Quest Journals
Journal of Research in Mechanical Engineering
Volume 10 ~ Issue 6 (2024) pp: 33-38
ISSN(Online):2321-8185
www.questjournals.org

Research Paper

Briquette Ni 60 as a Substitute for Alloys in the Production of Austenitic Steels and Reduction of the CO2 Footprint

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Abstract
Austenitic steels are stainless steels with a high content of chromium and nickel. In the production of these (whether it be the production of stainless steel in foundries or steel mills), alloying elements need to be added to the base charge in the form of ferroalloys, primarily ferrochrome (FeCr), and, for stainless austenitic steels, also nickel (usually in the form of cathodic nickel). Alloys or alloying elements are usually very expensive due to the production process itself, while their production and transport also result in a high carbon footprint. In the production processes at Ekstera d.o.o., a large amount of grinding dust is generated during the cleaning and grinding of nickel alloys. This dust is classified as hazardous waste and can only be handed over to an authorized waste management company. We have developed and patented a process for briquetting this dust, resulting in a final product named Ni 60. Testing has shown that this briquette can replace alloying elements such as nickel, which is typically added in the form of cathodic nickel, and chromium, in the form of ferrochrome, in the production of austenitic steels. This has reduced costs for foundries while also lowering the carbon footprint and, importantly, introducing circular economy practices in the truest sense of the term at our company. We turned waste into a valuable, high-quality product.

Keywords: *stainless austenitic steel, alloys, briquettes, nickel, carbon footprint*

R*eceived 27 Nov., 2024;* ***R****evised 04 Dec., 2024;* ***A****ccepted 06 Dec., 2024 © The author(s) 2024.* ***P****ublished with open access at* ***www.questjournas.org***

I. Introduction

Circular economy (European Parliament, 2021) is a concept based on finding solutions for the sustainable and environmentally harmonious survival of humanity in the future and advocates the principles of »reduce, reuse, and recycle.« The circular economy concept minimizes the need for new resources, thereby helping to reduce environmental pressures. The essence of the circular economy concept is that all raw materials and processes are designed in such a way that no waste is generated. At Ekstera d.o.o., through in-house expertise and research on the development of circular economy, a process was implemented that goes a step beyond the basic principles of circular economy. We developed an integrated process in which (potential) waste, through a parallel process alongside regular production, immediately becomes a secondary raw material.

Stainless steel is a general term for a large group of iron alloys that are resistant to rust. Unlike other iron alloys, stainless steel has a stable passive film that protects it from air and moisture. Due to this rust resistance, stainless steels are a good choice for many applications, especially in environments with external (atmospheric) influences, water, or other liquids, in the food industry, and in processes involving high temperatures. Like all steels, stainless steel is based on a mixture of iron and carbon. What distinguishes this family of alloys from other steels is that stainless steel contains at least 10.5% chromium. This element gives stainless steel its characteristic resistance to oxidation. When stainless steel is exposed to the atmosphere, the chromium combines with oxygen to form a thin, stable passive film of chromium (III) oxide (Cr_2O_3). This passive film protects the inner steel from oxidation and quickly regenerates if the surface is scratched, dented, or otherwise damaged. This passive film differs from so-called coatings (such as chrome plating, galvanizing, etc.). When damage penetrates or breaches a coating, its protective properties are lost. However, the chromium within stainless steel provides more than just surface protection, as the passive film regenerates whenever it is exposed to air. Thus, even if the stainless steel is severely damaged, the passive film will self-repair (Reliance Foundry, 2024).

In our case, we focused primarily on austenitic steels that have a high content of both nickel and chromium. Austenitic stainless steels have a cubic (FCC) crystal structure and are composed of iron, carbon, chromium, and at least 8% nickel. Due to their high content of chromium and nickel, they are highly resistant to corrosion and non-magnetic. Because of the high nickel content, austenitic stainless steels also maintain good mechanical properties at low-temperature applications.

Stainless steels are primarily used where corrosion resistance is required. Their main alloying element is chromium (Cr). Other alloying elements, such as nickel (Ni) and molybdenum (Mo), are added to modify the structure, increase corrosion resistance, and enhance the strength of stainless steel. In all cases, however, it is necessary to add alloying elements to the base charge during production (whether the production takes place in foundries or steelworks), primarily ferrochrome (FeCr), and, for stainless austenitic steels, also nickel (usually in the form of cathodic nickel).

