IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 11, Issue 4, April 2021, ||Series -I|| PP 01-08

Nickel alloy powder recycling and carbon footprint reduction

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Received 24 March 2021; Accepted 07 April 2021

Abstract:
Background: In accordance with the circular economy principles (reduce, reuse and recycle), the company Ekstera d.o.o. started to develop a unified process with which it introduced two parallel work processes. In addition to the company's primary production activity, where "waste," which should be handed over to authorized waste collectors as hazardous waste is generated, parallel production was introduced. Using "waste," the company thus made raw material suitable for immediate use as input material for steelworks and foundries.
Methods: A bigger problem than the technical development of the final product (Nickel alloy powder briquettes), which lasted less than two years, proved to be the legal inclusion of this procedure due to strict and vague environmental regulations and conditions arising from them. Through experiments, we led the process of recycling Nickel alloy powder to the final technological solution (a machine capable of producing up to 80 kg of briquettes per hour fully automatically), and with the correct legal formulations, we managed to include the procedure into the framework of environmental regulations and conditions, without the additional new environmental permit.
Results: In the final phase, recycling (pelleting) also significantly reduced the CO_2 footprint and greatly contributed to reducing emissions in the environment.
Key Word: Nickel alloy, dust powder, recycling, carbon footprint reduction

I. INTRODUCTION

The circular economy (Europian Parliamen, 2021) is a concept based on finding solutions for humanity's sustainable living in the future and advocates the »reduce, reuse and recycle« principle. The circular economy concept makes it possible to minimize the need for new resources, thus reducing the pressure on the environment. The essence of the circular economy concept is that all raw materials and processes are designed so that no waste is produced.

The production of products or semi-finished products directly affects the stock of resources and raw materials, the environment and waste generation, and indirectly also human health. To ensure the sustainable development of society, we must use our (still available) resources prudently. It has become clear that the existing "take-do-discard" economic growth model we relied on in the past is no longer sustainable in the long run, nor is it suitable for modern societies in a globalized world.

Our research and development are thus in accordance with Agenda 2030 (UN, 2015), unanimously adopted by the United Nations Summit in September 2015 (Agenda 2030 combines three balanced dimensions of sustainable development: economic, social and environmental, and covers five areas crucial for human progress and environmental protection, including the 17 Sustainable Development Goals).

In fact, we went a step further in our development and research. Simultaneously with the start of production or rather in one of our programs, we began to develop a uniform process in which (potential) waste would, through a parallel process (with regular production), immediately become secondary raw material.

Accordingly, we have left out quite a few phases from this closed circle, thus reducing it by a few steps: »**→ planning, design → production, processing → distribution → reuse, repair → collection → recycling → planning, design →.**« By planning and designing during production, we implemented, in addition to the final regular product, also a secondary raw material suitable for sale to end-users. Research (and consequently development) was focused on the reuse of Nickel alloy powder generated during our production that would otherwise be treated as waste in the absence of appropriate further processing.

II. Nickel

Nickel is a silver-colored, high-gloss metal that is relatively hard, easy to work with, magnetic and conductive, and used in about 300,000 products. It is estimated that approximately 4.5 million tons of nickel-containing waste are recycled annually, covering almost 25% of global nickel demand. Although it is also found in small amounts as a trace element in the human body, nickel is, in its pure form, toxic to humans, and experts have observed allergic reactions when inhaled or in contact with the metal as well as carcinogenic action.

Nickel is mainly processed in the production of alloy steel and other rust-resistant alloys. Over two-thirds of nickel production goes through this area. Special nickel alloys are used in the construction of airplanes for the production of turbine blades or other critical engine components. Nickel is also used in coin making, as a substitute for silver, and in batteries. In addition to the automotive industry, the construction industry is an important consumer of various alloy steel types. It is precisely the construction boom in China that is taking care of the growing need. In large cities in China, tall skyscrapers are growing very fast for the construction of which, due to their special composition, steel alloys are essential. High nickel prices reinforce the trend towards lower nickel content in alloys as well as the development of nickel-free steel refining.

However, nickel is one of the metals of the future, as it will be increasingly used in the production of batteries or accumulators for cars and will, as such, be even more relevant. The main nickel deposits can be found in Canada, Russia, Australia and Cuba - about 40% of world nickel production is shipped to Europe, followed by Asia and America. Due to skyrocketing steel production in China, nickel consumption is rising sharply on an annual basis. One-fifth of world nickel production is recorded in China.

