

## THE MICROSTRUCTURE, PHASE COMPOSITION, AND MECHANICAL PROPERTIES OF ELECTROSLAG-REMELTED LIGHTWEIGHT FE-MN-AL-C STEEL ALLOYED WITH CR, SI, AND CU

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### Abstract

This study examines the microstructure, phase composition, and mechanical properties of a lightweight Fe-Mn-Al-C steel alloy containing Cr, Si, and Cu that was processed through electroslag remelting. The alloy was synthesized through induction melting, followed by electroslag remelting. This process resulted in a uniform structure with a lower inclusion content. Detailed investigations using optical microscopy, scanning electron microscopy (SEM), X-ray diffraction, and local chemical analysis revealed that the as-cast steel has a dendritic morphology and a two-phase system consisting of  $\alpha$ -Fe and  $\kappa$ -carbides  $(\text{Fe Mn})_3\text{AlC}$ . The carbide precipitates were identified as both eutectic lamellae in the interdendritic regions and rounded particles at the dendrite boundaries. These particles are enriched in Al, Mn, and Cr and contribute to grain-boundary strengthening. Mechanical testing revealed that the alloy has an average microhardness of 3.7 GPa, surpassing that of the base Fe-Mn-Al-C composition. These results demonstrate the significant impact of adding Cr, Si, and Cu on improving the phase stability and mechanical performance of electroslag-remelted lightweight high-manganese steels, suggesting their potential for advanced structural applications.

**Keywords:** Fe-Mn-Al-C steel, electroslag remelting,  $\kappa$ -carbides, microstructure, mechanical properties

### 1. INTRODUCTION

The intensive development of transport, aviation, and power engineering drives the need to create structural materials that combine high strength, high ductility, and reduced density. At the same time, the materials must maintain high fracture energy absorption capacity, ensuring their serviceability under dynamic and impact loads [1–3].

A promising class of materials is the high-strength lightweight Fe–Mn–Al–C steel system. Due to the increased aluminum content (over 5–8 wt%), a 15–20 % reduction in density is achieved compared to traditional structural materials. Simultaneously, alloying with manganese and carbon helps expand the  $\gamma$ -region and stabilize the austenitic face-centered cubic (FCC) lattice, creating prerequisites for the realization of effective strain-hardening mechanisms, particularly the TWIP and TRIP effects [1, 4].

Depending on the chemical composition and heat treatment regimes, a single-phase or multi-phase structural state is formed in the steels of this system, represented by austenite,  $\delta$ -ferrite, and dispersed carbide phases. A special role is played by the ordered  $\kappa$ -carbides of the  $(\text{Fe Mn})_3\text{AlC}$  type, which are coherently bonded to the austenite matrix. Their dispersed precipitation provides effective strengthening of the material and forms the basis for the so-called Triplex steels, which are characterized by a combination of strength, ductility, and fracture toughness [1, 5].

At the same time, the production of high-alloyed Fe–Mn–Al–C steels is accompanied by several difficulties, including liquation phenomena, increased gas saturation of the melt, and the formation of non-metallic inclusions (sulfides, oxides, oxynitrides) and shrinkage defects. The presence of such heterogeneities negatively affects the isotropy and stability of the material's mechanical properties. In this regard, it is relevant to apply methods of special electrometallurgy, in particular electroslag remelting (ESR), which provides effective refining of the metal from harmful impurities, a reduction in gas content, and an increase in the structural homogeneity of the ingots [3].

Additional alloying of the Fe–Mn–Al–C steel system with elements such as Cr, Si, and Cu opens opportunities for the targeted control of the phase composition and microstructure. In study [8] that in the Fe-20Mn-12Al-1.5C steel, strength and ductility increase at a chromium content of up to 5 %. However, increasing the chromium content beyond 5 % leads to a sharp decrease in both strength and ductility due to the formation of the D0<sub>3</sub> phase and M<sub>7</sub>C<sub>3</sub>-type carbides.

Chromium promotes higher corrosion resistance and affects the stability of the carbide phases; silicon improves castability and thermodynamically stabilizes  $\kappa$ -carbides; while copper affects the kinetics of phase transformations and can contribute to strengthening due to dispersion effects. To date, there is limited literature on the influence of Cr and Si on the structure and properties of these steels, as the focus of researchers has been on steels with  $\approx 30$  wt% of Mn content. Therefore, further research is required for steels with a lower Mn content alloyed with Cr and Si.

Thus, investigating the patterns of phase composition and microstructure formation in lightweight, high-strength Fe–Mn–Al–C steels, both in the as-cast state and after heat treatment, additionally alloyed with Cr, Si, and Cu, and produced via the "induction melting — electroslag remelting" technological scheme, is an important scientific and practical task.

