La Metallurgia Italiana
International Journal of the Italian Association for Metallurgy

Advances in grinding sludge valorisation and recovery in the manufacturing industries

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Sludge generation worldwide yearly amounts to about 12 million tons. One of the hazardous waste products generated during iron and steel manufacturing is sludge. The industrialization of developing countries and the manufacturing of steel are expected to drive these figures even further upward. Sludge and slag waste management is challenging due to its value, unpredictability, and huge quantities produced at different sites. Another problem is the current frequent practice of landfilling. Since steel sludge is essentially constituted of iron, this study aims to investigate scalable, practical recycling methods currently used in present industrial processes. Among the methods to manage large volumes of sludge and provide immediate use are mechanical treatments, powder metallurgical, hydrometallurgical, and creative techniques. This review paper on sludge grinding in the bearing industry emphasizes the possibilities of bearing and transmission steel technology to turn low-value waste into valuable resources. It provides reasonably priced, ecologically acceptable approaches for industrially recycling metal waste. These processes not only promote industrial sustainability goals but also reduce environmental hazards for resource recovery by leveraging transmission steel technology, thereby providing a feasible road forward.

KEYWORDS: SLUDGE GENERATION, STEEL PRODUCTION, RECYCLING METHODS, MECHANICAL TREATMENTS, POWDER METALLURGY, HYDROMETALLURGY, BEARING INDUSTRY;

INTRODUCTION

Advancements in manufacturing processes and the current situation are undoubtedly worthy of recognition. Its idea and philosophy changed from the Stone Age, when the first weapon was most likely developed to kill animals. Later on, the production processes evolved through many phases, adding and using more modern ideas and technological advances; therefore, we are about to enter Industry 4.0. The first industrial revolution came with the creation of steam-powered machinery in the 18th century; since then, it has been always changing. Further, the core of Industry 3.0 is the mass production and usage of conveyor belts, which brought Industry 2.0 and the development of computers and electronic systems. This is the backbone of automation. Industry 4.0 originated with the introduction of a cyber-physical system like information and communication technologies and robots to give greater flexibility, adaptability, and improved production system productivity [1-4].

Industry 5.0 uses a human-cyber-physical environment to probably reinterpret people as the core of operations. Two insightful thoughts stand out in this context. One

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of them may be regarded as the duration between the industrial revolutions is much shorter, reflecting the fast contemporary technical development. The second observation relates to technical developments spanning the second to the fourth industrial revolution. These historical patterns indicate that during the next ten to twenty years the fifth industrial revolution will center on the mix of human, computer, and physical systems [5-8]. Figure 1 shows clearly the industrial revolutions with their different themes.

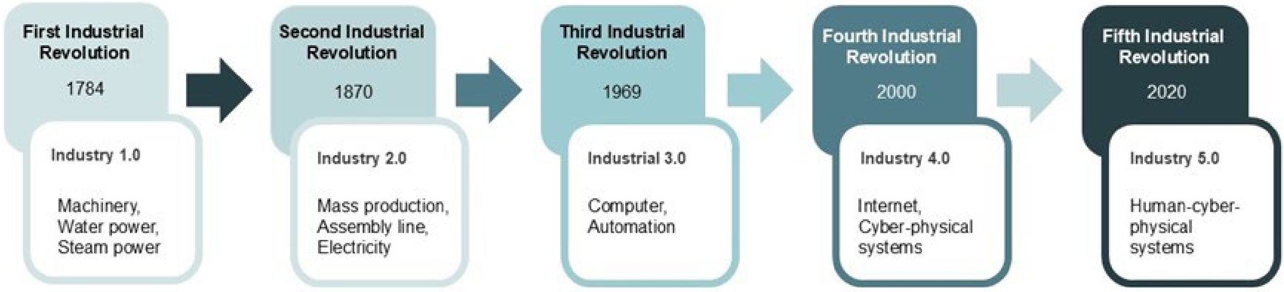

Fig.1 - Development of the revolutions in industry.

In past years, manufacturing was seen as turning raw resources into valued items to satisfy human needs. As life develops in many spheres, the rising need for sophisticated and advanced technologies to produce premium goods has grown as well [9-13]. As Figure 2 shows, industrial technology may be divided into four primary divisions in the current period [14-17].

