4-M steel, along with rather small sulfide inclusions (area up to 70 μm^2) which are also found in low-sulfur 42CrMo4 steel, there are some large stringer sulfide inclusions with an area up to 200 μm^2 (Fig. 3a). However, their relative content in 42CrMo4-M steel does not exceed 5–10% of the total number of detected stringer inclusions.

The analysis also shows a difference in the morphology of non-metallic inclusions of the globular-type (Fig. 3b). In the low-sulfur 42CrMo4 steel, almost all (99%) of the detected globular inclusions (mainly oxides) have an area less than 20 μm^2. In 42CrMo4-M steel, the very large globular non-metallic inclusions are also detected with the area of 200 μm^2 and more. The total number of globular inclusions with an area of more than 100 μm^2 in 42CrMo4-M steel amounted to 10% of all the detected inclusions of this type. The most frequently detected globular inclusions in 42CrMo4-M steel (46%) are inclusions with an area of up to 20 μm^2.

Thus, 42CrMo4-M steel contains a large number of non-metallic inclusions of various size, which is typical for the steels with improved machinability. The increase in the number of globular inclusions in 42CrMo4-M steel,

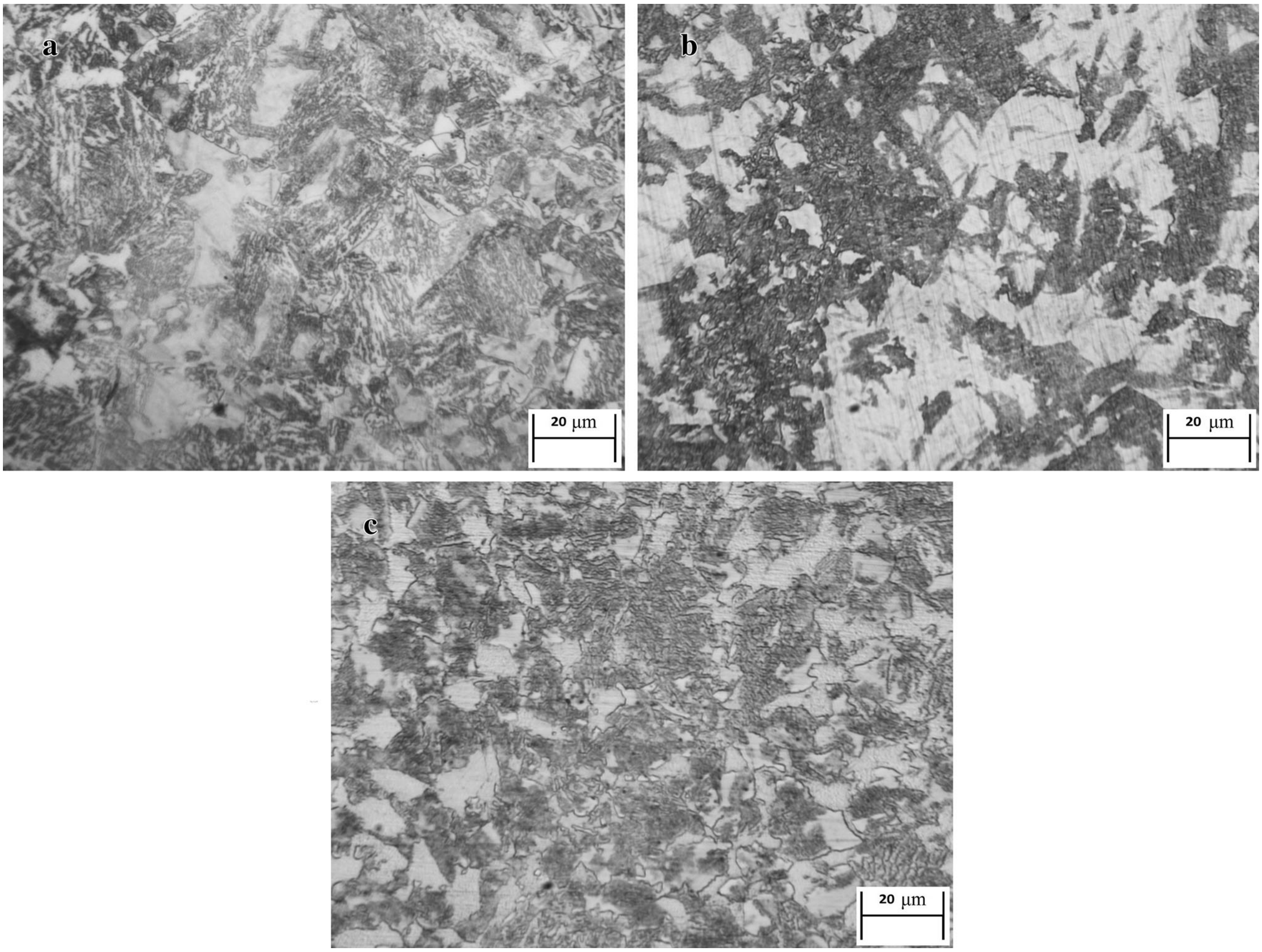

Fig. 5 Microstructure of the studied steels after cooling from 850 °C at a rate 1 °C/s: **a** 42CrMo4-M; **b** 42CrMo4; **c** 38CrMnMo

compared to the low-sulfur 42CrMo4 steel, is probably due to the presence of modified calcium aluminate inclusions, which, like the oxide inclusions in 42CrMo4 steel, have a globular shape.

A dilatometer study of 42CrMo4-M steel with improved machinability was carried out to compare the hardenability and the features of the austenite transformations with the low-sulfur steels 42CrMo4 and 38CrMnMo (Russian GOST 4543). The critical temperatures of austenite formation during heating of the investigated steels are as follows: 42CrMo4-M—A_{c1} = 765 °C, A_{c3} = 810 °C; 42CrMo4—A_{c1} = 730 °C, A_{c3} = 780 °C; 38CrMnMo—A_{c1} = 730 °C, A_{c3} = 770 °C. The higher values of the critical temperatures A_{c1} and A_{c3} of the 42CrMo4-M steel are likely due to the increased content of sulfur and calcium impurities.

The cooling of the 42CrMo4-M and 42CrMo4 steels from the temperature 850 °C at a rate 0.1–0.3 °C/s lead to the formation of some bainite in the microstructure, along with the ferrite-pearlite mixture, which has been registered both by a dilatometer and metallographic investigation (Fig. 4a, b). In 38CrMnMo steel, only the products of the diffusion austenite transformation (ferrite and pearlite) are formed at these cooling rates (Fig. 4c).

An increase in the cooling rate up to 1 °C/s provides the formation of martensite in 42CrMo4-M steel along with other microstructure constituents—ferrite, pearlite and bainite (Fig. 5a). After continuous cooling at 1 °C/s, the low-sulfur 42CrMo4 steel possesses the microstructure consisting of bainite and martensite mixture only (Fig. 5b), so that the formation of ferrite and pearlite get completely suppressed. The microstructure of the 38CrMnMo steel, after cooling at the same rate, contains a significant amount of ferrite and pearlite mixture (Fig. 5c) and, consequently, this steel has the lowest hardness (24 HRC) in comparison with steels 42CrMo4-M (35 HRC) and 42CrMo4 (38 HRC).

Further increase in the cooling rate provides a decrease in the amount of bainite and an increase in the amount of martensite in the microstructure of the studied steels, which

