Effect of copper on the structure and antifriction properties of cast hypoeutectoid steel

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Abstract. The structure, mechanical and tribotechnical properties of medium-carbon steel doped with 0...9 wt. % of copper with the 1% increment were investigated. During this study, the structural changes in the alloy with an increase of the copper amount were analyzed. Increase of the copper amount in the structure of medium-carbon steel leads to the gradually refinement of the ferrite grains and perlite components. In the samples doped with 9 wt. % of copper the tertiary cementite was found at the boundaries between ferrite grains and the colonies of lamellar perlite. The ε-Cu phase was revealed using X-ray diffraction of the cast steel with ~ 3 wt. % of Cu. Further increase of the copper amount promotes the increase of ε-Cu volume fraction. The change in hardness and wear resistance with an increase in the copper amount in medium-carbon steels was detected. The samples doped with ~ 6 wt. % of copper showed the maximum wear resistance at the non-fixed particles condition that corresponds to the hardness of material 240 HB.

1. Introduction
In some cases, copper-doped steel is used as tribotechnical material and is considered as an alternative material to expensive bronzes [1, 2]. The replacement of bronze on steel is the most economically rational decision at the manufacture of parts of large-sized heavy-loaded sliding friction units. The operating conditions of these units assume the presence of high specific loads. Thus, the materials for these applications must exhibit a high complex of strength and tribological properties.

Previously, the studies of such iron-carbon alloys as cast iron or hypereutectoidal steel have been done [3-5]. The effect of copper on the process of graphitization, as well as on the tribotechnical properties of cast irons, was described in [5]. When carrying out structural studies of alloyed cast iron by light metallography and transmission electron microscopy, a variety of shapes and sizes of the ε-phase particles was detected. Classification of ε-Cu particles by size and also the determination of the conditions for the formation of this phase were carried out in previous studies while the investigation of the cast iron doped with copper [3-5]. It is obvious that the influence of these particles makes a significant contribution to the complex of strength and tribological properties of the material. The strength characteristics of medium-carbon steels are significantly higher than those of cast irons. For this reason, the use of steels alloyed with copper for the manufacture of elements of sliding friction units is more promising than the use of cast irons. However, the influence of copper on the tribotechnical properties of steels is poorly represented in the literature. The purpose of this study is to
investigate the special aspects of influencing copper on the structure and tribotechnical properties of steels.

2. Materials and methods
The series of castings based on steel 45 (containing 0.45 wt. % of carbon) with a copper additions of 0...9 wt. % with the increment of 1% were made. Steel 45 and electrotechnical copper were used as a charge. The charge was melted in an induction furnace with acidic lining. The capacity of the furnace crucible was 40 kg. The weight of the casting of each chemical composition was 30 kg. Thus, 10 castings were performed. Elemental analysis of the steels obtained during the experiments was performed on the ARL-3460 optical-emission spectrometer. The results of the analysis are presented in Table 1.

| № of sample | C   | Mn  | Si  | P   | S   | Ni  | Cr  | Cu  | Al  | Fe  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0           | 0.58| 0.39| 0.84| 0.02| 0.02| 0.02| 0.02| 0.03| 0.16| bal.|
| 1           | 0.5 | 0.31| 1.44| 0.01| 0.02| 0.02| 0.02| 1.08| 0.15| bal.|
| 2           | 0.38| 0.19| 0.36| 0.01| 0.02| 0.02| 0.02| 2.05| 0.15| bal.|
| 3           | 0.39| 0.25| 0.73| 0.02| 0.02| 0.02| 0.02| 3.11| 0.16| bal.|
| 4           | 0.46| 0.3 | 1.05| 0.02| 0.01| 0.02| 0.02| 4.37| 0.09| bal.|
| 5           | 0.38| 0.26| 0.98| 0.02| 0.02| 0.02| 0.02| 5.36| 0.06| bal.|
| 6           | 0.51| 0.3 | 0.35| 0.02| 0.02| 0.02| 0.02| 6.06| 0.11| bal.|
| 7           | 0.38| 0.2 | 0.3 | 0.02| 0.02| 0.02| 0.01| 7.26| 0.1 | bal.|
| 8           | 0.39| 0.17| 0.5 | 0.02| 0.02| 0.02| 0.01| 7.88| 0.07| bal.|
| 9           | 0.38| 0.21| 0.39| 0.02| 0.02| 0.02| 0.02| 8.7 | 0.07| bal.|

Metallographic studies of the materials were carried out on a Carl Zeiss microscope Axio Observer Z1m. Structural studies at elevated magnifications were performed on a FEI Tecnai G2 20 TWIN transmission electron microscope. Phase analysis of the obtained alloys was studied using X-ray diffractometer ARL XTRA. The source of X-ray radiation was a copper tube (voltage 40 kV, current 40 mA). The analysis of the materials was performed in the geometry of the reflected radiation. Monochromatization of the primary and reflected radiation of the source was not applied. The average value of the beam wavelength λ was 0.15406 nm. For the X-ray investigations the energy-dispersed Si(Li) detector was used.

The diffraction patterns were recorded in a step mode Δ2θ = 0.02 and 0.05°, dwell time was 12 s. A pinhole spot emitter with diameter 1.5 mm was used. The hardness of the obtained castings was measured by the Brinell method in accordance with Russian standard 9012, load on a steel ball with a diameter of 10 mm was 3000 kg. Tests on the wear resistance of quenched and low-tempered steels under friction conditions with non-fixed abrasive particles were carried out in accordance with Russian standard 23.208-79. The friction path in the wear process was 942 m. River sand with a grain size of ~ 200 μm was used as an abrasive material. The rotational speed of the roller was 60 rpm. The pressing force of the roller was 44 N, cast steel 45 was used as the standard for determining the level of wear resistance.