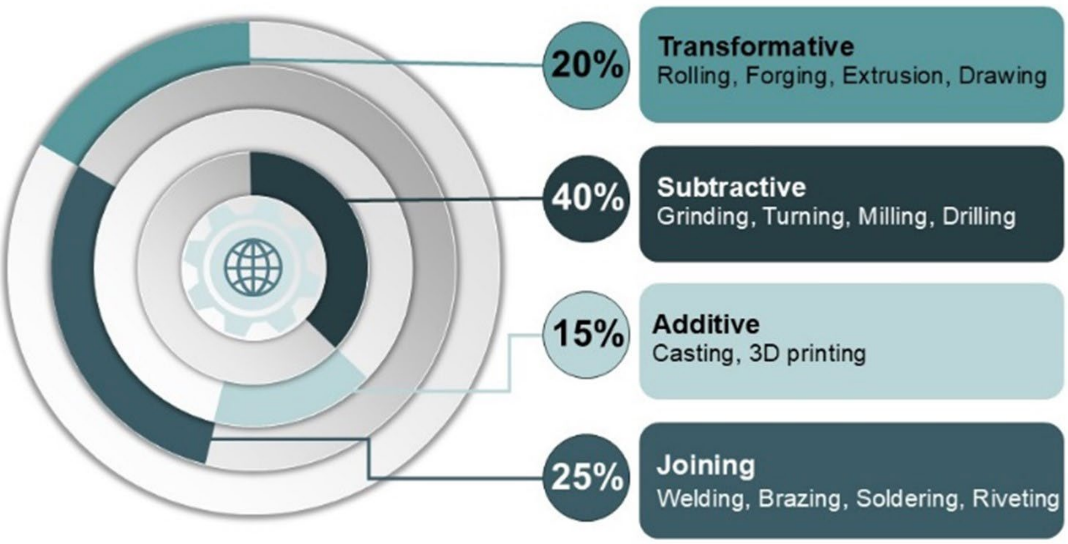

Fig.2 - Worldwide application and categorization of industrial technology.

Among the previously listed manufacturing categories, subtractive and transforming classes are used frequently in manufacturing. The main difficulty for the manufacturing sector is industrial competitive pricing as much waste sludge is involved in these operations. One of the usually utilized techniques for giving the components their final form and size is grinding. Steel sludge disposal greatly influences grinding bearings in the steel sector. Until 2035 in this field, the worldwide demand for steel and thus the quantity of produced trash is predicted to keep increasing [18].

The majority of sludge ends up in landfills, which is hazardous to the environment. With over 3% oil in the sludge, it should be disposed of in specific landfills costing more than 1200 € per ton [19]. Thus, sludge and waste material recovery not only promote environmental sustainability but also helps to save expenses. Developed following subtractive and transforming procedures for over a century, special recovery steel technologies have been widely documented and used in sectors [20-24]. The growing environmental rules and the need for sustainable waste management techniques have made sludge recovery a vital subject of study and development. Particularly in the metallurgical and manufacturing industries, the sludge produced from several industrial operations includes valuable elements that may be collected and used again [24, 25]. Figure 3 shows the most recent developments in sludge recovery techniques in industry, so this review article seeks to provide a summary of them.

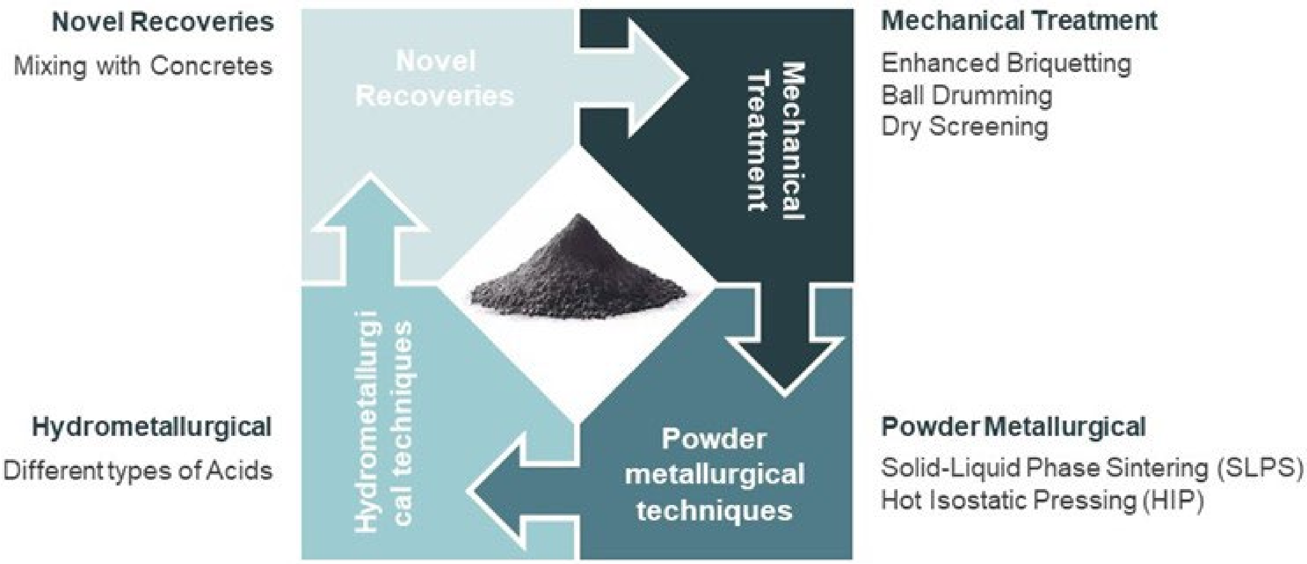

Fig.3 - Sludge recovery techniques used in industry.

