

RECYCLING OF FINE SCRAP AND HIGH-ALLOY STEEL WASTE BY ELECTROSLAG MELTING

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Abstract

Electroslag melting is a promising approach to the recycling of fine scrap and high-alloy steel waste. Owing to the refining capacity of slag and the controlled thermal conditions of melting and solidification, the process makes it possible to produce high-quality ingots of secondary metal suitable for further use in high-tech industries. This paper presents the results of experimental studies on the application of electroslag melting in a current-supplying mould for processing high-alloy steel waste. The features of the melting of fine and very fine metal fragments in a molten slag bath were determined, and the main routes for improving process efficiency were identified. The process was experimentally studied in the recycling of used small medical items made of high-alloy stainless steels, including injection needles and surgical instruments. Experimental trials carried out on semi-industrial equipment confirmed adequate retention of alloying elements and the production of ingots with a high-quality surface suitable for subsequent forming without additional surface conditioning. These results demonstrate the potential of this process for the recycling of fine scrap and high-alloy steel waste.

Keywords: High-alloy steel waste recycling, fine scrap, electroslag remelting, current-supplying mould, ingot

1. INTRODUCTION

In the context of global industrial transformation, the metallurgical industry is increasingly shifting toward circular economy principles, which involve returning secondary resources to production cycles, reducing waste, and lowering environmental impact. As a highly resource- and energy-intensive sector, metallurgy seeks to decarbonize production and reduce dependence on primary raw materials by increasing the share of secondary metal feedstock in charge materials [1–3]. Closed metal cycles are also essential for securing critical elements required by high-tech industries [1].

This is particularly relevant to the recycling of high-alloy steels and alloys, which are widely used in the aerospace, energy, chemical, tool, and medical industries. These materials contain significant amounts of valuable alloying elements. Their effective recovery and return to metallurgical production are important both for resource conservation and for improving the economic efficiency of recycling [4, 5]. Despite the high potential of high-alloy scrap as secondary raw material, its processing involves several technological constraints. One of the main challenges is maintaining the specified chemical composition of the metal during remelting, since alloying elements may be lost through oxidation. Studies on steel scrap recycling show that conventional large-scale remelting schemes do not always ensure the rational use and retention of these elements [5, 6].

Additional difficulties arise when processing small and finely dispersed scrap, including chips, trimmings, machining waste, small items, and complex-shaped parts. The volume of such waste is increasing due to the development of high-precision machining, medical instrument production, microcomponent manufacturing, and additive technologies. Unlike bulk scrap, small metal fragments have a high surface-to-volume ratio, which

promotes intensive oxidation and surface contamination by lubricating and cooling fluids, adsorbed impurities, and oxide films. The literature has repeatedly shown that the large specific surface area of metal chips and similar waste is one of the key factors reducing the yield of usable metal during remelting [7–9]. Although many studies in this area focus on aluminum, magnesium, or titanium alloys, the increased oxidation tendency of fine fractions is also highly relevant to fine high-alloy steel scrap.

In conventional recycling routes, small-sized scrap usually requires preliminary preparation, such as cleaning, drying, briquetting, pressing, sorting, or remelting together with bulk charge materials. These operations increase process cost and do not always ensure stable retention of alloying elements, since their loss requires subsequent correction of the metal composition. Therefore, the development of technologies capable of directly processing fine high-alloy scrap with minimal loss of valuable elements is an urgent task for modern green metallurgy.

Electrometallurgical processes, especially electroslag remelting, show promise for this purpose. ESR is widely used to produce high-quality ingots of special steels and alloys with improved chemical homogeneity, reduced non-metallic inclusion content, and controlled crystallization structure [10, 11]. However, conventional ESR requires a consumable electrode of defined shape and size, which limits the direct use of fine scrap, chips, and irregularly shaped waste. Their processing usually requires preliminary melting, electrode fabrication, and subsequent remelting, increasing energy consumption, process duration, and cost.

