RECYCLING OF ALLOY STEEL AND NICKEL ALLOY SCRAP AND WASTE BY ELECTROSLAG REMELTING PROCESS

Yurii KOSTETSKYI, Ganna POLISHKO, Yevhen PEDCHENKO, Volodymyr PETRENKO, Volodymyr ZAITSEV

E.O. Paton Electric Welding Institute (PWI), Kyiv, Ukraine, y.kostetsky@paton.kiev.ua

https://doi.org/10.37904/metal.2025.5069

Abstract

The recycling of metal waste and scrap is an essential component of a circular economy, which is predicated on the principles of reducing waste and consumption of resources through the reuse and recycling of materials. However, it is not always possible to process the metal while maintaining its chemical composition and producing high-quality ingots without complicating the technological process and incurring excessive costs. From this point of view, electroslag remelting can be an effective technology for recycling alloyed steel and nickel alloys to produce a high-quality material with reduced environmental impact and minimized toxic emissions. Modern two-circuit ESR technology with a current supplying mould significantly reduces the requirements for the geometry of the consumable electrode and greatly improves the ability to control the thermal processes taking place in the slag and metal bath. The research conducted has demonstrated the ability to effectively recycle various types of metal scrap, from used small tools to nickel alloy fragments, while preserving their chemical composition and producing quality ingots. The experiments also showed significant potential for processing metal chips and other similar metal wastes with production of quality ingots. The presentation reviews the technological aspects and the results of a series of studies on the recycling of various types of alloy steel and nickel alloy waste and scrap using the current supplying mould and two-circuit electroslag remelting technology.

Keywords: Metal waste recycling, electroslag remelting, two-circuit ESR, current supplying mould, ingot

1. INTRODUCTION

The emerging concept of the circular economy is encouraging the steel industry to innovate in the use of man-made metal waste to achieve the ambitious goal of "zero waste" [1] and ensure production competitiveness. This improves the environmental sustainability of production by saving primary raw materials and rationalizing the use of resources [2-4]. The recycling of alloy steel scrap in Europe is considered an integral part of the circular economy and green metallurgy, as the production of alloy steels consumes a large amount of energy and mineral resources for the production of ferro-alloys. Returning alloy scrap to the metallurgical cycle can significantly reduce both energy and resource costs [5].

Steel and nickel alloys have an extremely high potential for repeated recycling and return to the production cycle [6]. Typically, alloy steel and nickel alloy scrap is melted in electric arc or induction furnaces [7]. With this, it is important to minimize the loss of valuable alloying components, but it is difficult to ensure in electric arc melting [8]. Induction furnaces offer better retention of alloy impurities and lower overall metal losses due to oxidation [7]. However, it is difficult to realize the refining capabilities of the slag in induction melting and thus refine the metal from unwanted impurities and non-metallic inclusions. An additional problem with the traditional alloyed waste processing route is the difficulty in producing high quality ingots which have a high degree of physical and chemical homogeneity, as well as the loss of some metal during trimming and casting losses.

It is possible to improve the quality of cast metal by using electroslag remelting (ESR) technology [7,9,10]. The ESR process ensures metal purification from large non-metallic inclusions, homogenization of chemical composition, improvement of metal microstructure and macrostructure, and production of dense ingots without internal pores and shrinkage cavities. At the same time, the chemical composition of the alloy does not change significantly [9,10]. Electroslag remelting is widely used in industry to produce high quality ingots for critical applications from high alloy steels and nickel alloys [9].

However, the incorporation of electroslag remelting technology into the traditional recycling chain adds cost, which in many cases limits the feasibility of its application. To reduce end-to-end production costs, single-stage recycling processes based on electroslag technology have been proposed, using non-consumable electrodes and crucible electroslag melting [11,12]. In the former, fine scrap is fed into the gap between the mould wall and the electrode. Under certain conditions, it is possible to use a consumable electrode with the same chemical composition as the fine scrap. However, this process has obvious limitations with respect to the size of the scrap fragments. Crucible electroslag melting offers more flexibility in terms of the shape of the scrap to be melted, but the metal collected in the crucible must still be poured into a mold. As a result, it is not possible to ensure the quality of such ingots at the level of ESR ingots.