III. Method of calculating CO_2 reduction due to circular production

To save or reduce the CO_2 footprint in our (or because of our) circular production, we considered two surveys and their calculations as reference. The first research that is also the most referenced is the Report on the Environmental Benefits of Recycling (Griemes et al., 2008), which describes in detail the production of Nickel from sulphide and laterite ores, and finally gives a fairly accurate carbon footprint resulting from the production of one tonne of Nickel. The survey was conducted for the Bureau of Internal Recycling (BIR) as the reference international recycling office. The results of this survey can thus be considered credible.

Another such research, which shows the success of saving or reducing the CO_2 footprint due to the introduction of circular economy in our company, is also the research published in ScienceDirect: Analysis of the potential for negative CO_2 emission mine sites through bacteria-mediated carbon mineralization: Evidence from Australia (Siegrist et al., 2017). However, this research is limited to Australia, one of the world's largest nickel producers. So, if we add the CO_2 footprint created by transport due to the great distance between Australia and Europe or Slovenia to the CO_2 footprint produced during the production of a ton of nickel, the footprint grows even more. However, this research is limited to the production of nickel ore only and not to further production from it into pure nickel or any of the nickel commercial alloys (however, it illustrates how large a CO_2 footprint is created only by mining). Both studies are presented below.

In our case, we considered the power of all electric motors on devices and machines that will be used in the recycling of nickel powder or in processing into pellets to calculate the carbon footprint.

Primary and secondary nickel production

The International Nickel Research Group cites a primary production of 1.44 Mt of nickel in 2007. It is estimated that 0.35 M tonnes of nickel are recycled each year from 4.5 Mt of residues (Griemes et al., 2008).

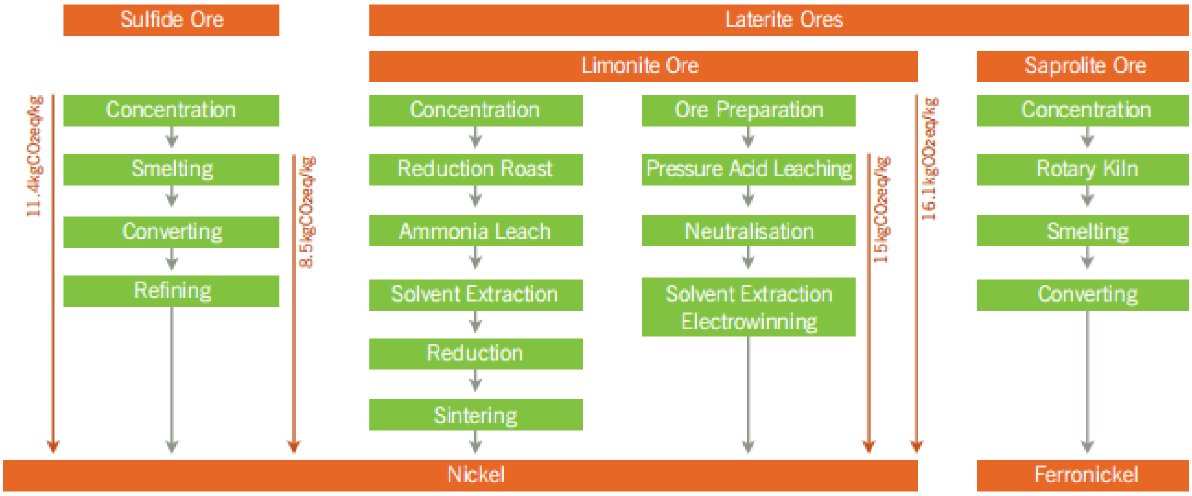
Primary production: There are two types of nickel ores that are processed in different ways. Common ores are nickel sulfides (containing about 2% Nickel), which are used through a pyrometallurgical process. Laterite oxide ores (Limonite and Sapronite ores containing about 1% Ni) are processed hydrometallurgically for the production of nickel-metal or pyrometallurgically for the production of ferronickel:

- The pyrometallurgical process involves the concentration of sulfide ores, followed by melting to obtain a concentrate, which is later converted to nickel metal and then refined. The final process of nickel refining is often carried out by electrolytic processes.
- Laterite ores with nickel concentrations higher than 1.7% (saprolite ores) are processed pyrometallurgically in rotary and electric furnaces to obtain ferronickel. Laterite ores with less than 1.5% nickel (limonite ores) are processed by hydrometallurgical separation, whereby the metal is produced electrolytically.