A promising way to overcome these limitations is electroslag remelting in a current-supplying mould [12, 13]. This approach expands the technological capabilities of the process by reducing the requirements for consumable material geometry, improving heat flux control in the slag bath, and enabling the direct melting of small metal fragments. Fine scrap can be fed directly into the slag bath, where it is heated, melted, interacts with refining slag, and then forms a metal bath that solidifies in a water-cooled mould. This allows for the combination of processing secondary raw materials and producing high-quality ingots suitable for subsequent forming.

The efficiency of this approach depends on a set of interrelated physicochemical processes, including heat transfer between the slag bath and metal fragments, immersion and melting rates, mass transfer in the metal–slag system, oxidation of alloying elements, and the conditions of metal bath formation and crystallization. These factors determine process productivity, metal yield, preservation of alloying elements, and surface quality of the ingot. Although the literature provides detailed information on electrode melting, metal refining, and ingot formation during ESR [10, 11], the melting of fine high-alloy scrap directly in a slag bath remains insufficiently studied.

Thus, the relevance of this work is determined by the need to develop resource-efficient technologies for processing fine high-alloy steel scrap in accordance with the principles of the circular economy and green metallurgy. Direct electroslag remelting of fine metal waste in a current-supplying mould can reduce the number of processing stages, minimize alloying element losses, and produce high-quality secondary metal. This approach opens prospects for recycling categories of waste that are difficult or economically inefficient to process using conventional methods.

The aim of this study is to investigate the features of electroslag remelting of fine high-alloy steel scrap in a current-supplying mould and to identify ways to improve the efficiency of the recycling process. Attention is paid to the melting of small and very small metal fragments in the slag bath, the retention of alloying elements, and the formation of ingots suitable for further metallurgical processing.

2. EQUIPMENT, MATERIALS AND METHODS

Experimental studies on the remelting of fine-alloyed scrap were conducted at the Electroslag Technologies Laboratory of the E.O. Paton Electric Welding Institute (PWI). These studies used a modernized research complex that included a P-951-type electric slag furnace and a flux-melting unit. This complex allows to

produce round-section ingots with a current-supplying mould and a downward ingot withdrawal scheme. The electroslag furnace is equipped with two independent power sources, each with a capacity of 724 kVA, to implement a dual-circuit power supply scheme. These power sources have been modernized for smooth regulation of the output voltage. This setup enables the electroslag remelting process to be carried out according to various schemes, including with (**Figure 1a**) or without a consumable electrode (**Figure 1b**).

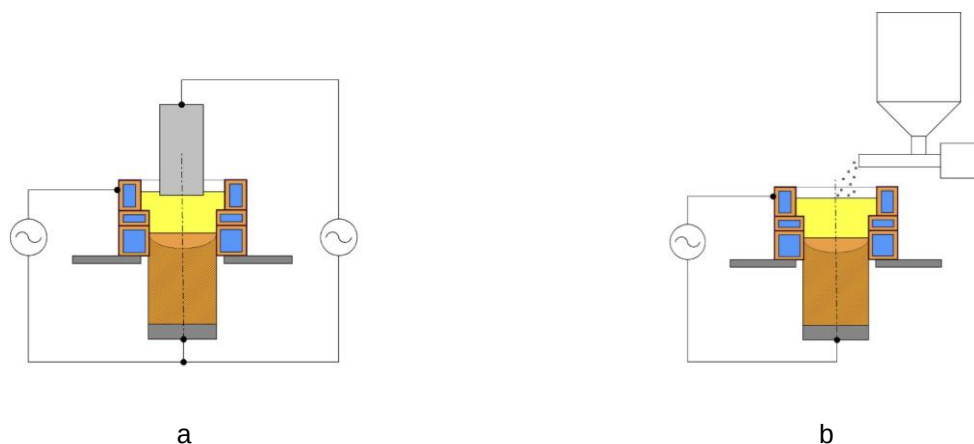


Figure 1 Variants of the electroslag process using a current-supplying mould

The specific features of electroslag remelting using a two-circuit power supply scheme with a current-supplying mould, as well as the design features of this mould, are described in [12, 14]. In this study, the remelting of non-compacted fine alloyed scrap in a current-supplying mould without the use of a consumable electrode was investigated. Under these conditions, the electroslag process and slag heating occur solely due to the electrical power supplied to the current-supplying section of the mould. In the experiments, a mould with a forming section diameter of 180 mm was used.