The main limitation to using standard ESR technology to solve recycling problems is the need to use a consumable electrode with geometric parameters that are unchanged along its length [13]. This is due to the need to maintain process stability. Usually, custom made cast or deformed electrodes are used. It is clear that it is difficult to implement a one-step recycling process based on classical ESR technology.

Electroslag remelting with two independent power circuits (ESR TC) using a current supplying mould [14,15] (**Figure 1**) can significantly simplify the requirements for the geometry of the consumable electrode. In ESR TC, current is supplied through two circuits: "consumable electrode - stool" and "current supplying mould - stool". At a result, the periphery of the slag bath is heated by the current from the current supplying section of the mould. This makes it possible to break the rigid dependence of the process temperature on the electrode melting rate, to control the heat input into the slag and metal baths, and to distribute the power between the circuits in a wide range of ratios [14]. The ESR TC has been successfully used to produce ingots of complex steels, superalloys and titanium [16].

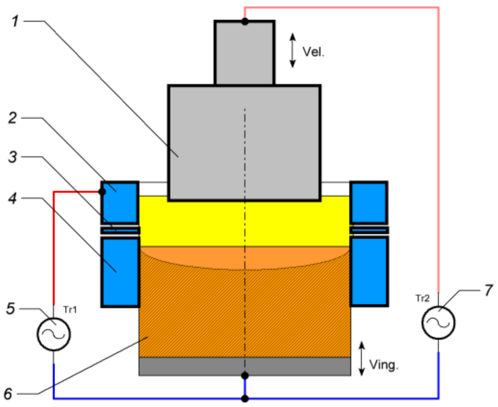

Figure 1 Schematic representation of the ESR in a current supplying mould with a two-circuit power supply scheme (1 - consumable electrode; 2 - current supplying section of the mould; 3 - separating section of the mould; 4 - forming section of the mould; 5,7 - power supply; 6 - ingot)

This paper presents the results of the research on the experimental testing of the ESR TC technology using a current supplying mold to solve the problems of remelting various types of metal wastes of alloyed steels and nickel alloys in the paradigm of the one-step recycling scheme to obtain a high quality ingot suitable for direct further use in the production cycle.

2. EQUIPMENT, MATERIALS AND METHODS

Experimental studies on the production of ingots of circular cross section were carried out in the Laboratory of Electroslag Technologies of the E.O. Paton Electric Welding Institute (PWI) on the R-951 furnace using a current supplying mould according to the scheme of ingot extraction from a short collar mould down. In order to implement the two-circuit scheme, the furnace is equipped with two independent power supplies of 724 kVA each (transformers type TSHP-10000/1 (A-622)), modernized for smooth regulation of the output voltage.

The electroslag remelting of the experimental ingots was carried out in a current supplying mould with a mold section diameter of 180 mm. The mould was a sectional unit (**Figure 1**). The upper section of the mould serves as a non-consumable electrode (2), and the lower section (4) ensures the formation of the surface of the ingot to be melted. The separating section of the mould (3) acts as an insulator to prevent breakdown between the current supplying section and the forming section. The design of the current supplying section ensures the rotation of the slag bath in a horizontal plane [17,18]. The automatic process control system installed on the furnace allows electroslag remelting in the current supplying mould in an automatic mode with both liquid and solid start.

For experimental melts, consumable electrodes were made from scrap metal of the appropriate type (**Figure 2**).

a b c

Figure 2 General view of consumable electrodes formed from different types of metal scrap (a - tool steel scrap; b - variable cross-section model electrode; c - nickel alloy scrap)

In order to study the recycling of P6M5 tool steel scrap, electrodes were assembled from small used tools by welding individual pieces into a single electrode (**Figure 2a**). Remelting of these electrodes was performed under ANF-29 flux.