Secondary production: Nickel is recycled in various ways depending on the original use. Its alloys are often recycled as the same alloys, e.g., nickel in stainless steel. Approximately 40% of the nickel used in the production of stainless steel comes from production residues in the manufacture of stainless steel products. The remaining secondary nickel is mainly recycled from primary nickel melts.

The data on energy needs (consumption) and carbon footprint stated in the literature can be found in the following two figures. The data are expressed in gross energy requirements (GER) in MJ / kg and as carbon footprint in kg CO_2eq / kg Ni.

Table no 1: Carbon footprint table for nickel (Griesman et al., 2008)



Carbon footprint in nickel production

Norgat's (Norgat in Griesman et al., 2008) data for the entire life cycle (from nickel-containing sulfide ore mining to nickel recycling by melting and Sgerritt-Gordon refining for the recovery of 78% nickel and assumption of 35% energy efficiency) give GER equal to 114 MJ / kg and carbon footprint 11.4 kg CO2eq / kg Ni. The smelting and refining processes alone, as stated, require 2900 kWh / t of electricity, producing 8.5 kg of CO_2eq / kg Ni carbon footprint.

Thus, the data for the entire life cycle of 1% laterite ore (by recovering nickel by pressure acid leaching followed by solvent extraction and electrolysis to remove 92% nickel, assuming 35% energy efficiency) give a GER value of 194 MJ / kg and a value of carbon footprint 16.1 kg CO_2eq / kg Ni. Pressure leaching, solvent extraction and electrolysis as steps of the hydrometallurgical process require, as stated, 7651 kWh / t of electricity, resulting in a carbon footprint of 15 kg CO_2eq / kg Ni.

The study of the effect of ore concentration on GER and carbon footprint should show that lowering the ore level from 2.4% to 0.3% increases GER from 130 MJ / kg to 370 MJ / kg and carbon footprint from 18 kg CO_2eq / kg Ni to 85 kg CO_2eq / kg Ni.

For comparison, the following table shows the energy needs for the production of nickel-metal from primary mineral concentrate and secondary nickel material from residues and secondary sources.

Table no 2: Energy needs for 1kg Ni production and carbon footprint in 1t Ni production

Nickel Recovery Method	Energy Requirement (MJ/kg Ni)	Carbon Footprint (tCO_2/t Ni)
Primary Production of Nickel	20.64	2.12
Secondary Production from Scrap	1.86*	0.22**

*Theoretical minimum requirement to melt assuming furnace efficiency of 50%
**Based on melting recovery using UK average electricity emission factor to estimate CO_2 emissions

If the comparative data for primary and secondary production of nickel from the delivered mineral concentrate or from residues are taken into account, the energy needs for the production of 100 000 tonnes of nickel are:

- Energy needs for primary nickel production: 2064 TJ,
- Energy needs for secondary nickel smelting: 186 TJ

Considering the energy data, the carbon footprint for primary and secondary nickel production is on the same basis:

- Carbon footprint for primary nickel production: 2.12 t CO_2/ t Ni
- Energy needs for secondary nickel smelting: 0.22 t CO_2/ t Ni

Analysis of the potential of negative CO_2 emissions in nickel ore production - Australia (Siegrist et al., 2017)

Another such indicative indicator of how much CO_2 is produced in the production of a tonne of nickel ore is a study carried out by Siegris et al. (2017), who used Australia, one of the largest producers of Ni in the world, as the reference country.

Since September 2016, the Australian Mining Atlas has listed 129 mines (historical, operational, planned) and 207 nickel-containing deposits. Australia is one of the largest nickel producers in the world, with a production of 246 kt. It has about a quarter of the world's estimated economic nickel resources, which constituted 81 million tonnes in 2014.

Nickel can be found in two main types of ores: sulfide and laterite ores. Sulfide often includes copper and/or cobalt and sometimes precious metals such as gold, platinum or palladium (PGM). Laterite ores are formed or occur near the equator or in arid regions such as South Africa or Western Australia. In the past, most nickel production was from sulfide ores due to lower costs and less complex processing requirements compared to laterite ores. However, considering natural resources, about 60% of Ni reserves are found in laterite, while 40% are found in sulphide-containing ores.

