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Solid state recycling of metal scrap for manufacturing net-shaped parts

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ABSTRACT

A comprehensive examination of the published literature details with compelling clarity the generation and re-use of metal scrap in the industries spanning manufacturing industries. Most of the metal scrap is often processed using smelting practices for the purpose of possible reuse. However, scrap in the form of chips along with finely divided metallic scrap is also getting increased attention as a potentially viable and economically affordable raw material for the purpose of obtaining usable parts or products directly after solid state recycling.

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1. Introduction

Metallic scrap is an indispensable component of raw material that has been used for manufacturing products at a competitive cost, thereby making it both affordable and economically viable. During the bygone days, metallic scraps, particularly the iron oxides (mill scale) and slag, were often recycled during secondary steelmaking. The particulate dust and sludge were often considered to be waste and usually used as a land-fill. However, environmental issues associated with both steel making and landfill are no longer acceptable based on prevailing industrial ecology norms.

Recycling strongly supports sustainability of the following: (i) reducing the amount of waste sent to landfills and incinerators, (ii) conserving the natural resources, (iii) increases economic security by tapping on a domestic source for the materials, (iv) prevents pollution by reducing and/or minimising the need to collect new raw materials, and (v) saves energy. Solid state recycling of metallic scrap has often been attempted to put to use metallic shop floor waste, and even sludge without much processing, i.e. without the need for re-melting and/or chemical processing [1–10].

2. Generation of metallic scrap

There are few to several varieties of waste that is often generated in processing units of manufacturing industries. The largest quantity of waste that is generated in the industrial plants is in the form of (i) chips, (ii) sludge, (iii) deposits, and even (iv) dust. Non-metallic waste often includes the following: (i) water, (ii) sludge constituents, (iii) hydrocarbons, and (iv) carbonaceous emissions. There are several preventive guidelines proposed and practiced with the key intent of minimising pollution made possible by an increased awareness of its role and contribution on environmental impact.

The strategies for waste reduction suggest three-phase control. These are the following:

(a) In the first phase, the hazardous waste is separated from trash. This is often followed by direct recycling without treatment.
(b) In the second phase, equipment and processes for an elimination of the waste are modified, and
(c) The third phase an effort is made to both study and concurrently address intrinsic wastes through a synergism of complex recycling and reuse activity [11,12].

Over the years, there have been several modifications, such as a change in raw materials and catalysts for curtailing the metallic waste. Yet, tons of metallic scrap (ferrous/non-ferrous) are generated. Details of scrap generation are briefly discussed in the following section and elegantly elaborated upon in the following sections [13–47].

2.1. Generation of ferrous metal scrap in the manufacturing industries

Raw materials in the form of ingots, slabs, rods, sheets are often made by metal casting, forming and finishing

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(machining) operations. Subsequently, they are used for the manufacturing of parts and assemblies. Waste is often generated in the industries of interest as follows:

2.1.1. Iron and steel making

The ferrous metal scrap that is generated during metal working, such as in the form of chips, rusted parts and damaged parts, sludge, and dust from mills, is consumed in a blast furnace, BOF (20–35% scrap), EAF (the major input material being scrap). The waste material that is generated in an iron and steel making plant, such as (i) flue dust, (ii) coke dust, (iii) mill scales, and (iv) iron oxide dust, are also recycled in a blast furnace through the use of sinters [13–16]. Although iron and steel production put(s) to use metallic scrap for the purpose of melting, this production route is intensive in terms of energy, material and human resources, and adverse impact on the ecosystem [17,18]. An overview of the major energy, emission and waste generation in iron and steel making is summarized in Table 1.

The challenges in recycling of the waste that is generated during steel making, such as sludge, dust, and scales, that remain are (i) cost savings, (ii) quality, (iii) productivity enhancement, (iv) energy, and (v) environmentally sustainable processing. There are several recent developments, which have been proposed to simplify continuous production processes in the smaller plants so as to ensure sustainability.