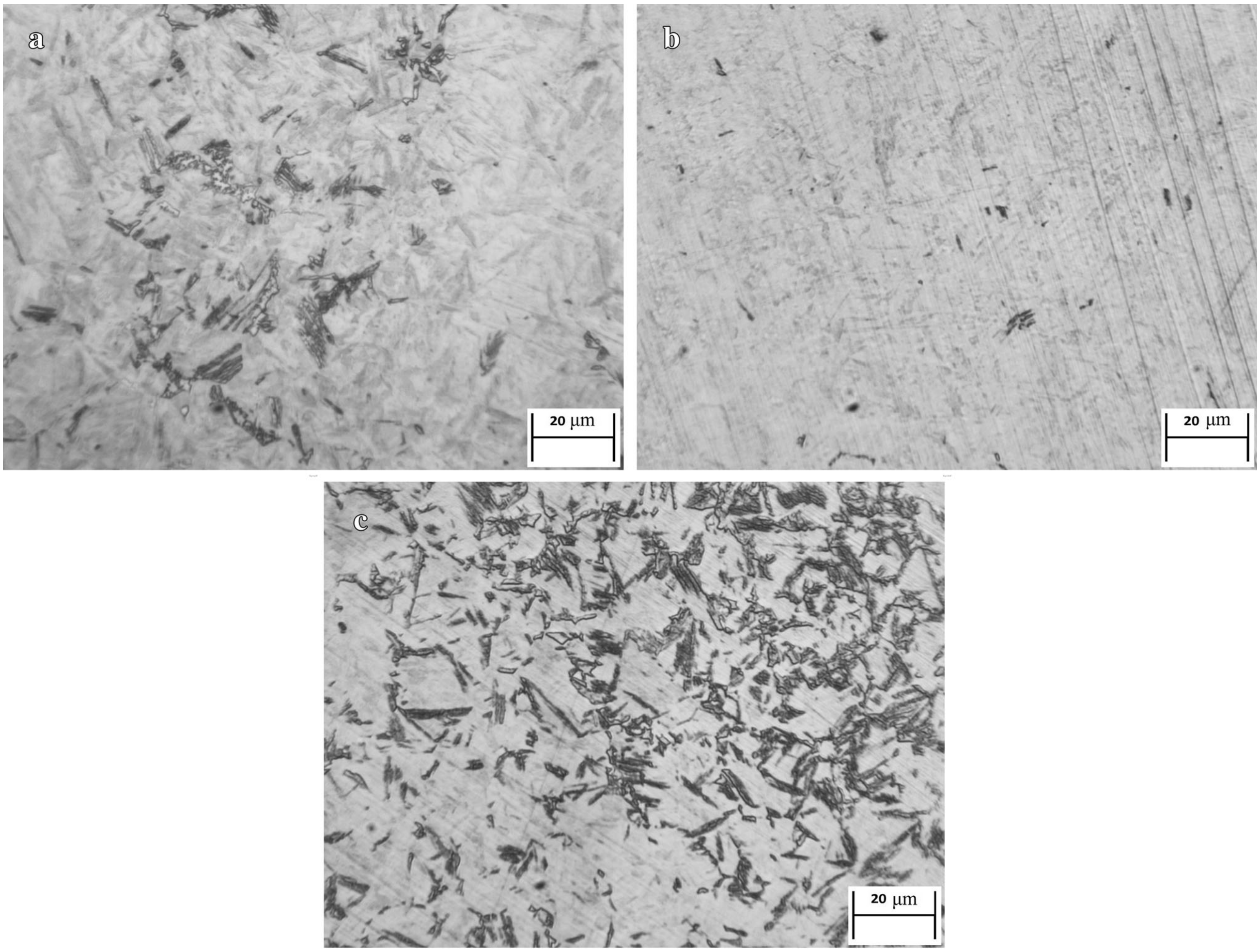

Fig. 6 Microstructure of the studied steels after cooling from 850 °C at a rate 10 °C/s: **a** 42CrMo4-M; **b** 42CrMo4; **c** 38CrMnMo

is accompanied by an increase in steel hardness. Predominantly martensitic microstructure and the maximum level of hardness for the steels 42CrMo4-M and 42CrMo4 (55–56 HRC) are achieved after continuous cooling at a rate of 10 °C/s and more (Fig. 6a, b). At the same time, a significant amount of bainite is still observed in the microstructure of 38CrMnMo steel (Fig. 6c), which is the reason of its lower hardness level (48 HRC).

Based on the results of the dilatometer, metallographic studies and the hardness measurements, the CCT diagrams of the studied steels 42CrMo4-M, 42CrMo4 and 38CrMnMo have been plotted (Fig. 7). The 42CrMo4-M steel with improved machinability possesses almost the same hardenability as the low-sulfur 42CrMo4 steel, which is significantly higher than less alloyed 38CrMnMo steel. Thus, in terms of ensuring the required hardenability of steel parts during the heat treatment, the 42CrMo4-M steel is comparable to the clean, low-sulfur steels of similar alloying composition.

It is generally believed [9–11] that an increased content of impurities and non-metallic inclusions in steel, especially stringer sulfides, significantly reduces the complex of mechanical properties—in particular, ductility and toughness. A comparative study of mechanical properties of the low-sulfur medium-carbon Cr–Mn–Mo steels and 42CrMo4-M steel with improved machinability was carried out to prove that the uniform distribution of the globular non-metallic inclusions did not deteriorate the steel properties.

It has been established (Fig. 8) that an increase in the tempering temperature from 200 to 600 °C lead to a decrease in strength properties of 42CrMo4-M steel (yield strength—from 1590 to 930 MPa) and to an increase in viscosity and plasticity characteristics (elongation—from 9 to 16%; reduction of area—from 35 to 57%; Charpy impact strength—from 0.2 to 0.9 J/mm^2). Similar dependence of mechanical properties on tempering temperature was obtained for the 42CrMo4 steel with low sulfur content.