## 2. RESEARCH METHODOLOGY

An ingot of the experimental Fe–Mn–Al–C–Cr–Si–Cu steel was obtained by induction melting followed by electroslag remelting. The microstructure of the steel was investigated using optical microscopy (MIM-9) and scanning electron microscopy (Tescan Vega 3 and Axia ChemiSEM). The phase composition was determined by X-ray diffraction using a Rigaku Ultima 4 diffractometer with Cu-K $\alpha$  and Co-K $\alpha$  radiation. Mechanical properties were evaluated using automatic micro indentation (Micron-Gamma hardness tester) and a PMT-3 device, both applying an indenter load of 100 g. Brinell hardness was measured using a 3-t load.

## 3. RESULTS

The chemical composition of the obtained steel is given in **Table 1**.

**Table 1** Chemical composition of the experimental steel

| Mass fraction in percent |      |      |      |     |      |      |      |      |     |       |       |
|--------------------------|------|------|------|-----|------|------|------|------|-----|-------|-------|
| Fe                       | C    | Si   | Mn   | Cr  | Ni   | Cu   | Mo   | Ti   | Al  | S     | P     |
| Basis                    | 0.54 | 1.05 | 16.3 | 2.7 | 0.12 | 0.25 | <0.1 | <0.1 | 9.4 | 0.005 | 0.010 |

Investigation of the steel microstructure after electroslag remelting (ESR) revealed (**Figure 1**) that the alloy has a dendritic structure with carbide precipitation observed in the interdendritic space (**Figure 1f**), while more massive carbide precipitations are present along the grain boundaries. According to local chemical analysis (**Table 2**) and X-ray diffraction analysis, the as-cast alloy contains a BCC solid solution and a  $\kappa$ -carbide of the (Fe Mn)<sub>3</sub>AlC type with an L1<sub>2</sub>-type crystal structure (**Table 3**).

The heat treatment (annealing and normalization) conducted at a temperature of 850 °C revealed significant changes in the microstructure of the steel. Thus, after annealing, carbide phase precipitation is observed within the grains, whereas in the interdendritic space, the amount of the carbide phase increases and regions of the FCC phase appear. According to the X-ray analysis, two types of carbides,  $(\text{Fe Mn})_3\text{AlC}$  and  $\text{Me}_7\text{C}_3$ , precipitate during annealing. However, after normalization, an increase in the fraction of the BCC phase from 88 % to 96 % is observed in the steel structure, while a minor number of  $\kappa$ -carbides is preserved (**Figure 1f, Table 3**). Additionally, in the heat-treated alloys, carbon-depleted zones (**Figure 1c, e**) free of carbide precipitates are observed along the grain boundaries.