The first element to determine the potential for CO_2 generation in this study was past nickel ore production in various mines across the country. Based on the data on nickel mines in Australia, key sites for the mines were selected. Data from these selected mines were enriched with publicly available information from expertly-reviewed literature and company reports. The second step included assessing the remaining ore from Australian nickel production (past and future).

While nickel production from sulphide ore mines accounted for the vast majority of past production, laterite ore mines have about twice as many reserves as sulfide ore mines. Therefore, their calculations predict that nickel from laterite ore mines will account for the majority of future Australian nickel production.

Table no 4: The option to generate CO_2 from potential nickel ore reserves (Siegris et al.)

	Past ore production	Total Reserves	Sequestration from past production	Sequestration from future production
	(Mt ore)	(Mt ore)	(Mt CO_2)	(Mt CO_2)
Selected sulfide and laterite nickel mines				
Nickel sulfide mines	336	1,210	111	421
Nickel laterite mines	36	1,992	12	492
Total selected mines	**372**	**3,202**	**123**	**913**
Remainder of Australia				
1967 – 2007 (Mudd)	243		82	
2008 – 2015 (OCE)	195		66	
Inferred Resources (IR)		3,560		
Total remainder of Australia	**438**	**3,560**	**148**	**987**
Sequestration (Mt CO_2)			**271**	**1,900**
Total sequestration (Mt CO_2)				**2,171**

The sulphide and laterite mines selected in their study included 23 mines, most of which are in Western Australia. This list represented some of the largest and most important nickel mines in Australia, which have relevant mineral and geological data available to assess the potentials of CO_2 release into the atmosphere. These mines produced 812 kt of nickel and about 372 Mt of ore. The selected mines' estimated reserves amounted to 23,316 kt of nickel, which means 3,202 Mt of nickel ore.

For this article's purpose, the concentration of nickel in the final data was assumed to be 0.5%, which is lower than in the previous production, as the concentration decreases over time.

The results are given in the table below. Based on them, the carbon footprint in the production and processing of one tonne of nickel ore was calculated. However, the calculation does not give a carbon footprint for further processing into nickel or any of its commercial alloys.

Thus, to illustrate, mining produces one tonne of nickel ore obtained (meaning concentrate), without further production into pure nickel or any of its commercial alloys 0.33 t CO_2.

IV. Development and research of nickel-alloy powder briquetting and environmental definition

Environmental definition of nickel alloy powder briquetting

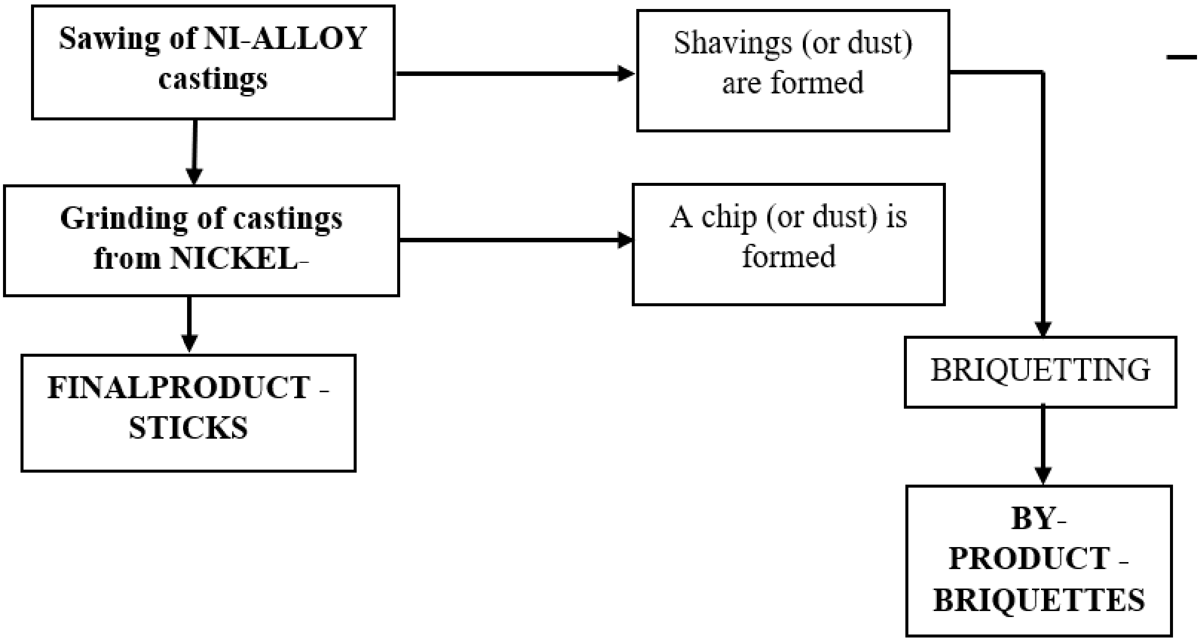
During the development and research of nickel-powder briquetting, we encountered not only technical but also legislative and environmental challenges. Thus, we had to set up and define the production method itself to meet the strict environmental standards. For this purpose, we decided on a uniform procedure that corresponded to the already obtained environmental permits.