Small pieces of waste medical instruments, mainly made of X18H10 steel, that had undergone preliminary thermal treatment were used as fine metal feedstock. As the provided photographs show (**Figure 2**), it is difficult to separate and sort the different types of instruments after sintering.



Figure 2 General view of the fine scrap used in the experiments, in its transport container (a) and in a typical pile (b)

Melting was initiated by forming a slag bath in the mould with molten ANF-28 flux. Then, the metallic charge was fed in batches onto the surface of the slag bath. As the charge melted, the ingot was withdrawn downward from the mould at a preset rate, which was adjusted according to the liquid metal level sensor readings. During

the experimental melts, the technological parameters of the ESR process were continuously monitored and recorded.

Samples were taken from the produced ingots to assess their internal quality and to perform chemical analysis.

3. RESULTS AND DISCUSSION

The first experiment studied the behavior of the charge during loading into the melting chamber, determined the power level at which active melting of the charge occurs in the slag bath, and evaluated the melting rate. To this end, charge samples weighing 300, 400, and 500 grams were prepared, with two samples for each weight. During the experiment, it was found that the charge does not immediately sink into the slag bath after loading but rather remains on its surface for a period of time. The charge melted more intensely at the periphery of the slag bath because the greatest amount of heat is released at the interface between the mould's walls and the slag in a current-supplying mould. The power supplied to the melting chamber was set at 170 kVA. Under these conditions, the melting time was 14 s for a 300-g sample, 16 s for a 400-g sample, and 19 s for a 500-g sample. The results confirmed the fundamental feasibility of the selected remelting scheme for processing fine scrap.

Further experiments aimed to refine the technology, optimize the melting parameters, and evaluate the behavior of the slag bath. One experiment involved gradually increasing the input power from 100 to 200 kVA while remelting. This experiment showed that power levels below 150 kVA are insufficient for a stable process. With these lower power levels, the charge melts slowly and freezing is observed in the central part of the slag bath. Increasing the supplied power from 150 to 200 kVA doubled the charge's melting rate.

It has also been established that solid plastic degradation products dispersed in the charge significantly slow down the melting process and contaminate the slag, altering its physicochemical properties. In particular, the slag becomes more viscous and its electrical conductivity changes (**Figure 3**). During the development of this technology, these accumulations were mechanically removed using a scraper to maintain the achieved melting rate of the charge. Consequently, the remelting capacity did not exceed 15 kg/h at a power of 175–200 kVA.

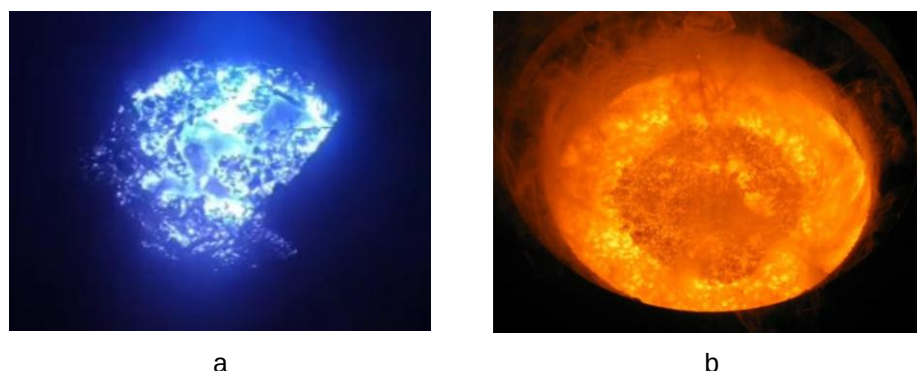


Figure 3 Condition of the slag bath surface during remelting: a – when the charge is too contaminated with plastic degradation products; b – clean slag bath surface