To simulate the remelting of waste rolls from continuous casting machines, a variable-section electrode with sections of 150, 110, and 80 mm in diameter was used to simulate the remelting of real rolls without first cutting off the necks (**Figure 2b**). With this electrode geometry, the filling factor was gradually changed from 0.69 to 0.37 and to 0.2 during remelting. To fix the current configuration of the molten metal bath during melting, ferrous sulfide was introduced into the melting zone at certain intervals.

The electrodes for the remelting of scrap nickel alloy EP648 were formed from a 70 mm diameter cylindrical cut, rejected due to shrinkage defects, and half rings of the same alloy (**Figure 2c**). The individual fragments were welded together with minimal filler metal. The design of the electrode did not allow a high current to pass through it. Therefore, the remelting was carried out using a quasi-passive electrode. That is, the main electrical power was supplied to the mould and minimal power was supplied to the electrode. The remelting was carried out under a flux consisting of 90% ANF-29 and 10% CaF_2 with argon protection of the melting space.

We also conducted a study of remelting fine alloyed metal scrap in a current supplying mould without the use of a consumable electrode. Under these conditions, the slag bath is heated only by supplying current through the water-cooled current supplying section of the mould (**Figure 1**). The scrap was a small waste of medical instruments made of X18H10 steel and similar. Melting began with the introduction of a slag bath of ANF-28 flux. The metal charge was added to the surface of the slag bath in portions. The melting process was visually monitored.

Samples were cut from the control ingots to determine their internal quality, examine their macrostructure, and perform chemical analysis.

3. RESULTS AND DISCUSSION

Experiments with remelting electrodes of tool steel scrap (**Figure 2a**) under different modes showed that the configuration of the composite electrode directly affects the stability of the process and the quality of the resulting ingot. It was found that the remelting of composite electrodes with irregular geometry should be carried out with the main power (≥75%) supplied to the mould. In this way, the electrode can be melted evenly and with constant productivity, and a high-quality ingot can be produced. The chemical composition of the metal of the control ingot, weighing 129 kg, obtained from tool steel scrap, corresponded to the chemical composition of P6M5 steel [19].

Remelting of the regular geometry variable cross section electrodes (**Figure 2b**) was conducted to determine the conditions under which a stable depth and profile of the liquid metal bath is maintained throughout the remelting process, resulting in a stable ingot metal quality along the length. Remelting performance was found to be controlled by the power applied to the consumable electrode. The effect of the power in the mould circuit on the remelting performance is not significant, but it has a strong influence on the shape of the liquid metal bath. In order to maintain stable parameters of the liquid metal bath, it is necessary to run a process with constant productivity and stable current density at the periphery of the slag bath [20].

Based on the results of remelting consumable electrodes from nickel alloy waste (**Figure 2c**), it was determined that the rational power distribution between the electrode and mould during the process is 1/3. With this, the remelting rate averaged 80 kg/h. According to the developed modes, control ingots of 1.10 m and 1.25 m in length were produced. The chemical composition of the metal after ESR was similar to that of the original EP648 alloy (**Table 1**). The oxidation loss of the high activity elements Al and Ti did not exceed 0.1% and 0.15%, respectively, under the experimental conditions. The experimental ingots were transferred to production, where they were forged into rings that successfully passed the control for compliance with current industrial quality standards.

Table 1 Chemical composition of the metal after ESR of nickel alloy waste, wt%

Ni	Cr	Mo	Nb	Ti	Fe	W	Al
52,87	33,66	2,30	1,44	0,96	0,58	4,96	0,67

The experiments on the remelting of small-pieces of alloyed metal waste in a current supplying mould using an electrode-free scheme (**Figure 3a**) showed that in the absence of a central electrode in the slag bath, there is a ring-wall heat generation character (**Figure 3b**). However, with the correct choice of remelting mode, the temperature field of the slag bath inside the mould is effectively averaged due to mixing under the influence of the electromagnetic field. A special device can also be used to control the bath speed and changing the rotating direction.