Ferrochrome (FeCr) is a type of ferroalloy, an alloy of iron and chromium, which typically contains 50 to 70 mass % chromium. Based on the chromium content in %, different types of ferrochrome are distinguished: FeCr suraffine (Cr min. 60%, C 0.03–0.10%), FeCr carbure (Cr min. 63%, C 6–8%), and FeCr PLASMA (Cr approx. 50%, C approx. 8%) (MSViscom, 2024). Nickel is typically used primarily in the form of refined cathodic nickel (containing 99.9% nickel).

In 2010, global production of chromite ore ($FeCr_2O_4$), the primary mineral obtained for the production of chromium, was 25 million tons. Ferrochrome production was approximately 7 million tons, while the production of metallic chromium was about 40,000 tons. Ferrochrome is produced exclusively in electric arc furnaces. During ferrochrome production, the temperature generated by the electric arc furnaces reaches 5070°F (2800°C), causing coal and coke to reduce the chromite ore through a carbothermic reaction. Once enough material has melted in the furnace, the molten metal is drained before being crushed and solidified into large ingots. According to statistics from the United States Geological Survey, the largest producers of chromite ore in 2009 were South Africa (33%), India (20%), and Kazakhstan (17%). The largest ferrochrome producers were Xstrata, Eurasian Natural Resources Corp. (Kazakhstan), Samancor (South Africa), and Hernic Ferrochrome (South Africa) (Bell, 2019).

Nickel is primarily obtained from nickel sulfides, which contain approximately 1% nickel content, and iron ores that contain about 4% nickel. Nickel ores are mined in 23 countries, and nickel is smelted in 25 countries. Due to the natural iron content, the final product of most smelters working with such ores is ferronickel, which steel manufacturers can use after removing impurities such as silicon, carbon, and phosphorus. Pure nickel (with a content of over 99.9%) is obtained through electrolysis.

By country, the largest producers of nickel in 2010 were Russia, Canada, Australia, and Indonesia. The largest producers of refined nickel were Norilsk Nickel, Vale S.A., and Jinchuan Group Ltd. Currently, only a small percentage of nickel is produced from recycled materials (Bell, 2019).

Alloying elements and alloys are strategic materials due to their relatively high prices, both in foundries and steelworks. Their production is often ecologically controversial, and they are also a major contributor to the carbon footprint, not only due to the production itself, but also because of the distance between the producing countries and Europe and the U.S. These regions, along with China, are the largest consumers of alloying elements, which also contributes to the carbon footprint due to transportation.

II.Recycling of Nickel Alloys into Ni 60 Briquettes and Their Use

2.1 Recycling of Nickel Alloys into Ni 60 Briquettes

As mentioned earlier, the recycling of nickel is very limited, and very little is reused. Through in-house development, the company Ekstera d.o.o. has brought the nickel alloy waste to a level where it can be directly used in metallurgical processes. The subject of the innovation is the briquette with the commercial name Ni 60, which has a known chemical composition (between 60% and 70% nickel content) and predominantly contains nickel and chromium. This briquette is produced in a side or parallel process (recycling, complete circular economy) within the company's production. The Ni 60 briquette replaces nickel alloys (cathode nickel) and chromium alloys (FeCr). It is significantly more cost-effective than the aforementioned alloys (with the same effect) and is also well soluble in the base melt due to its porosity, which leads to faster melt preparation and requires less energy. And, most importantly, the primary production of the alloy, from the residuals used to make the briquettes, is highly environmentally burdensome. However, when producing secondary material (i.e., in a circular economy), the environmental impact is reduced by more than 95%, as shown by the LCA analysis.

Since the abrasive material from which the briquettes are made is homogeneous, its chemical composition is constant (between 13 and 15% chromium, between 60 and 70% nickel, and between 4 and 5% molybdenum). Due to the known chemical composition (which always falls within the declared limits), loading into the base material (based on previous calculations – mass balance, required for melt preparation) is straightforward and accelerates the preparation of the charge, while also ensuring the proper chemical analysis of the melt during pre-casting control. Additionally, its mechanical properties are good, as despite its porosity, it does not break down into abrasive material, thus facilitating the filling (or charging) of the furnace.

In preparing the melt, two important factors are the melt preparation time (and consequently energy consumption) and the required final chemical analysis or composition of the melt, all of which affect the cost of the final product — the cast (be it product, semi-finished product, or finished product). The melt preparation for casting can be carried out in various furnaces (depending on the type of melt), but for the preparation of gray, nodular, and steel castings, the melt is mostly prepared in induction furnaces. The melt preparation process is as follows:

1. The furnace is loaded with a base charge (depending on the required melt, primarily sheet metal of various grades — based on the required final melt composition), with circulating material, and with alloys — to closely match the desired chemical composition of the melt before casting.
2. The base charge is melted.
3. A sample is taken for analysis — to check the suitability of the chemical composition.
4. If the chemical composition is suitable, the melt is poured into molds. If the composition deviates from the required one, it is adjusted (with alloys) or diluted (with base material) as necessary. This can be repeated several times.