The basic operations in iron and steel processing are the following: (i) iron ore treatment, (ii) iron and steel making in a blast furnace/basic oxygen furnace, (iii) refinement of the molten steel, and (iv) casting and rolling. The iron ore is often processed in a series of steps starting with crushing of the iron ore. This is followed by reduction through a carbothermic reduction in a blast furnace. Finally, the molten steel is refined in a ladle, degassed in vacuum, followed by casting and rolling to get the desired end product. An overview of the metallic waste that is generated in the iron and steel industries is provided in Table 2 [19,20].

Table 2. Material wastage during iron and steel making steps.

Steps	Material Wastes and Forms
Sintering	Dust (particulates), sludge (solid)
Blast furnace	Dust (particulates), slag (solid)
BOF/EAF	Dust (particulates), slag (solid), sludge (solid)
Ladle Refining and vacuum degassing	Slag (solid)
Casting (Continuous/ingots)	Flashes (solid), sludge (solid)
Rolling	Mill scale (solid), sludge (solid)

2.1.2. The casting/foundry industry

The manufacturing process starts with melting of the ingot and scrap [secondary steel source]. The sources for metal waste in this industry are the following:

(a) Slag generated during melting/fluxing while melting in a hearth or crucible using Cupola or an Electric arc furnace or an Induction furnace.
(b) The risers, gates, and even flashes during casting
(c) Dust (a mixture of fine particles) that is generated during the casting operation.

The major metal waste, like (i) risers, (ii) gates, and (iii) flash, are often reused during melting. The slag is used in the construction industry as a useful constituent of cement subsequent to pulverisation. The dust is usually disposed off into the chosen landfill [21–24].

The foundries tend to discharge gaseous waste, such as (i) emissions of metals, (ii) semi-volatile, and (iii) volatile organic compounds, during melting. The metallic emissions from the foundries tend to vary with the furnace used. The core making and mould making processes generate a small amount of metallic waste. The metal waste that is generated during the pouring operation gradually increases with an increase in temperature of the molten metal. The solid-state waste largely contains a mixture of sand and slag, but it is the metallic waste during casting that contributes to significant quantities. The metal pieces that are generated during both cleaning and grinding are usually send to landfill [16,25].

Table 1. Energy, emission and waste generation in iron and steel making.

Step	Energy per Ton $\times 10^3$ kW	Emissions	Waste Generations
Sintering	0.45	Iron, sulphur oxide, carbonaceous, chlorides compounds	Dust/sludge
Blast Furnace	4.72 (gross) 3.54 (net)	Fe_xO_4, MgO, carbonaceous compounds	Slag, dust
BOF	0.26	Fe_xO_4, heavy metal fluorides	Slag, dust, sludge
EAF	1.52 – 1.64	Fe_xO_4, CaO	Slag, dust (oxides of Fe, Zn, Cr)
Refining and Casting	0.81 (ingots) 0.08 (continuous casting)	Dust containing iron and other oxides	Mill scale, sludge

Energetics, Inc., Energy and Environmental Profile of U.S. Iron and steel industry, DOE/EE − 0229, U.S. Department of Energy, Washington, DC, 2000.

2.1.3. The forging and forming industry

In the forging specific industries, sequential operations on the parts often creates a different kind of material waste. A genesis of the metallic waste in a forging shop is shown in Figure 1 The raw material for forging can be ferrous, nonferrous or have different alloying components, which does exert an influence on both the quantity and type of waste that is generated. In hot forging, the major wastage is often generated in the form of oxide scales with exhaust gases and waste liquids, which are also formed during the cold forging operation. The flash due to forging is often removed by trimming. The finishing operation essentially consists of (i) shot blasting, (ii) machining, and (iii) grinding, during which process the shot particles, chips and grinding sludge are generated [27–30].

The forging scale is a product of oxidation of the metal during the hot forging operation. It is not produced during the cold forging operation. The rate of formation and quantity of oxide scale often depends upon the following:

(a) Operating temperature of the hot forgings,
(b) Size of components,
(c) Type of hot forging process, and
(d) Surface area in contact with ambient air.

It contains about 70 percent total iron in both the metallic form and oxide form [30,31].