During the experiments, a melt rate of about 45 kg/h was achieved. The high quality of the ingot surface was obtained at an input power of 175-200 kVA. After remelting, the steel contained 17-18% Cr, 9.0-9.3% Ni.

a

b

Figure 3 General view of the process of remelting of small-pieces of alloyed metal waste in a current supplying mould (a) and the view of surface of the slag bath under wall heat generation (b)

4. CONCLUSION

Experimental studies have identified and demonstrated the possibility of recycling various types of metal waste from alloyed steels and nickel alloys based on the technology of electroslag remelting using a current supplying mould to obtain high quality ingots suitable for direct use in the production cycle of metal products.

The peculiarities and rational methods of remelting electrodes of variable section from alloyed steel and nickel alloy waste were studied in a semi-industrial electroslag remelting plant. The technology of remelting of small-pieces of alloyed metal waste in a current supplying mould according to the electrode-free scheme was tested and the possibility of its application for recycling small medical instrument wastes was experimentally proved.

REFERENCES

[1] BRANCA, T., COLLA, V., ALGERMISSEN, D., GRANBOM, H., MARTINI, U., MORILLON, A., PIETRUCK, R., ROSENDAHL, S. Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. *Metals*. 2020, vol. 10, 345. DOI 10.3390/met10030345

[2] HAMPUS, A., LJUNGGREN, M. Towards comprehensive assessment of mineral resource availability? Complementary roles of life cycle, life cycle sustainability and criticality assessments. *Resources, Conservation and Recycling*. 2021, vol. 167, 105396 DOI 10.1016/j.resconrec.2021.105396

[3] ZBYKOVSKYY, Y., SHVETS, I., TURCHANINA, O., CASTELBRANCO, A. Investigation for a Sustainable Use of Fossil Coal through the Dynamics of Interaction of Smokeless Solid Fuel with Oxygen. In: *4th European International Conference on Industrial Engineering and Operations Management*. Rome, IEOM Society International, 2021, ID 173, pp. 171-182.

[4] PYSHYEV, S., ZBYKOVSKYY, Y., SHVETS, I., MIROSHNICHENKO, D., KRAVCHENKO, S., STELMACHENKO, S., DEMCHUK, Y., VYTRYKUSH, N. Modelling of Coke Distribution in a Dry Quenching Zone. *ACS Omega,* 2023, vol. 8 (22), pp. 19464–19473.

[5] XIE, J., XIA, Z., TIAN, X., LIU, Y. Nexus and synergy between the low-carbon economy and circular economy: A systematic and critical review. *Environmental Impact Assessment Review*. 2023, vol. 100, 107077. DOI 10.1016/j.eiar.2023.107077

[6] GRAEDEL, T. E., ALLWOOD, J., BIRAT, J., BUCHERT, M., HAGELÜKEN, C., RECK, B. K., SIBLEY, S. F., SONNEMANN, G. What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology*. 2011, vol. 15, issue 3, pp. 355-366. DOI 10.1111/j.1530-9290.2011.00342. x

[7] WU, L., LIU, K., MEI, H., BAO, G., ZHOU, Y., WANG, H. Thermodynamics Analysis and Pilot Study of Reusing Medium and High Alloy Steel Scrap Using Induction Melting and Electroslag Remelting Process. *Metals*. 2022, vol.12, issue 6, 944. https://doi.org/10.3390/met12060944

[8] VARVARA, D.A.I., TINTELECAN, M., ACIU, C., BOCA, I.M.S., HĂDĂREAN, A., RUS, T., MARE, R. An assessment of the substance losses from charge composition used to the steelmaking – Key factor for sustainable steel manufacturing. *Procedia Manufacturing*. 2019, vol. 32, pp. 15–21. DOI 10.1016/j.promfg.2019.02.177