Industry Straight-Forward Method Review

Sludge recycling is now a major component of industrial waste management as cost-effectiveness and sustainability for the environment define it. Particularly in the metallurgical and manufacturing industries, industrial operations produce large volumes of bearing steel sludge, a byproduct including precious metals. Sludge recovery, arranged from industrial and scholarly points of view, is the process by which waste products are turned into useful resources. From an industry standpoint, the focus is on scalable, pragmatic ideas easily applied to current procedures. Important techniques falling under this area consist:

- Mechanical Treatments
- Powder Metallurgical
- Hydrometallurgical
- Novel techniques

Mechanical Treatments

Mechanical treatment methods assist in recovering sludge by reducing moisture content, improving sludge properties, and preparing it suitable for future use or processing. These techniques increase sludge management's efficiency and efficacy by use of separate mechanical procedures. Enhanced briquetting, ball drumming, and dry screening are the major techniques used in this scheme. Every technique contains characteristics and variables that aid in maximizing sludge recovery in industrial-scale operations.

Mechanical Treatment –Enhanced Briquetting

Borowski et al [26] investigated an affordable approach to treat ball-bearing manufacturing metal waste. Their goals were to find appropriate binders, ascertain the physical-chemical characteristics of the waste product, and examine variables influencing briquette strength.

The technique called for pre-treated sludge with an initial humidity of 25% utilizing both stamp presses and roll presses. This test plan has as its variable's unit pressure, kind of briquetting machine, usage of molasses instead of non-bio additives, and briquette seasoning. Sludges' mechanical performance improves more if they are seasoned for around 120 hours. Molasses adds much to the sludge's stickiness. For producers of steel mills, achieving sludge moisture levels ranging from 4.5% to 6.5% was acceptable. Figure 4 shows the suggested method for an industrial operation on a large scale wherein the wastes are air-dried on a sludge-drying bed. Additionally shown in their research was the schematic of the process line with thermal waste drying.

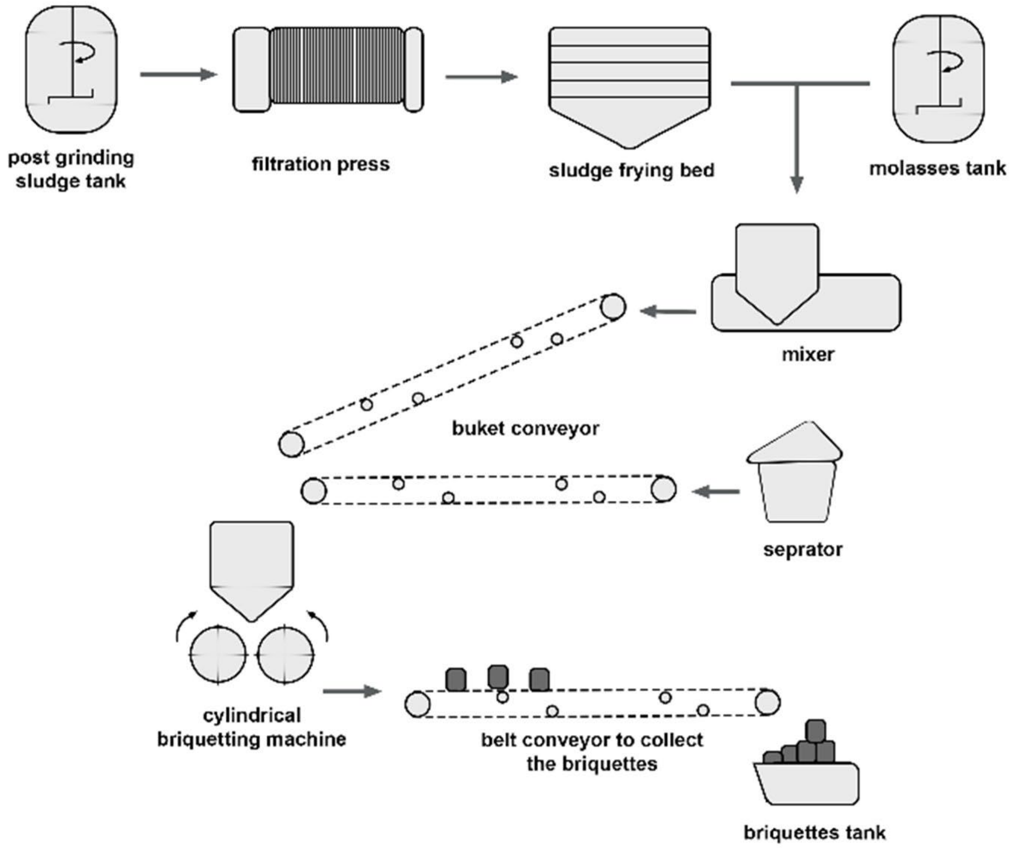

Fig.4 - The mechanical suggestion for the line of briquette-making [26].