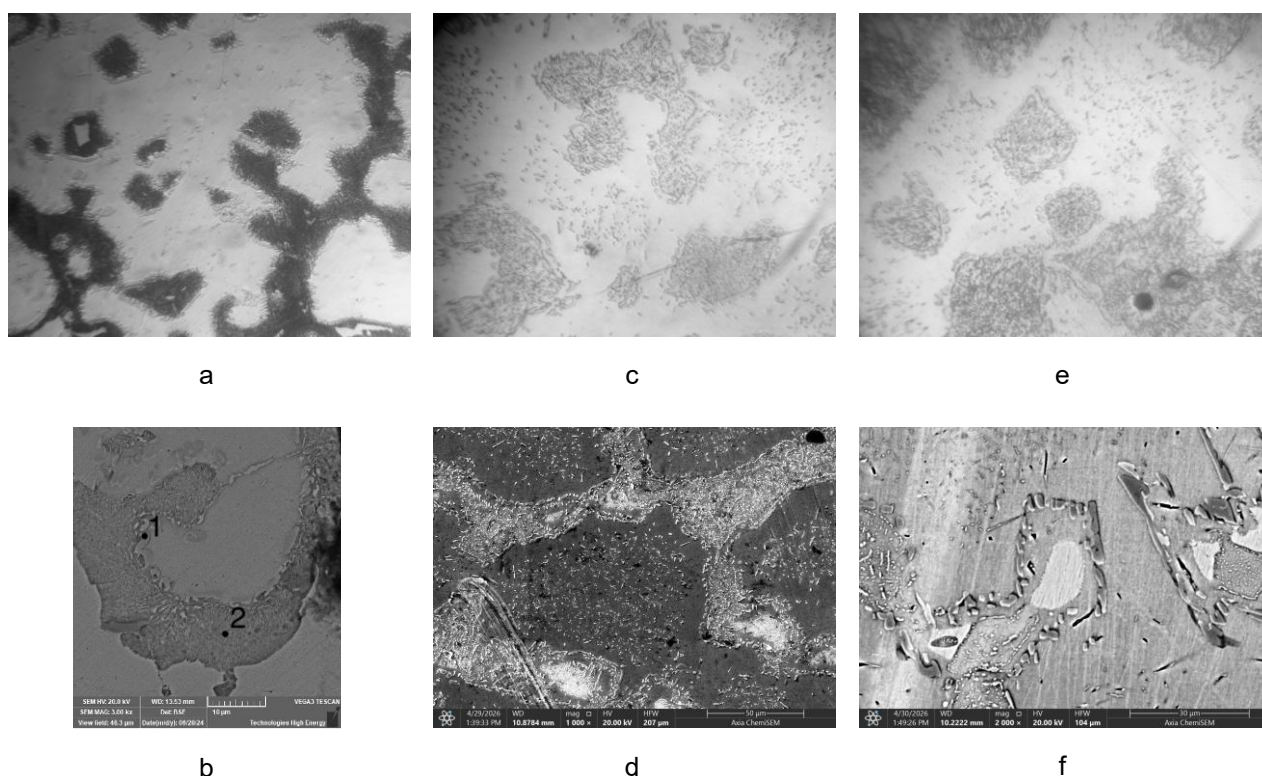


**Figure 1** Optical and SEM microstructure of steel in as-cast (a, b), after annealing (c, d) and normalization, at 850 °C (e, f)

**Table 2** Chemical composition of phases according to LRSA data of as-cast steel

| Point | Elements (at.%) |      |      |      |       |       |
|-------|-----------------|------|------|------|-------|-------|
|       | C               | Al   | Si   | Cr   | Mn    | Fe    |
| P.1   | 18.85           | 4.11 | 0.44 | 3.59 | 12.85 | 60.15 |
| P.2   | -               | 7.44 | 0.96 | 4.57 | 17.38 | 69.65 |

**Table 3** Phase composition and lattice parameters of ESR-steel in different state

| State         | Phase composition              | Phase (%) | Type structure  | Lattice parameters |        |
|---------------|--------------------------------|-----------|-----------------|--------------------|--------|
|               |                                |           |                 | a (nm)             | c (nm) |
| As-cast       | BCC                            | 88        | A2              | 0.2898             | -      |
|               | (Fe Mn) <sub>3</sub> AlC       | 12        | L1 <sub>2</sub> | 0.3777             | -      |
| Annealing     | BCC                            | 72        | A2              | 0.2892             | -      |
|               | FCC                            | 9         | A1              | 0.3673             | -      |
|               | Me <sub>7</sub> C <sub>3</sub> | 9         | hexagonal       | 1.3938             | 0.4480 |
|               | (Fe Mn) <sub>3</sub> AlC       | 10        | L1 <sub>2</sub> | 0.3782             | -      |
| Normalization | BCC                            | 96        | A2              | 0.2896             | -      |
|               | (Fe Mn) <sub>3</sub> AlC       | 4         | L1 <sub>2</sub> | 0.3785             | -      |

Since Si is practically insoluble in  $\kappa$ -carbide, according to the local EDS analysis, its content is minimal at a level of 0.5 % after both types of heat treatment (**Table 4** (P.2) and **Table 5** (P.3)). The presence of Al is observed in the  $M_7C_3$ -type carbide (**Table 4** (P.3)). The dissolution of Al in the  $M_7C_3$  carbide occurs because it can substitute Cr and Fe positions in the crystal lattice, and its content reaches 6 at.%. Additionally, after annealing (**Figure 2a**), an enrichment of the  $\kappa$ -carbide with chromium from 2.9 % to 3.8 % is observed, indicating the substitution of Fe atoms by Cr atoms in its crystal lattice. According to the EDS analysis in P.1, after normalization (**Figure 2b**, **Table 5**), local regions of  $\gamma$ -phase precipitation are observed, although it was not detected by X-ray diffraction (XRD) due to the strong texturing of the sample.