The forged parts are often shot blasted to both descale and remove the oxide(s) from the surfaces of the workpiece. Both flash and chips are often produced during the trimming process. For delicate and high-precision forgings, the flash can be ground or trimmed using different methods. During machining, the chips are produced. Metallic content in the chips is highest among all forms of waste in the forging industry. The metallic content decreases should the chips get oxidised due on account of excessive heating [32].

Grinding sludge and swarf is the product of cutting and conditioning operations subsequent to the machining process. The grinding sludge often comprises of microscopic grindings and grinding media (i.e. non-

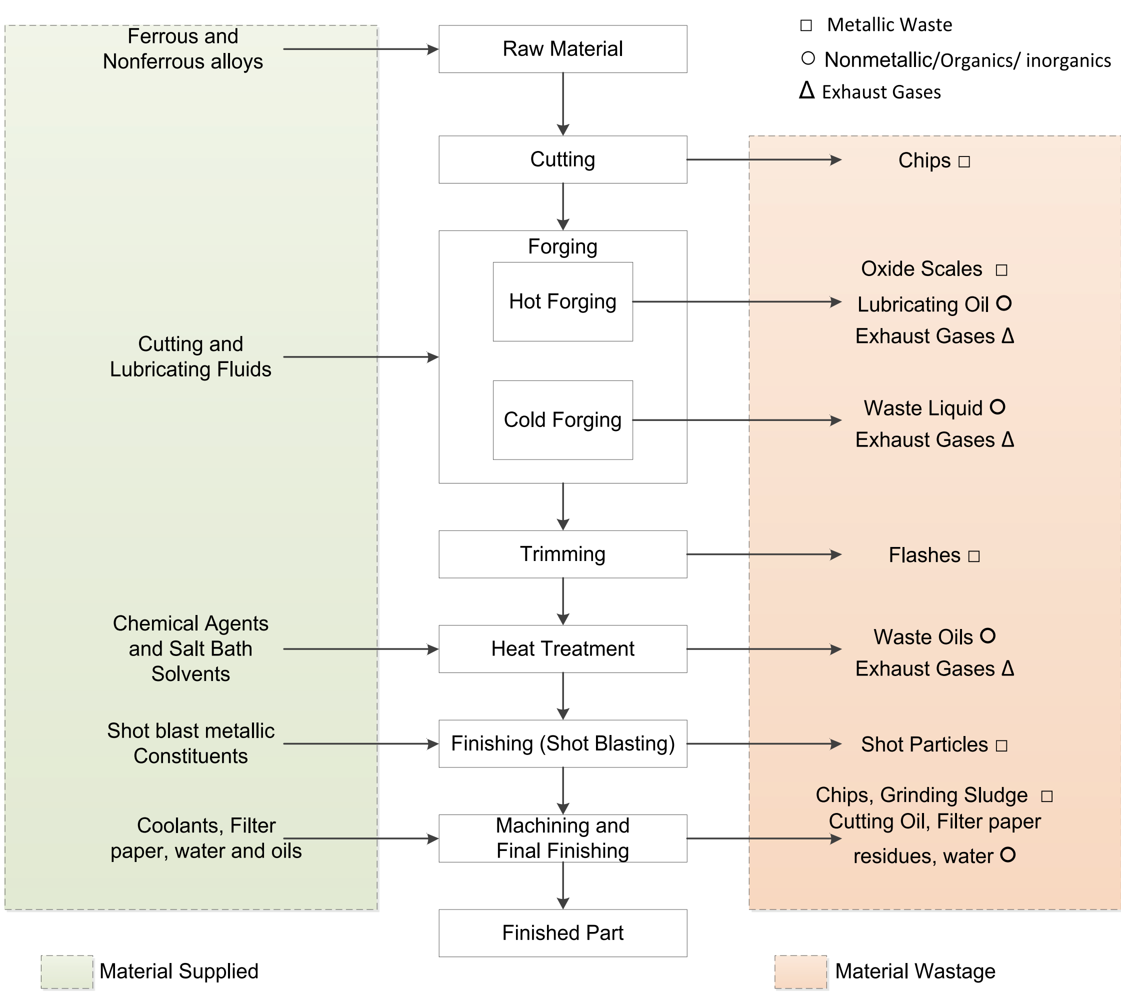

Figure 1. Flow chart depicting the manufacturing process in the forging industry.