According to the findings of the studies, the briquettes could be recycled in furnaces used in steel-making. Other garbage-related businesses can benefit as well from the apparently universal approach suggested to solve this kind of waste management issue. Additions made during the stage of the briquette consolidation operate, inter alia, as iron oxides reducing agents in steelmaking operations producing a decrease in slag foaming [26-28].

Using carbon-containing briquettes derived from stainless steel manufacturing waste, YANG et al. [29] examined smelt reduction in an electric arc furnace (EAF). Under a 3.5 kg load, laboratory simulations showed that briquettes resisted heating at 1,186°C without disintegrating and could be added to the melt without causing any splashing. Briquettes laden with slag formers provide high-carbon concentration zones for the best metal recovery. To maximize carbon reduction of metal oxides and achieve efficient recycling in EAF or induction furnaces, the research revealed that silicon concentration near briquettes should be decreased. Figure 5 provides the test setup for this study.

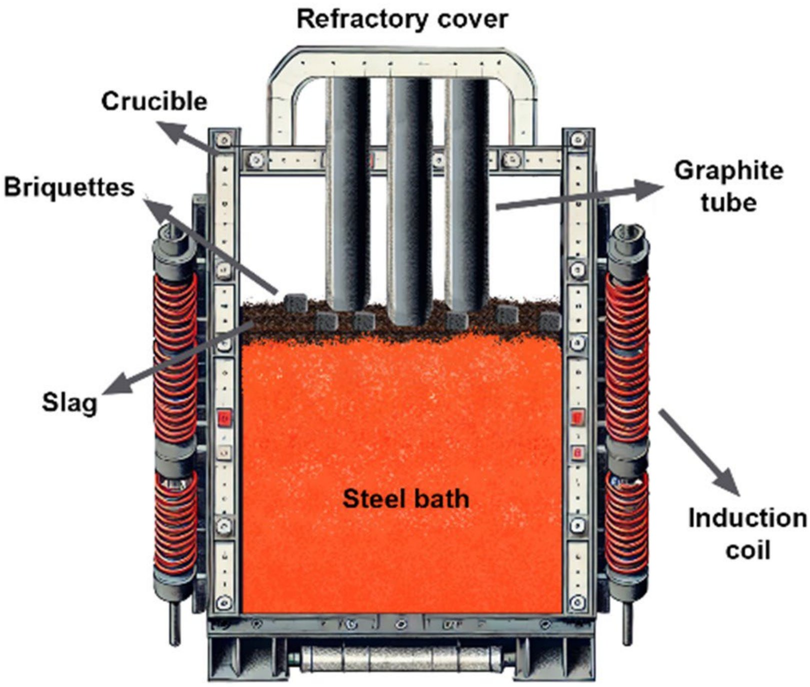

Fig.5 - Set up the examinations in an EAF [29].

Mechanical Treatment –Ball Drumming

Deng et al. [30] developed a novel rotating-drum drying technique using hot steel balls (FIG. 6). Waste heat of metallurgical slag heated steel balls. This test plan used Drummer Rotating Speed, Steel Ball Diameter, Sludge Mass, and Steel Ball Temperature as its variables. Under this approach, the sludge was dewatered in drums containing hot steel balls. This method reduced the water content by around 15%, therefore producing less than 5% of sludge.

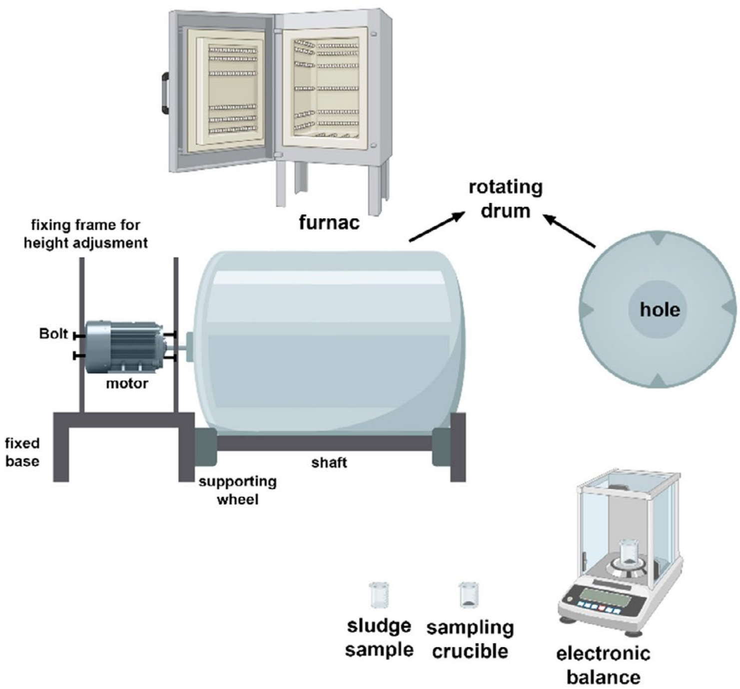

Fig.6 - Experimental setup of rotating drum [30].