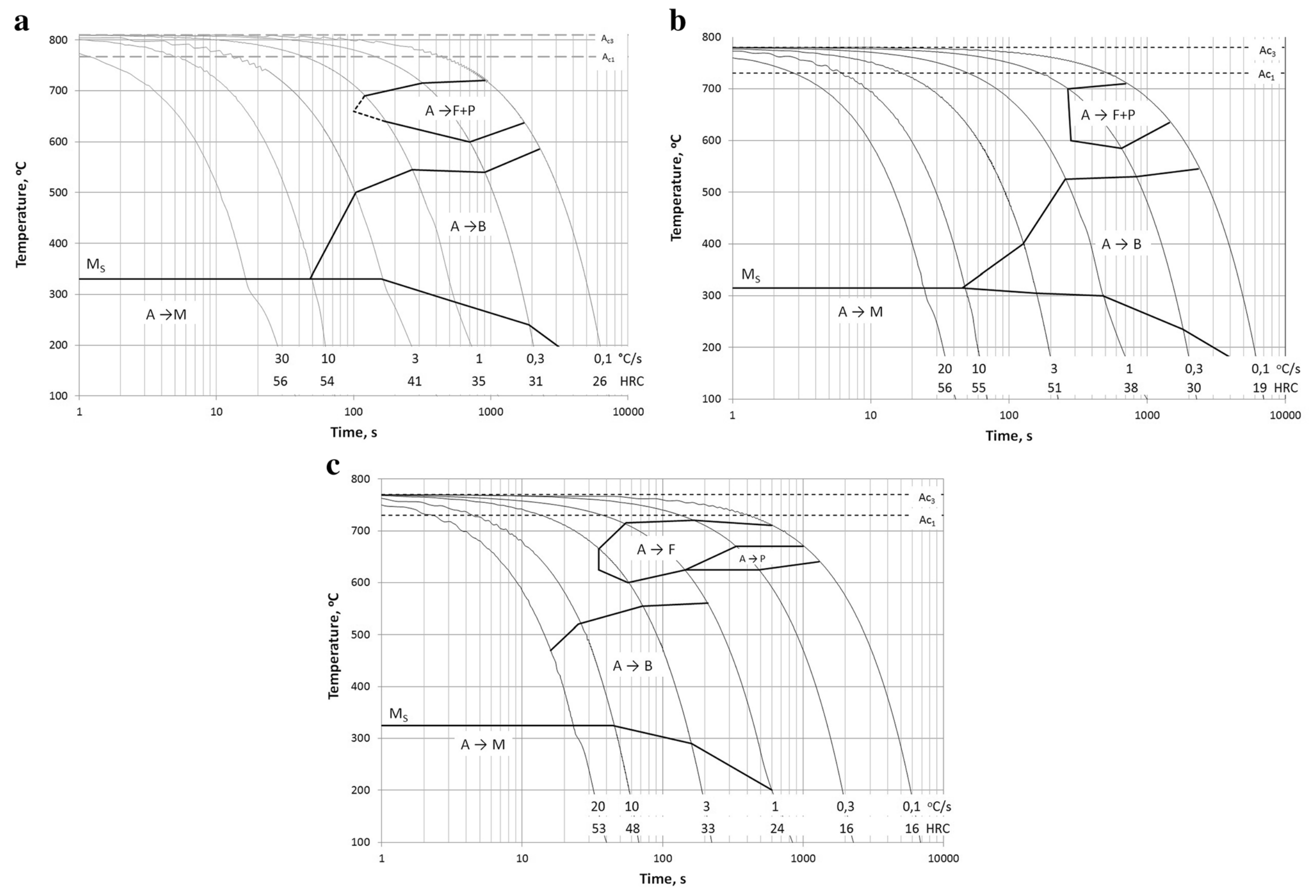

Fig. 7 Continuous cooling transformation (CCT) diagrams of the steels under study (austenitization 850 °C, 15 min): **a** 42CrMo4-M; **b** 42CrMo4; **c** 38CrMnMo

Table 2 shows the results of mechanical tests of 42CrMo4-M steel with improved machinability after quenching in oil and tempering (hardness 42–46 HRC), in comparison with a number of similar low-sulfur steels with the same level of strength after the heat treatment. It is evident that the 42CrMo4-M steel can provide the same level of impact strength (0.30–0.50 J/mm^2) and plasticity (elongation 8–11%) after the heat treatment as the clean steels.