3. Results and discussion
Non-doped steel 45 in the cast state had a ferrite-pearlite structure. The amount of ferrite was ~ 30 %. The average grain size of ferrite was ~ 50 μm.

With an increase in the copper amount the size of structural components decreases. The average size of ferritic grains in the alloy containing 5 wt. % copper was ~ 30 μm. With a further increase of
copper amount to 9 wt. % the average size of the ferritic grains doesn’t decrease (Figure 1). The volume fraction of ferrite doesn’t change with increasing copper amount.

![Figure 1](image1.png)

**Figure 1.** Effect of copper on the size of ferritic grains in steel 45 (a – 0.03 % Cu, b – 8.7 % Cu).

An increase in the copper amount is accompanied by an increase of the degree of dispersion of perlite components. The interlaminate distance becomes smaller, the thickness of the cementite plates decreases. The reason for this is probably due to a change in the rate of the alloys cooling. In its turn, the increase of the cooling rate is associated with a change of the thermal conductivity with an increase of copper content in the alloy [6]. This is due to the fact that the thermal conductivity of copper is 5 times higher than the thermal conductivity of iron [7]. Another confirmation of this statement is the rim of the tertiary cementite which located at the interfaces of the ferrite grains and the lamellar perlite colonies in the samples with 9 wt. % of copper (4 in Figure 2a). The precipitation of this structural component is due to a decrease of the solubility of carbon in α-iron at the cooling stage of castings below 727 ° C.

![Figure 2](image2.png)

**Figure 2.** Structure of medium-carbon steel, (a) optical metallography of steel containing 8.7 wt. % of copper, (b) TEM of steel, containing 3.1 wt. % of copper (1 – ferrite, 2 – perlite, 3 – ε-Cu, 4 – Fe₃C).

With the method of transmission electron microscopy (TEM) ε-Cu particles were revealed inside the ferritic grains (on the left in Figure 2b) and inside ferritic interlayers of perlite (on the right in Figure 2b). Some ε-Cu particles are located on the surface of the cementite plates.

Copper-based inclusions were observed metallographically in alloys containing not less then 4 wt. % of copper. In castings with 5 wt. % of copper inclusions have a size of 2.5...3 μm and are
predominantly compact. In steel with 9 wt. % of copper the size of the copper-containing particles reaches 8 ... 10 μm (Figure 3). In the alloys with 7 ... 9 wt. % of copper the part of inclusions are located on the grain boundaries and has an elongated shape.

![Figure 3](image_url)

*Figure 3. Special aspects of Cu-based particles, formed in medium-carbon steels (a – 7.88 % Cu, b – 8.7 % Cu).*

The X-ray diffraction patterns of cast steel 45 with different amount of copper are shown in Figure 4. X-ray diffraction patterns of non-alloyed steel 45 peaks corresponding to α-iron were detected. A complex analysis of X-ray diffraction and microstructural studies allows to conclude that fixed peaks correspond to ferrite phase. On the pattern corresponding to steel with 3 % copper both the peaks of α-iron and the peaks of ε-Cu were found. X-ray diffraction patterns corresponding to samples with 6 and 9 wt. % of copper show an increase of ε-Cu peaks the intensity.

The effect of copper addition on the hardness of medium-carbon steel castings is illustrated in Figure 5. An increase of the copper amount to 6 wt. % promotes raise the hardness level of cast non-heat treated steels from 180 to 230 HB. Further growth of copper amount to 9 wt. % is accompanied by a decline of the hardness level to 200...210 HB (Figure 5).

The dependence of the mass loss of cast steels on the copper amount is shown in Figure 5. The mass loss of cast alloys containing 3.11, 6.06 and 8.7 wt. % of copper is approximately the same. In the castings with copper amount of 6.06 wt. %, the level of wear resistance reaches a maximum value, which is associated with a significant growth of the hardness level of material.

### 4. Conclusions

An increase of the copper amount from 0 to ~ 5 wt. % in the structure of medium-carbon steel is accompanied by a gradual decrease in the size of the ferritic grain from ~ 50 μm to ~ 30 μm. The change in the volume fraction of ferrite was not found. The degree of dispersion of perlite increases with increasing copper amount. The structure of the medium-carbon steel alloy with 9 wt. % of copper addition has a rim of tertiary cementite at the interfaces of ferrite grains and lamellar perlite colonies.

The X-ray patterns of the cast steel with ~ 3 wt. % of copper have peaks belonging to ε-Cu phase. With a further increase of the copper content the volume fraction of ε-Cu increases. Using TEM methods ε-Cu particles with an average size of 20 nm were revealed in ferritic grains and ferritic perlite layers in the samples with copper addition not more than ~ 1 wt. %.

The hardness of the material increases from 180 to 240 HB with an increase in the copper amount to ~ 6 wt. %, further increase of copper to ~ 9 wt. % leads to the declining of hardness level to 225 HB. The wear resistance of the material in a friction condition with non-fixed abrasive particles varies in full accordance with the change of the hardness level.
Figure 4. X-ray diffraction patterns of the cast steel 45 with different amount of copper.

Figure 5. Dependence of hardness on the copper amount in the castings of medium-carbon steels (1) Effect of copper on weight loss of steels during wear testing in a condition of non-fixed abrasive particles (2).

Acknowledgments
This study was supported by Russian Science Foundation (project No. 15-19-00230).

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