The key element of this approach was to use sludge with 15% to 20% coolant. To get the necessary starting conditions, pre-processing methods like filter-press, briquetting, or dry-screening were thus combined. According to the results, this suggested technique is practical and effective. Reducing the sludge treatment mass, raising the steel ball temperature and diameter, and choosing a suitable drum rotating speed helped sludge drying to be better. Thus, this method tackles the limitations of conventional technologies by having cheap costs, great efficiency, and complete drying.

Mechanical Treatment – Dry Screening

Although there have not been any study studies on this technique, it seems that few businesses provide indirect low- and high-temperature dry screeners creating dried sludges with less than 5% coolant concentration. SHINCCI, a Chinese company, is one of these ones. A sophisticated technique for lowering sludge volume, stabilizing, sterilizing, and reusing sludge waste is the sludge dryer. The sludge drying process's overall layout is shown in Figure 7. Running effectively 24/7 with little control, the dryer lowers sludge moisture content from 80% to 10%, volume by 67%, and weight by 80%. Eliminating supplementary water treatment and lowering odor emissions are two advantages of this system. Figure 8 presents the sludge drying system's schematic mechanical concept [31]

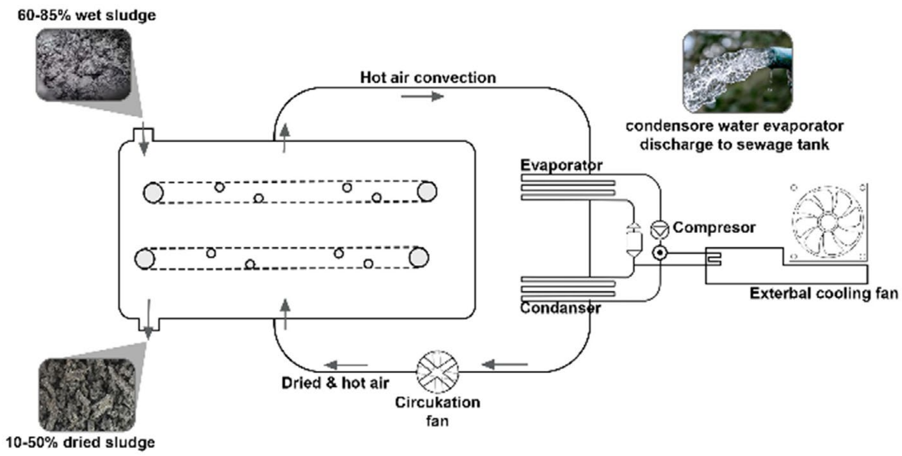

Fig.7 - The sludge dry screening process's schematic [31].

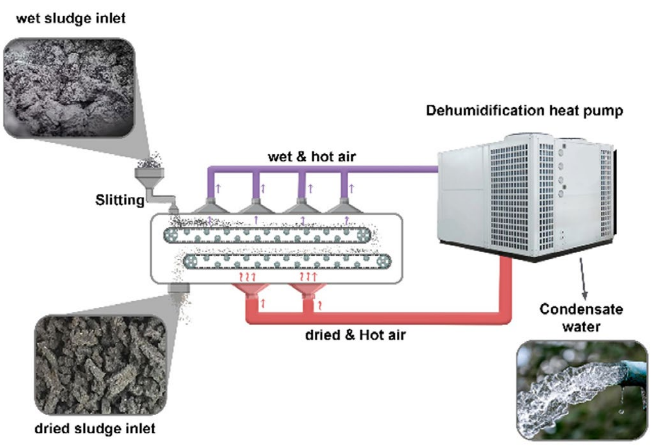

Fig.8 - The schematic idea behind the dry screening technique [31].

Tab.1 - he typical technical knowledge about SHINCCI company's supplied dry screener [31].

Dry screener technical specifications	
Structure	Assembled Set
Cooling Method	Water Cooling SL (Δt=12℃)
Refrigerant	R134a
Drying Temperature	48~56℃ (recycle air)/ 65~80℃ (supply air)
Control System	Touch screen + PLC programmable controller

POWDER METALLURGICAL TREATMENT

Powder Metallurgical (PM) Treatment includes creating metal samples from powdered metals by mixing, compacting, and heating them while regulating the volume and quality of the components, resulting in complicated geometries with minimum waste. Authors [32] suggested a sustainable PM technique using residual lubricant and abrasive particles as secondary raw material to recycle tool steel grinding sludge. Publications on recycling different materials, swarf, and scrap have been investigated stressing the efficiency, waste reduction, and quality improvement in manufacturing different metal components on the laboratory level [21, 23, 32-34].