The obtained data indicate that the plasticity and impact strength of the 42CrMo4-M steel containing the significantly higher number of the non-metallic inclusions is only slightly lower (by 10–20%) compared to the low-sulfur steel with low content of impurities. The properties of the 42CrMo4-M steel in general correspond to the reference data on the mechanical properties of the clean 42CrMo4 steel [20].

In addition to the tensile properties comparable to conventional low-sulfur steels and high machinability, a key advantage of the M steel is its improved fatigue strength, particularly in the transverse direction (Fig. 9). This is useful for the components that are exposed to cyclic stresses. The main factor of the improved fatigue performance of the M steel is the spheroidal shape of the inclusions evenly distributed in the volume of the metal. A conventional steel features long and thin MnS inclusions that act as stress concentrators. That gives a satisfactory fatigue properties in the longitudinal direction (i.e., parallel to the length of the inclusions), but poor fatigue performance in the transverse direction. In contrast, M steel offers good fatigue strength in both the longitudinal and transverse directions.

Thus, from the mechanical strength data and toughness requirement of the product delivered from the steel mill, the calcium modified alloyed 42CrMo4-M steel with improved machinability can be successfully used instead of the low-sulfur medium-carbon Cr–Mn–Mo steels for the production of engineering parts, including heavy duty and critical ones, since it is capable of providing a similar hardenability and the level of mechanical properties. At the same time, the high durability of metalworking tools is provided even in the case of processing parts in a high strength state, due to the presence of special modified non-metallic inclusions containing calcium aluminate and