Preliminary purification of the charge removed impurities and increased process productivity to 45 kg/h. **Figure 4** shows the resulting ingot, which has a diameter of 180 mm, a length of 440 mm, and a mass of 87 kg. The ingot's surface quality clearly reflects the effect of changes in remelting power on process stability. The bottom of the ingot exhibits corrugations, flash, shrinkage cavities, and slag inclusions. This indicates that remelting at 140–150 kVA does not ensure a high-quality ingot surface with a diameter of 180 mm. However, after

increasing the power to 175–180 kVA, the ingot surface was completely defect-free. The surface became smooth and took on the appearance characteristic of ingots produced by electroslag remelting.



Figure 4 General view of the reference ingot and its main surface condition

Analysis of the ingot revealed that its body structure is generally dense and fine-grained. It is free of pores, slag inclusions, and other defects. However, small, localized, closed cavities of a blister-like type were detected in the head part of the ingot. The origin of these cavities requires further investigation. The shape and location of these cavities do not allow for them to be unequivocally attributed to shrinkage. The process may require the use of a specific technique to complete the process.

The chemical analysis of the test ingots showed the following elemental content: chromium, 15.6–18.5%; nickel, 8.9–9.3%; manganese, 0.35–1.0%; copper, up to 0.22%; and titanium, up to 0.1%. These values are close to the content of the corresponding elements in typical stainless steels. However, the carbon content in the metal was found to be excessively high, reaching 2.5% in the initial melts. This is evidently a consequence of the charge being contaminated with plastic degradation products. Preliminary cleaning of the charge reduced this value by a factor of three. This indicates the necessity of cleaning this type of charge of dispersed residues of carbon-containing combustion products prior to remelting.

The focus of this study was to determine the fundamental feasibility of the remelting process without a consumable electrode, establish the characteristics of charge melting and ingot formation, and evaluate the process's potential productivity. The highest productivity achieved during the experimental melts was 40–45 kg/h (0.67–0.75 kg/min). Calculations showed that 31–35% of the electrical power is consumed melting the metal charge. Thus, the total losses are approximately equivalent to those in a short circuit of an ESR furnace.

4. CONCLUSION

The experimental results confirmed the feasibility of recycling fine high-alloy steel scrap by electroslag melting in a current-supplying mould without using a consumable electrode. The proposed scheme enables small metal fragments to be fed directly into the slag bath, where they are heated, melted, refined by molten slag, and solidified as an ingot in a water-cooled mould.

Process stability and productivity were found to depend strongly on the power supplied to the current-supplying mould. At power levels below 150 kVA, melting was unstable and partial freezing occurred in the central region of the slag bath. Increasing the power to between 175 and 200 kVA ensured stable charge melting, improved ingot surface quality, and provided a maximum productivity of 40–45 kg/h.

The charge condition also had a significant effect on process performance. Plastic degradation products and other carbon-containing residues slowed melting, contaminated the slag bath, altered its physicochemical properties, and increased carbon content in the remelted metal. Preliminary cleaning of the charge improved process stability and reduced carbon pickup, confirming that charge preparation is essential for recycling this type of fine scrap.

The produced ingots had a dense, fine-grained structure without pores, slag inclusions, or other major internal defects in the ingot body. Their chemical composition showed adequate retention of the main alloying elements, including chromium and nickel, and remained close to that of typical high-alloy stainless steels.

Thus, electroslog melting in a current-supplying mould is a promising route for processing fine and very fine high-alloy steel waste that is difficult to recycle by conventional methods. Further work should focus on optimizing slag composition, power input, charge feeding, and final-stage solidification to improve productivity, reduce carbon pickup, and eliminate local defects in the ingot head.

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