Two main techniques relevant to recycling in the industrial setting are solid-liquid phase sintering (SLPS) and hot isostatic pressing (HIP). These techniques are fit for large-scale production operations as they provide dependable and effective ways to generate premium metal components from powdered materials.

POWDER METALLURGICAL TREATMENT – SLPS AND HIP

Hankel et al. [35] proposed a feasible recycling method for recovering metallic components of industrial sludge produced from cold work tool steel grinding. According to this approach, the completely dried sludge particles sinter in vacuumed sinters using the SLPS process. Grain sizes of powders offered a benefit relevant to PM technology. The criteria in this process were sintering temperature, pretreatment scenario for powder, and sintering time. At 129 ℃, a sintering temperature, a maximum density of 76 vol% was recorded. Reusing swarf as a precursor for SLPS has thus shown encouraging effects.

Jäger et al. [36] noted and published a methodology based on powder metallurgy called HIP. The authors focused on produced samples from HIP and SLPS. Unlike previous sintering techniques, the SLPS method required no pre-pressing of the powder to a green body and then sintering. Rather, sintering started right from the powder spill. Figure 9 shows the schematic sintering procedures of an SLPS system. The aim of the HIP approach was to evaluate the HIP process using sludge powder and a combination of 100Cr6 gas-atomized powders. Figure 10 shows the usual methods. The variables of this process were single powder and mixed powder, pre-pressing against non-pressing, sintering time, and sintering temperature. With 100 MP of pressure at 105℃, authors found up to 84% of low sample density using argon gas in 4 hours. Consequently, in this paper, the produced samples from SLPS and HIP revealed quite big pores and a low sample density (SLPS: 86.02% and HIP: 84.00%). With much lower pores of smaller size, the treated mixtures produced denser samples (SLPS: 98.00% and HIP: 98.00%).

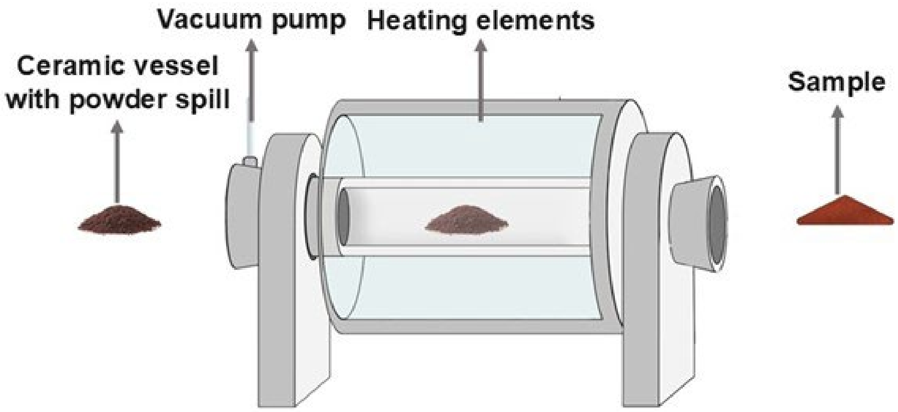

Fig.9 - A SLPS process's schematic approach [36].

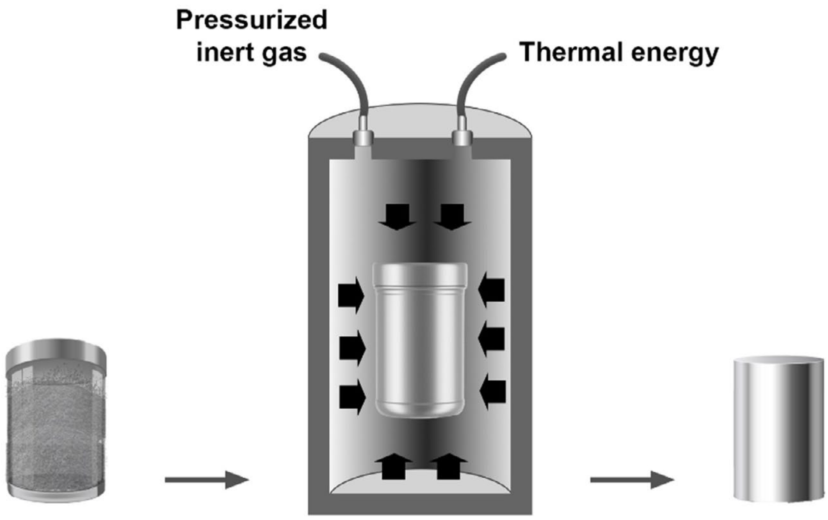

Fig.10 - The HIP process's schematic method [36].

Hydrometallurgy

Iron was extracted from the swarf via hydrometallurgy, which included leaching with hydrochloric acid and then precipitating and filtering the resulting iron chloride solution to remove metal impurities. Each stage of the process was planned and adjusted to discover simple but flexible solutions to make the recycling process economically viable and capable of dealing with changes in the grinding swarf [37].