Due to the loss of time and energy (electricity) from repeatedly "adjusting" the melt, it is best to calculate and prepare the charge accurately when loading the furnace, which the Ni 60 briquette allows, just like the alloys.

Another important factor in melt preparation is the alloys, especially since they are relatively expensive (e.g., cathodic nickel – as a source of nickel, FeCr – as a source of chromium, FeMo – as a source of molybdenum, etc.), and, of course, all are imported. In highly alloyed castings, the consumption of alloys is high, which consequently increases the costs of melt preparation, thus impacting the final price of the casting (product).

With our innovation, the Ni 60 briquettes, we have positively impacted both key factors: the time required for melt preparation and the reduction in melt costs. Due to the consistent chemical composition of the briquettes and their structure (which allows for very good dissolution of the briquettes), the melt preparation time has been shortened. With proper preparation of the charge (if the charge content is correctly calculated), both time and energy are saved, as there is no need to repeat, add, or "dilute" the melt. At the same time, the cost of the charge has been reduced with the briquettes, as they are a much cheaper and effective substitute for standard casting alloys, serving as a source of nickel.

Through its own development, primarily through testing over a year and a half since the beginning of briquetting residues, the company has arrived at a final product: briquettes made from residues of nickel alloys, which are directly usable as raw materials or alloying elements in steelworks or foundries. It is important to note that, until now, residues from nickel alloys were classified as hazardous waste, and the costs associated with handling and disposal by authorized waste collectors were very high. By developing our own briquetting technology and correctly legally defining the production process (thus avoiding the need to obtain a new environmental permit), the company has simultaneously resolved several issues (Naglič, Šumah, Šumah et al., 2021).

In practice, it has been shown that the molten metal (liquid steel) in qualities containing a high percentage of nickel and chrome, when alloyed with briquettes, is significantly cheaper than molten metal alloyed with conventional alloys (cathodic nickel and ferrochrome). A test was conducted for the preparation of molten metal for two types of high-alloy steels, and savings ranged from 9% to 16%. When preparing molten metal, the key factors are the time required for melting (and thus the energy consumption) and the required final analysis or composition of the molten metal, as all of these influence the final price of the finished product – the casting (product, semi-finished product, or finished product). With the Ni 60 product, it was possible to replace conventional alloys (which are significantly more expensive) with Ni 60 briquettes, which, through practical testing, showed excellent results in reducing both the cost of the charge (and consequently the cost of the molten metal, and ultimately the casting) and the same or even shorter melting time, thus saving energy. Additionally, it should be emphasized that the carbon footprint was significantly reduced through production or recycling compared to primary cathodic nickel production (and the reduction in the carbon footprint did not even take into account the reduction compared to the primary production of ferrochrome).

2.2 Ni 60 as a Substitute for Cathodic Nickel and Ferrochrome

In practice, it has been shown that the molten metal (liquid steel) in grades containing a high percentage of nickel and chromium, when alloyed with the briquette, is significantly cheaper than molten metal alloyed with conventional alloys (cathodic nickel and ferrochrome). Tests with steels in grades W.Nr.: 1.4581 and W.Nr.: 1.4408 have shown that the final cost of the molten metal (liquid steel) alloyed with Ni 60 is more cost-effective than the molten metal produced with conventional alloys.

Example of molten metal W.Nr.: 1.4581:

The cost of the charge for preparing the molten metal with Ni 60 briquette alloying is €1.763 per kg, while the cost with conventional alloying is €1.866 per kg, which means a savings of 9.5% per kg of molten metal.

Example of molten metal W.Nr.: 1.4408:

The cost of the charge for preparing the molten metal with Ni 60 briquette alloying is €2.070 per kg, while the cost with conventional alloying is €2.472 per kg, which means a savings of 16.2% per kg of molten metal.

The melting time (and consequently the energy consumption) is the same or shorter compared to conventional alloying.

III. Discussion

In addition to the innovativeness of our briquettes made from nickel alloy scrap, namely the Ni 60 briquette, which allows for significant savings in molten metal production, it is also worth noting the reduction in carbon footprint. The use of Ni 60 briquettes, due to the recycling system, significantly lowers the carbon footprint compared to the nickel alloys used in the melting and alloying of the base molten metal, while also reducing the cost of the molten metal. The Ni 60 briquettes also reduce the consumption of chromium alloys (FeCr or ferrosilicon chromium), although this was not included in the carbon footprint reduction calculation.