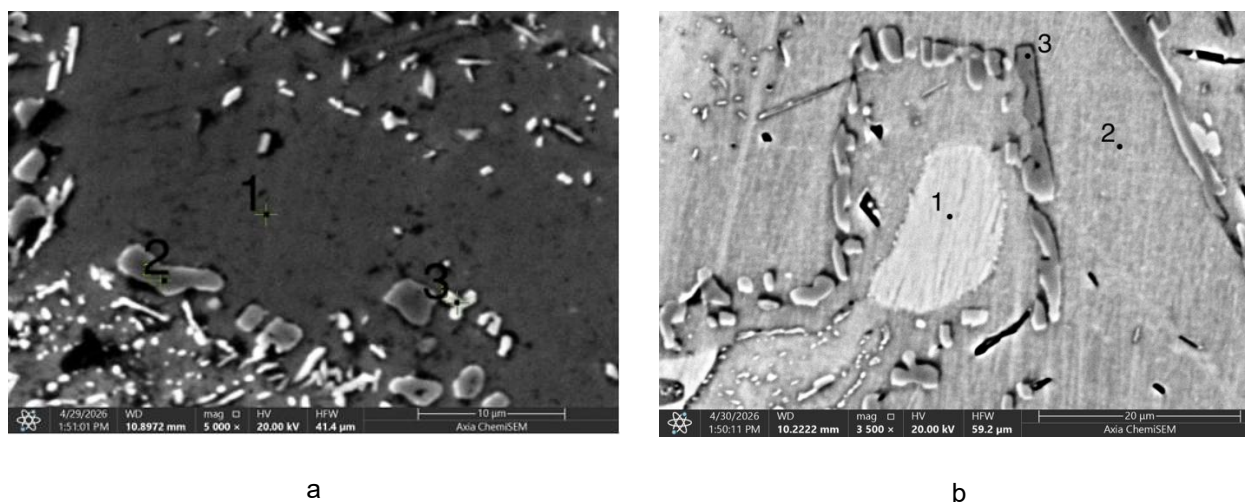


**Figure 2** SEM structure after annealing (a) and normalization (b)

**Table 4** Chemical composition of phases according to LRSA data of as-cast steel after annealing

| Point | Elements (at.%) |      |     |      |      |      |
|-------|-----------------|------|-----|------|------|------|
|       | C*              | Al   | Si  | Cr   | Mn   | Fe   |
| P. 1  | 18.1            | 15.3 | 1.9 | 1.5  | 10.5 | 52.7 |
| P. 2  | 25.7            | 15.7 | 0.5 | 2.9  | 15.7 | 39.5 |
| P. 3  | 35.7            | 6.3  | 1.0 | 12.6 | 13.0 | 31.4 |

**Table 5** Chemical composition of phases according to LRSA data of as-cast steel after normalization

| Point | Elements (at.%) |      |     |     |      |      |
|-------|-----------------|------|-----|-----|------|------|
|       | C               | Al   | Si  | Cr  | Mn   | Fe   |
| P. 1  | 18.6            | 13.6 | 1.6 | 2.9 | 12.7 | 50.6 |
| P. 2  | 16.5            | 15.0 | 2.0 | 2.0 | 10.8 | 53.7 |
| P. 3  | 23.1            | 16.5 | 0.5 | 3.8 | 16.1 | 40.0 |

**Table 6** Hardness, microhardness and modulus of elasticity of steel in different state

| State         | HB  | H <sub>μ</sub> (GPa) | H <sub>IT</sub> (GPa) | E (GPa) |
|---------------|-----|----------------------|-----------------------|---------|
| Electrode     | 285 | 3                    | 6.2                   | 211     |
| As-cast       | 335 | 3.7                  | 6.32                  | 223     |
| Annealing     | -   | 3.56                 | 6.11                  | 222     |
| Normalization | -   | 3.9                  | 6.43                  | 223     |

Mechanical properties were evaluated using the Brinell method (HB, P = 3t), Vickers microhardness testing (P = 100 g), and automatic indentation using a Berkovich indenter (Micron-Gamma instrument, P = 100 g). Compared with induction-melted samples, electron beam smelting (EBS) results in a significant increase in hardness from 285 HB to 335 HB, while microhardness increases from 3 GPa to 3.7 GPa (**Table 6**). After annealing, a decrease in hardness is observed due to the formation of an FCC phase in the structure; however, the elastic modulus remains at a high-level owing to the presence of two types of carbides ( $\kappa$ -carbide +  $\text{Me}_7\text{C}_3$ ). After normalizing, accelerated air-cooling leads to partial hardening of the steel with an increased fraction of the BCC phase, which results in a substantial increase in hardness.

#### 4. CONCLUSION

It was established that after ESR processing the steel exhibits grain refinement and the formation of a BCC phase and  $\kappa$ -carbides, which leads to an increase in hardness and elastic modulus. After annealing at 850 °C, the appearance of the  $\gamma$ -phase and precipitation of two types of carbides— $\text{M}_7\text{C}_3$  and  $(\text{Fe Mn})_3\text{AlC}$ —are observed, resulting in a decrease in hardness. After normalizing from the same temperature, an increase in the fraction of  $\alpha$ -Fe is detected by X-ray analysis, which leads to an increase in hardness up to 6.43 GPa. Local analysis revealed partial substitution of Fe atoms by Cr in  $\kappa$ -carbides, as well as the participation of Al in the composition of  $\text{M}_7\text{C}_3$  carbides, indicating the complex nature of phase formation. Overall, it was established that heat treatment significantly influences both the phase composition and the mechanical properties of the steel. Compared with annealing, which leads to the precipitation of  $\kappa$ -carbides, along with the formation of BCC and FCC solid solutions and  $\text{M}_7\text{C}_3$ -type carbides, normalizing results in an increased fraction of the BCC solid solution while retaining a small number of  $\kappa$ -carbides of the  $(\text{Fe Mn})_3\text{AlC}$ -type.

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