[9] ARH, B., PODGORNIK, B., BURJA, J. Electroslag remelting: a process overview. *Materials and technology*. 2016, vol. 50, issue 6, pp. 971–978. DOI 10.17222/mit.2016.108

[10] WALEK, J.; ODEHNALOVÁ, A.; KOCICH, R. Analysis of Thermophysical Properties of Electro Slag Remelting and Evaluation of Metallographic Cleanliness of Steel. *Materials*. 2024, vol. 17, issue 18, 4613. DOI 10.3390/ma17184613

[11] BIKTAGIROV, F.K., VERETILNYK, O.V., SHAPOVALOV, V.O., HNATUSHENKO, O.V., IGNATOV, A.P., BARABASH, V.V. Comparative indices of different methods of processing shavings of high-alloyed steels and alloys. *Electrometallurgy Today*. 2021, issue 4, pp. 11-15 DOI 10.37434/sem2021.04.01

[12] KUSKOV, Yu. M., RYABTSEV, I.A., KUZMENKO, O.G., LENTYUGOV, I.P. *Electroslag technologies of surfacing and recycling of metal and metal-containing waste*. Kyiv: Interservice, 2020.

[13] MITCHELL, A. Electrode manufacture for the remelting processes. *Ironmaking & Steelmaking*. 2021, vol. 48, issue 5, pp. 505-513, DOI: 10.1080/03019233.2020.1855690

[14] TSYKULENKO, A., LANZMANN, I., MEDOVAR, L., CHERNETS, A., SHEVCHENKO, V., FEDOROVSKY, B., GRABOVSKY, Ts., US, V. Two-circuit scheme of electroslag remelting of consumable electrode. *Problems of Special Electrometallurgy*. 2000, issue 3, pp. 16-20.

[15] DONG, Y., JIANG, Z., CAO, H., HOU, Z., YAO, K. Study of single-power, two-circuit ESR process with current-carrying mold. Development of the Technique and its Physical Simulation. *Metallurgical and Materials transactions B*. 2016, vol. 47, issue 6, pp. 3575–3581. DOI:10.1007/s11663-016-0813-8

[16] MEDOVAR, L., STOVPCHENKO, G., JIANJUN, G. State of the art of electroslag refining and challenges in the control of ingot cleanness. In: *12th International Conference of Molten Slags, Fluxes and Salts MOLTEN 2024 Proceedings*. Brisbane: AusIMM, 2024, ID: P-04120-D5P7M3.

[17] KUSKOV, Yu. M., PROSKUDIN, V.M., ZHDANOV, V.A., OKONYK, L.L. Current-conducting mould in electroslag technologies. *The Paton Welding Journal*. 2022, issue 7, pp. 35-38. DOI: 1037434/tpwj2022.07.06

[18] KUSKOV, Yu. M., SOLOVYOV, V. G. Experimental study of slag and metal bath rotation during electroslag process in current-feeding mould. *Automatic welding*. 2018, issue 7, pp. 41–43. DOI 10.15407/as2018.07.07

[19] PEDCHENKO, Ye., MEDOVAR, L., KOSTETSKY, Yu. Electroslag remelting as a method of recycling non-compact high-speed steel tools. In: *Proceedings 31st International Conference on Metallurgy and Materials*. Brno: TANGER Ltd, 2022, pp. 142-148. DOI 10.37904/METAL.2022.4455

[20] PEDCHENKO, Ye. O., PETRENKO, V. L., KOSTETSKYI, Yu. V., POLISHKO, G. O., ZAITSEV, V. A. Electroslag remelting of variable cross-section electrodes using a two-circuit scheme. In: *Proceedings of the VIIth International Conference on Welding and Related Technologies WRT 2024.* Yaremche: CRC Press, 2025, pp. 25-28. DOI 10.1201/9781003518518-5