At the same time, the Ni 60 briquette is a very attractive product on the market due to its price and properties, as it is cost-effective (compared to traditional alloys), and its mechanical properties are also excellent.

The use of Ni 60 briquettes is associated with the use of stainless steels and corrosion-resistant steels containing nickel, chromium, and molybdenum as alloying elements. The development of steel metallurgy has taken different directions in various countries, especially after the 2009 economic crisis, when ferrous metallurgy (particularly steelmaking) experienced significant reductions in production capacity. The production volume that remained must be supported by new products and technologies to enable further development. This includes Ni 60 briquettes, which have already proven themselves well in practice.

To date, tests with Ni 60 briquettes have been conducted at the Croning Livarna d.o.o. foundry, where they are very satisfied with the product, as they produce a large number of castings from alloyed steels containing a high percentage of nickel and chromium. By using Ni 60 briquettes, they have reduced costs and increased their competitiveness.

Ni 60 briquettes are suitable for all foundries that produce various qualities of alloyed castings with a high nickel and chromium content. In Slovenia, besides Croning Livarna d.o.o., there are several others, such as OMCO Metals d.o.o. in Žalec or Kovis d.o.o. in Štore. However, these are foundries for gray, nodular, or other types of cast iron (not steel castings), so our briquettes are only relevant in smaller quantities here. Moreover, Ni 60 briquettes are also commercially attractive for the broader European market.

For the purposes of savings or reducing the carbon footprint in production, we have taken as a reference a study and calculations based on the following research. The most referenced study is the *Report on the Environmental Benefits of Recycling* (Grimes et al., 2008), which provides a detailed description of nickel production from sulfide and laterite ores, and ultimately offers a fairly accurate carbon footprint associated with the production of one ton of nickel. The study was conducted for the Bureau of International Recycling (BIR), a recognized international bureau in the field of recycling, and therefore the results of this research can be considered highly credible.

Another such study, which demonstrates the success of savings or reduction of carbon footprint due to the introduction of a circular economy at Ekstera d.o.o., is the study *Analysis of the Potential for Negative CO2 Emission Mine Sites through Bacteria-mediated Carbon Mineralisation: Evidence from Australia* (Siegrist et al., 2017). However, this study is unfortunately limited to Australia, one of the largest nickel producers in the world. It does not account for the large transportation distance from Australia, so it is only useful for comparison.

Additionally, the recycling and reuse of scrap from nickel alloys is also crucial for significantly reducing the carbon footprint.

Our calculations showed a high percentage of savings or reduction in carbon footprint (which was also confirmed by the LCA analysis, which took into account significantly more factors than we did in our calculations).

The carbon footprint of primary nickel production is 2.12 t CO2/t Ni (Grimes et al., 2008).
In our case, namely with the introduction of circular economy and a unified process in production, the carbon footprint is calculated based on the following assumptions (5):

- The total power of the electric motors driving the machines in production is 10 kW.
- Approximately 80 kg of nickel briquettes with a content of 65% Ni produced per hour.
- For one ton of nickel, 19.23 working hours are required.

19.23 h × 10 kW = 192.3 kWh.

- 1 kWh of electricity consumed, according to the standard for Slovenia, results in 0.335 kg CO2e/kWh.
- Therefore, the carbon footprint per ton of briquettes produced will be: 193 kWh x 0.335 kg CO2e/kWh, which amounts to 64 kg CO2 or 0.064 t CO2/t Ni.

The reduction in carbon footprint is 2.05 t CO2/t Ni, or 93%, due to the nickel production process, specifically the recycling process, even before the melting and preparation of the melt, when comparing the use of Ni 60 briquettes for basic melt alloying instead of conventional nickel alloys (cathode nickel).
Our findings were confirmed by the LCA study (Čož and Brgant, 2023), conducted by an independent institution, which showed that the input materials, the nickel alloys Inconel 713C and Inconel 713LC (made from primary raw materials), are environmentally highly burdensome (as indicated by all environmental indicators). The actual production or processing process of reusing primary material has only a minimal environmental impact (mostly less than 5% influence on environmental indicators) compared to the production of the base material of the superalloy Inconel 713C and 713LC (which contains more than 65% nickel). Such a result was also expected due to the energy-intensive processes of mining, metal extraction, alloy production, and the transportation of materials from countries rich in mineral resources.