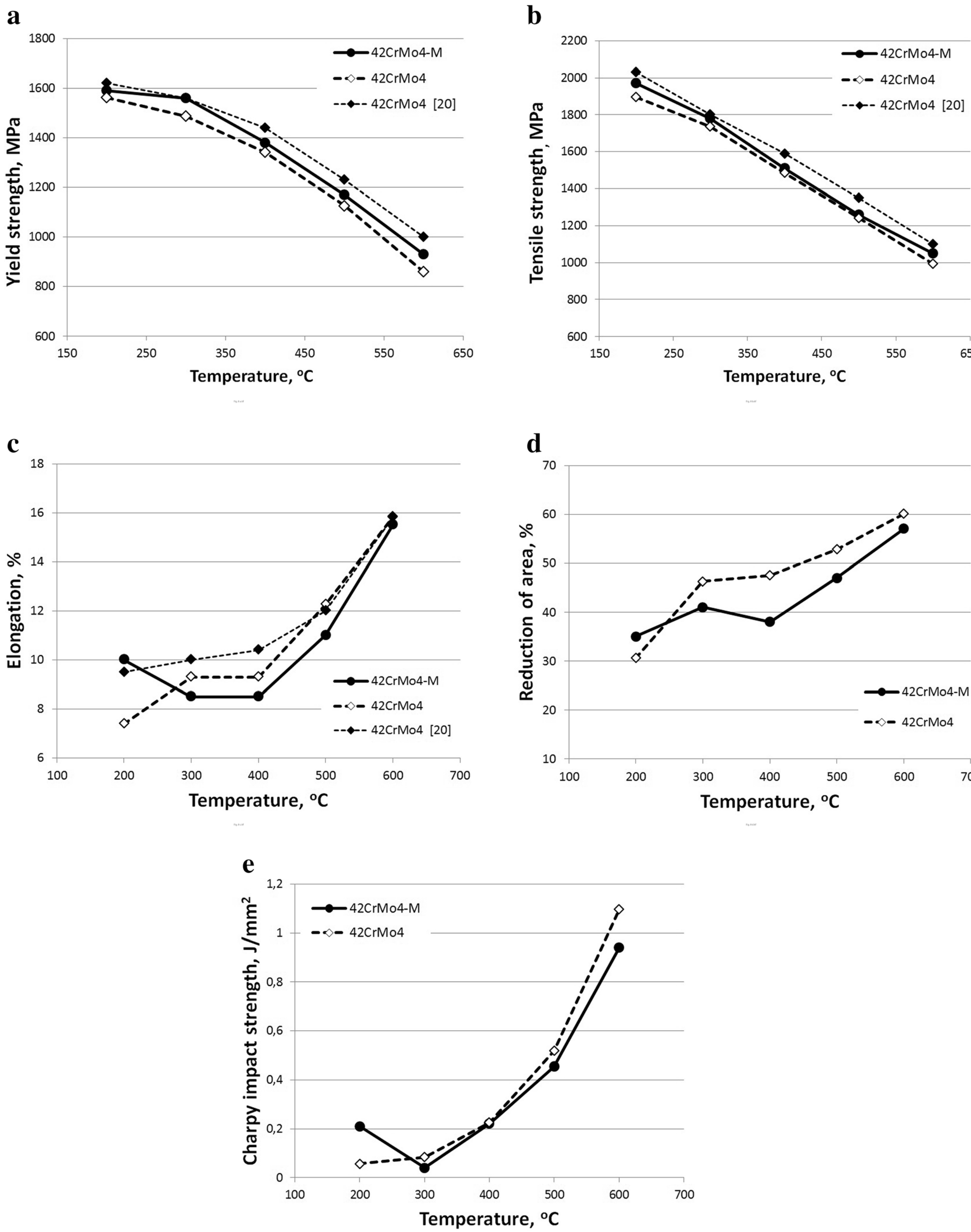

Fig. 8 Dependence of mechanical properties of 42CrMo4-M steel on tempering temperature in comparison with low-sulfur 42CrMo4 steel and reference data [20]: **a**, **b** strength: **c**, **d** plasticity: **e** Charpy impact strength

Table 2 Mechanical properties of Cr–Mn–Mo medium-carbon steels after oil quenching (850 °C, 60 min) and tempering (400…450 °C, 3 h, air cooling) for obtaining the same hardness level 42…46 HRC

Steel	$\sigma_{0.2}$, MPa	σ_B, MPa	δ_5, %	ψ, %	Charpy impact strength, J/mm^2
42CrMo4-M	1260	1370	10.0	43	0.35
42CrMo4	1300	1365	10.5	49	0.43
38CrMnMo	1245	1325	9.5	48	0.38
42CrMo4-MOD1	1235	1365	11.0	50	0.38
42CrMo4-MOD2	1260	1360	8.0	31	0.31

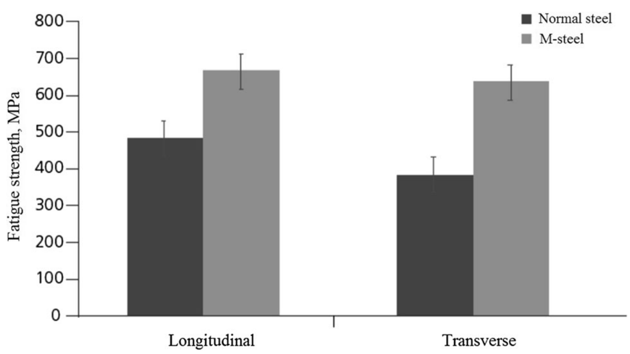

Fig. 9 Comparison of fatigue strength of the conventional steel and M steel in the quenched and tempered condition

manganese sulfide. This allows the M steel to be used for the automated production of the heavy duty steel parts.

For example, M steel 42CrMo4 has been compared to three different heats of the conventional 42CrMo4 steel for the manufacturing of the high strength quenched and tempered shafts. The M steel shafts have far fewer problems with straightness, vibration and chip performance, so the tool life is extended fivefold, and the cost savings of the shaft production reach 24%.

4 Conclusions