Chen et al. [38] reported that for manufacturing sectors, large-scale equipment made of stainless steel has remarkable performance and durability. This approach studied hydrometallurgical techniques, including chemical precipitation, solvent extraction, and acid leaching. Alloys were extracted from the pre-treated sludge using several kinds of acids under varied process conditions and then by an extractor. Water was removed using a muffle furnace (LE 6/11, Naberthem, Lilienthal, Germany) for pretreatment oil; the residue was pulverized by a ball mill at 260 rpm for 24 h and sieved with a 100-mesh screen to enhance the leaching percentages of iron, nickel, and chromium. Different acids (HCL, H_2SO_4, HNO3), extractant pH value, extractant concentration, aqueous-organic ratio, and reaction time were the guidelines of this process. Figure 11 shows the whole process of the experiment.

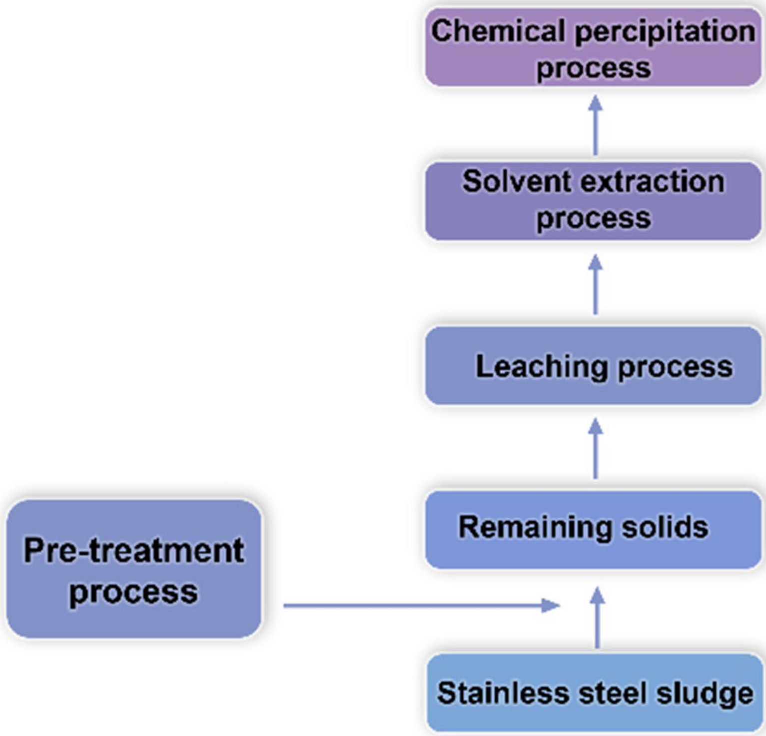

Fig.11 - The process of iron, nickel, and chromium recovery systems from stainless steel sludge [38].

After eight hours of calcination at 300 °C, the sludge was leached by 4 mol/L HCl. Of iron, nickel, and chromium, the leaching percentages were correspondingly 97.6%, 98.1%, and 95.7%. By means of 0.1 mol/L bis(2- ethylhexyl) phosphate (D2EHPA), Fe (III) was efficiently recovered in the two-stage solvent extraction method with an aqueous or organic ratio of 1 over 10 min at pH 1.5. Nickel's and chromium's recoveries at last were, respectively, 99.5% and 75%, thanks to chemical precipitation.

Novel Recoveries – Mixing with Concrete

A 2016 publication by Roslan et al. [39] basically reported the results of laboratory studies on the substitution of cement substitutes in concrete from electric arc furnace steel slag and steel sludge (byproducts from steel manufacturing companies). Their approach tested a combination of varying doses of completely dry sludge powder with cement. Flexural strength analysis, pozzolanic, thermogravity and mechanical properties assessment were measured in the study. This process included sludge dosage and cement dosage as its variables. Compressive strength increased when 15% and 20% steel sludge and steel slag were added correspondingly. Controlling the mix, especially at later curing ages, helped to provide stronger results.

Alwaeli [40] stated that replacing raw sand in a concrete building with scale and steel chip waste may be ecologically friendly. The impact of various percentages of these wastes on concrete characteristics like compressive strength and radiation attenuation was examined in this work. According to the findings, the concrete combined with steel chips increases its strength. In this research, the average utilization of 25% replacement came out to be. The results also underlined the possibilities for improving material qualities and fostering sustainability by means of industrial waste used in concrete manufacturing.

It was found that the approaches included in this review article effectively satisfied industry-scale demands and controlled environmental sustainability simultaneously. Sludge recycling has interesting future prospects and calls for thorough attention on enhancing and maximizing the given techniques as well as on finding fresh ideas. Table 2 lists the important books on sludge recovery methods in mass industrial production.