For the briquetting of nickel - alloy powder, we defined that the dust is a by-product and not waste, which is explained below. When briquetting nickel - alloy powder, it is necessary to begin with three key issues:

- What is waste?
- What is a by-product?
- When does waste cease to be waste?

and from this on, which legislation applies:

- on waste
- on products
- REACH
- ??? (or something else)



Picture no 1: Uniform process - for the purpose of recycling Nickel-alloy powder (source: Own)

What makes our product a by-product and not waste

We had to define why the residue from the production is not waste but a by-product. We thus used the European Commission's Interpretation on Waste and By-Products (2007) and the REACH Regulation, i.e., the European Union regulation adopted to improve the protection of human health and the environment from the risks posed by chemicals.

1. The Communication from the European Commission to the Council and the European Parliament on the Interpretative Communication on waste and by-products (COM (2007) 59 finalized on 21 February 2007) states (European Commission, 2007):

Example: Chips and other similar material

In more general terms, excess material from the primary production process, or material that is deficient only in a cosmetic way but that is materially similar to the primary product, such as rubber compound and vulcanisation mix, cork shavings and pieces, plastic scrap, and similar material may be seen as by-products. For this to be the case, the material has to reusable either directly in the primary production process or in other integrated productions where reuse is also reliable. Materials of this type can thus be considered to fall outside the definition of waste.

2. Unnecessary additional registration or additional environmental permit

Article 2 (7) of REACH states that registration is not required for (European Commission, 2007):

(b) substances listed in Annex V (…substances present in nature, provided they are not chemically modified: minerals, ores, ore concentrates, etc.)

(d) substances, on their own, in preparations or in products, which have been registered in accordance with Title II and which are processed in the Union if:
(i) the substance that results from the processing is the same as the substance that has been registered in accordance with Title II; and
(ii) the processing plant has access to the information required in accordance with Article 31 or 32 in relation to a substance registered in accordance with Title II.

Our answers to basic legal dilemmas:

- Nickel alloy dust is the residue of production (by-product or waste)
- Further use of the residue is ensured:
    - The holder does not have sales contracts (because nickel is a raw material, the price of which varies significantly on the stock exchange, and long-term fixed-price contracts do not make economic sense), the demand for raw materials such as nickel is constant or even increasing.
    - A long-term market is guaranteed (Ni as an alloying element and in the field of superalloys).
    - The residue of the production is fully usable in the form of briquettes.
    - The base has not been stored for more than three years.
- As the residue of the production, it can be used without any further processing, only by compressing (briquetting as a typical industrial process).
- The residue of the production is created as an integral part of the production process.
- The residue of the production meets the requirements set for the use of such a substance or object that regulate products, VO, and human health protection, and its continued use will not have a detrimental effect on the environment.
- In accordance with the Communication from the Commission to the Council and the European Parliament: Interpretation on waste and by-products (COM (2007) 59 final of 21 February 2007).
- In accordance with Article 2 (7) of REACH, point (d), which states that registration is not required.

Procedure according to the scheme for deciding whether or not a material is waste:

1. Is the intended use of the material legally justified?
   - YES. The intended use of the material is legally justified!
2. Was the process adapted for the production of the material?
   - NO. The process was not adapted for the production of the material!
3. Is the use of the material reliable?
   - YES. The use of the material is reliable!
4. Is the material ready for use without further processing?
   - YES. The material is ready for use without further processing!
5. Is the material produced as an integral part of the production process?
   - YES. The material is produced as an integral part of the production process!

According to the decision scheme, our material is a non-waste by-product!

With this procedure, i.e., with parallel production, we have solved the legal-formal dilemma of whether our production creates waste or a by-product.