1. The non-metallic inclusions were analyzed in 42CrMo4-M steel with improved machinability and low-sulfur 42CrMo4 steel. The number of inclusions in 42CrMo4-M steel was significantly higher (approximately 6 times) than in the clean steel with low content of sulfur and calcium. The size range of the detected inclusions in the steel with improved machinability was also larger: the maximum area of the stringer-type sulfide inclusions and the globular-type oxide or calcium aluminate inclusions in 42CrMo4-M steel reaches 200 μm^2, in the low-sulfur 42CrMo4 steel—70 μm^2.
2. The hardenability of the 42CrMo4-M steel with improved machinability was at the same level as the low-sulfur 42CrMo4 steel and much higher compared to the 38CrMnMo steel with lower content of main alloying elements. The microstructure formed in 42CrMo4-M steel after continuous cooling at the various cooling rates (0.1–30 °C/s) was similar to the low-sulfur 42CrMo4 steel, as the CCT diagrams of the corresponding steels have shown.
3. The mechanical properties of the 42CrMo4-M steel with improved machinability did not significantly differ from the ones of the low-sulfur 42CrMo4 steel after oil quenching and tempering in the temperature range of 200–600 °C. The plasticity and impact strength of the 42CrMo4-M steel containing the significantly higher number of the non-metallic inclusions was only slightly lower (by 10–20%) compared to the clean steel with low content of impurities.
4. Given the good basic mechanical properties of the 42CrMo4-M steel, it could be accepted for further field testing of heavy duty steel parts, such as shafts in high strength condition.

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