IV. Conclusion

Circular economy (European Parliament, 2021) is a concept based on finding solutions for the sustainable and environmentally harmonious survival of humanity in the future and advocates the principles of »reduce, reuse, and recycle.« The circular economy concept minimizes the need for new resources, thereby helping to reduce environmental pressures. The essence of the circular economy concept is that all raw materials and processes are designed in such a way that no waste is generated.

Production of products or semi-finished goods directly impacts the stock of resources and raw materials, the environment, and the generation of waste, and indirectly affects human health. To ensure sustainable development of society, we must use our (still available) resources wisely. It has become clear that the existing economic growth model of »take-make-dispose,« which we relied on in the past, is no longer sustainable in the long term nor suitable for modern societies in a globalized world.

Our research and development were also aligned with the 2030 Agenda (UN, 2015), which was unanimously adopted by the United Nations summit in September 2015 (the Agenda 2030 connects the three dimensions of sustainable development: economic, social, and environmental, encompassing five key areas crucial for the advancement of humanity and the preservation of the environment, including 17 Sustainable Development Goals).

In fact, in our development and research, we have taken it a step further. With the commencement of production in one of the programs, we began developing an integrated process in which (potential) waste immediately becomes a secondary raw material through a parallel process (alongside regular production).

In this closed loop **»→design, development → production, processing → distribution →reuse, repair →collection → recycling → design, development →«** we have eliminated several stages, thus reducing the cycle by quite a few steps. Through design and development, we introduced a parallel recycling production process in the company, so that, alongside the final regular product, we also have secondary raw material at the output, suitable for sale to end-users. Research (and consequently development) has been focused on the reuse of scrap nickel alloys generated during production, which, if not further processed, would be treated as waste.

Thus, the innovative product, Briket Ni 60 briquette, has proven its practicality, allowing the company Ekstera d.o.o. to achieve a true circular economy, successfully reduce its carbon footprint, and, of course, introduce a product to the market that is attractive, mainly due to its cost-effectiveness, to many foundries.

References:

[1]. **Reliance Foundry (2024).** A Complete Guide to Stainless Steel: Stainless Steel Grades, Composition, Molecular Structure, Production, and Properties. Available at: https://www.reliance-foundry.com/blog/stainless-steel.
[2]. **MSViscom (2024).** Ferokrom – FeCr. Available at: https://www.ms-viscom.com/barvne-kovine-ferolegure-grodelj/ferolegure/ferokrom.
[3]. **Bell, T. (2019).** Metal Profile: Chromium. Available at: https://www.thoughtco.com/metal-profile-chromium-2340130.
[4]. **Bell, T. (2019).** Nickel Metal Profile. Available at: https://www.thoughtco.com/metal-profile-nickel-2340147.
[5]. **Čož, Ž. and Brgat, M. (2023).** LCA study of the product, Ni 60 alloy briquettes. Ljubljana, Linking map d.o.o.
[6]. **Naglič, Šumah, Šumah et al. (2021).** Nickel Alloy Powder Recycling and Carbon Footprint Reduction. IOSR Journal of Engineering (IOSRJEN), ISSN (e): 2250-3021, ISSN (p): 2278-8719 Vol. 11, Issue 4. April 2021, Series -I, PP 01-08.

[7]. **Grimes et al. (2008).** Report on the Environmental Benefits of Recycling, Imperial College London.
[8]. **European Parliament (2021).** Available at: https://www.europarl.europa.eu/news/sl/headlines/economy/20151201STO05603/krozno-gospodarstvo-definicija-pomen-in-prednosti.
[9]. **United Nations, Department of Economics and Social Affairs (2015).** Transforming Our World: The 2030 Agenda for Sustainable Development.
[10]. **Siegrist et al. (2017).** Analysis of the Potential for Negative CO2 Emission Mine Sites through Bacteria-mediated Carbon Mineralisation: Evidence from Australia. Elsevier.
[11]. **European Commission (2007).** COM (2007) 59: Communication from the Commission to the Council and the European Parliament on the Interpretative Communication on Waste and By-products.
[12]. **European Commission (2007).** REACH Legal Text. European Parliament and Council Regulation (EC) No 1907/2006 (Corrigendum 29 May 2007) e.g. Roska, V., Martincevic, I., Sesar, V. (2018, April 19-20). Accounting Education for Better Employment – Case study in Croatia [Conference presentation]. Economic and Social Development – 28th International Scientific Conference on Economic and Social Development, Paris. https://www.esd-conference.com/past-conferences.