Briquetting process

Briquetting: Briquetting is the compression of material under high pressure, and the result is that the material adheres to a predetermined shape (briquette) without additional bonding elements. The purpose of briquetting is to reduce the volume of waste and residues, facilitate the manipulation of the material, change the purpose of the material and create added value of waste or residues.

A year and a half after the beginning of powder briquetting, our own development, mainly through tests, resulted in the final product - powder pellets from Ni-alloys, which are directly useful as raw material or alloying elements in steelworks or steelworks.

Tests of different briquetting parameters

We decided on the briquetting process because a rather fine powder of Ni-alloys was formed during our production process, which, without further processing, would have been treated as waste. In one year of various tests, we found that the powder can be properly compressed into briquettes, and the relevant parameters that can be used in nickel briquetting were identified.

After comparing different test results, we found that the optimal parameters are:

• The recommended cross-section of the briquettes is 30 mm.
• Bulk height 100 mm.
• The compressibility of the powder is 60 - 55%.

• The required force is 30 - 35 N / mm2.
• The obtained density of nickel briquettes is approx. 4 kg / dm3, which corresponds to approx. 45% density of pure nickel. However, because there are other metals and oxides in the NI powder, the actual density is over 50% of the base alloy, which is an excellent result!

Picture no 2: Briquettes - made from Ni-alloy powder

V. Reducing the carbon footprint

It is also important that we have greatly reduced our carbon footprint when recycling and reusing Ni-alloy powder.

Calculation of savings or reduction of CO_2 footprint

The carbon footprint for primary nickel production is 2.12 t CO2 / t Ni (Griemes et al., 2008). In our case, i.e., with the introduction of the circular economy and the uniform process in production, the carbon footprint is calculated according to the following assumptions:

- The total power of the electric motors that will drive the machines in production is 8.5 kW.
- Approximately 80 kg of Nickel briquettes will be produced per hour.

It will therefore take 12.5 working hours per tonne.
12.5 x X 8.5 kW = 106.5 kWh
1 kWh of electricity consumed according to the standard for Slovenia causes 0.335 kgCO_2 e / kWh.
The carbon footprint per tonne of briquettes produced will thus be:
106.5 kWh X 0.335[1] kgCO_2 e / kWh which amounts to 35.6 kg CO_2 or 0.0356 t CO_2/ t Nickel.
However, since there is between 72% and 78% of nickel in the powder, the carbon footprint increases accordingly and, in our case, amounts to:
0.0356 t CO2 / 0.72 = 0.0495 t CO_2 / t Ni
Thus, the reduction in nickel production due to the circular economy, uniform process and recycling is actually **2.07 t CO_2** or **97%.**

VI. Conclusion

According to the planned production of briquettes from Ni-alloy powder, which should be approx. 2 t / month, the company will, with the introduction of a complete circular economy (uniform process, recycling) in production, reduce the carbon footprint on an annual basis by approx. 49.5 tons of CO_2. At full occupancy of our capacities (if all our machines were working full time in two shifts), which of course depends on the orders, our production of Ni briquettes would increase to approx. 50 tonnes per year, which means that the reduction in carbon footprint would double. Thus, thanks to our innovative production method, the global carbon footprint would be reduced by almost 100 tons of CO_2.

[1] The factor that applies to Slovenia, 1kWh, has an average carbon footprint of 0.335 kg of CO2 in Slovenia

Picture no 3: Packaging of Ni-briquettes ready for transport

However, transport is not included in this reduction (which is very important as it causes a considerable carbon footprint). The world's largest producers of Ni are Russia, Australia and Canada, followed by the Asian countries and the USA, i.e., countries that are very far from us. We will sell our product locally (the market in Slovenia is very interesting due to a large number of foundries and steel mills. However, the quantities we will produce annually are only a small part of the total need for Ni in Slovenia) and also (locally / globally) greatly reduce the CO_2 footprint of transport.

Another environmental aspect (except for the CO_2 footprint), which is by no means negligible, is the use of Nickel dust in a uniform process; before we started the intensive development of recycling (briquetting) of this dust, it was disposed of as waste. Our development of the prototype took more than two years (since we took over the production independently; this used to be done by another contractor, and in the meantime, the legislation has tightened), and we successfully completed it, which is confirmed by more than two tons of briquettes produced. By introducing a uniform process and recycling, we have also reduced the burden on the environment.

Thus, in addition to reducing the CO_2 footprint, our production, in the spirit of the circular economy, reduces the other side of the burden on the environment, and from an environmental point of view, the investment in machinery is justified.

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