Tab.2 - The list of studies documenting many facets of industrial-scale sludge recovery

Citations	Components	Technique	Significant results
Borowski et al. [26]	Fine-grained grinding sludge	Briquette-making	Briquetting sludge to recycle ball bearing manufacturing metal waste.
YANG et al. [29]	stainless steel sludge	Briquette-making	Investigating effects of operating circumstances on metal recovery rates.
Deng et al. [30]	converter sludge	Ball drumming	Using a suggested rotating-drum-drying method helps to optimize operational parameters for drying.
Hankel et al. [35]	steel grinding sludge	SLPS	Showing excellent and creative reusing strategies.
Jäger et al. [36]	Metallic grinding swarf	SLPS and HIP	Concentrating on the swarf's performance characteristics and recycling path
Ottink et al. [37]	Steel swarf	Hydrochloric acid leaching	Obtaining abrasive and metal selective separation from cutting fluid.
Chen et al. [38]	Stainless steel sludge	Acid leaching	Developing a better recovery mechanism and maximizing the extraction effectiveness.
Roslan et al. [39]	Steel slag and sludge	As cement replacements.	Evaluating in concrete the performance of steel slag and steel sludge.
Alwaeli [40]	Steel chips	As a substitute for sand	Using scale and steel chip waste helps to improve concrete properties.

Research results draw a variety of knowledge. Some addressed articles derived from quantitative data, including sludge volume or extraction efficiency. These outcomes allow us to evaluate many approaches to recovery based on past studies. This information helps us to determine how to implement scholarly results in useful industrial environments, thus optimizing large-scale manufacturing. Table 3 contains the papers about the recovery of steel sludge from various recycling procedures using different waste sources.

Tab.3 - Metals recovered from stainless steel waste using various recycling procedures.

Citations	Components	Technique	Significant results
Zhang et al. [41]	Pickling sludge	Reduction and magnetic separation	Extraction efficiency: Fe 70.1%, Ni 60.3%, Cr 53.7%.
Liu et al. [42]	Stainless steel dust	Carbon-thermal reduction	Extraction efficiency: Fe 79.7%, Ni 83.6%, Cr 90.7%.
Wu et al. [43]	Pickling sludge	Direct reduction and magnetic separation	Extraction efficiency: Fe 95.3%, Ni 97.5%, Cr 88.7%.
Chen et al. [38]	Stainless steel sludge	Chemical precipitation	Extraction efficiency: Fe 99.9%, Ni 99.5%, Cr 75.1%.
Chen et al. [38]	Stainless steel sludge	Acid leaching	Extraction efficiency: Fe 97.6%, Ni 98.1%, Cr 95.7%.
Ottink et al. [37]	Steel swarf	Hydrochloric acid leaching	Leaching: 24.600 mg/l Fe, 150 mg/l Mn, 12 mg/l Ni and <1 mg/L Cr and Mo.
Jäger et al. [36]	Metallic swarf	SLPS and HIP	Densification: SLPS: 98.00 % and HIP: 98.00 %.
Hankel et al. [35]	Steel sludge	SLPS	Metal recovery: Up to 50 wt%.
Zhang et al. [41]	Pickling sludge	Reduction and magnetic separation	Extraction efficiency: Fe 70.1%, Ni 60.3%, Cr 53.7%.

CONCLUSIONS

In industrial uses, mechanical sludge treatment and recovery techniques include improved briquetting, ball drumming, and dry screening. Every technique has different advantages; thus, the level and type of their parameters in every method are computed to maximize sludge recovery. While ball drumming offers notable dewatering and dry screening, which shows promise for production, enhanced briquetting enhances sludge characteristics and adhesion; minimal academic study was noted in this situation.

By powder metallurgical treatment, steel grinding sludge may be recycled sustainably and effectively. Two exciting and high-potential treatments used in industrial sectors which recycle up to 85% of sludge are HIP and SLPS. Through the conversion of industrial sludge into useful raw materials, both attractive techniques improve the quality of the final sample.

Through acid leaching and solvent extraction, hydrometallurgy studies efficiently remove iron, nickel, and chromium from swarf and stainless-steel sludge. High recovery rates were found in hydrometallurgical techniques by optimizing parameters including acid type, concentration, and extraction conditions. These methods so show the performance of hydrometallurgical methods in manufacturing processes.

For building applications, one of the creative recovery methods combines slag and steel sludge with concrete producing positive results. In this example, the studies showed that adding 15–20% steel sludge and slag improves compressive strength, especially at later curing stages, supporting sustainability in this sector, and thereby emphasizing the possibilities of industrial waste sludge in concrete structures.

ACKNOWLEDGMENTS

This publication is also part of the project PNRR-NGEU which has received funding from the MUR-DM117/2023 for one of the writers (MD), [Project No: MUR DM 117/ Tsubaki Nakashima – Recovery, reuse and reduction of waste sludge in the production of balls and rolls for rolling bearings] (Nov. 2023- Oct. 2026), which is gratefully acknowledged.

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