metallic particulates from the grinding wheel), such as (i) silicon carbide, (ii) aluminium oxide, (iii) other non-hazardous solids like filter paper dust, and (iv) a residue of cutting oil and water. The metallic constituents in the grinding sludge are similar to those in the chips. However, overall proportion of metallic constituents in the sludge varies between 40% and 50% since the non-metallic contents, such as oil and filter paper constituents, are also mixed in the water during both oil filtration and sludge formation [33,34].

2.1.4. Fabrication/assembly shops

The fabrication shops essentially work on manufacturing of products from sheet metals. A major operation in the fabrication industries is the following:

(a) Cutting of metallic stocks to required size.
(b) Blanking/Piercing: Metallic sheets are cut to the desired shape by blanking followed by piercing/lancing operation to generate the required holes.
(c) Bending of the metal stock to the required point.
(d) Welding of two or more stocks for the purpose of assembly.
(e) Tapping, grinding, and shaping.

There are several other operations performed in both the fabrication and assembly shops. These operations tend to generate metallic scrap like waste sheet and waste stock during the cutting, blanking and piercing operations. The scrap is usually utilised in allied works or sent for secondary steelmaking. Grinding dust (particulate), burs and sludge are often generated during the welding and tapping operations, which are not recycled are usually disposed for the purpose of landfilling [35–37].

2.1.5. Machining/finishing industries

Machining produces the parts or shapes having the required dimensional tolerances by removal of unwanted metal stock, such as (i) drilling, (ii) milling, (iii) turning, and (iv) grinding, are the most common operations. The unwanted stock is removed either in the form of chips or burs during the operation of drilling, milling and turning, followed by the two finishing operations of grinding and buffing. The grinding operation generates scrap in the form of sludge/swarf, which contains about 45–50% metallic particulates along with mixtures of non-metallics and water. The rejected parts, chips and burs are often recycled during secondary steelmaking [38,39].

2.1.6. Advanced and non-conventional manufacturing processes

2.1.6.1. Powder metallurgy/metal injection moulding [MIM]. The process uses metallic/ceramic powder for the purpose of manufacturing net-shaped parts. The process involves operations like (i) powder shaping (compactions/injection moulding), (ii) debinding [for the MIM process], and (iii) sintering. The parts obtained after sintering require less or no post-operation(s). The metallic waste is minimal in the powder metallurgy/metal injection moulding [PM/MIM] process except for particulates (dust) on the shop floor and few rejected parts [40].

2.1.6.2. Non-conventional machining process. Wire electric discharge machining, laser machining/joining, plasma machining, ultrasonic machining, and water jet machining/abrasive jet machining are considered to be non-conventional/advanced machining processes. The advanced machining processes are often used for both the precision cutting and machining operations where material wastage is less when compared to conventional machining operations. This is essentially because these processes are capable for the removal of only small stock of material during machining. The waste material, in the form of dust/sludge, or oxides of the metal, is generated during the non-conventional machining operations [41–43].

2.2. Generation of nonferrous metal scrap in the manufacturing industries

In the industries devoted or focussing on the manufacturing and finishing of nonferrous metals, the metallic waste is often generated in the form of (i) dust, (ii) slag, (iii) sludge, (iv) machining waste, and (v) scales. The major nonferrous metals, such as: (i) aluminum, (ii) copper, (iii) titanium, (iv) lead, and (v) nickel, are often obtained through primary smelting of the ore followed by refining. The solidified metals are subsequently shaped through (i) rolling, (ii) extrusion, and (iii) drawing of the continuously cast ingots. The metallic waste that is generated during the above-mentioned operations on the non-ferrous metals is summarized in Table 3 [44–47].

3. Recycling of ferrous metal scrap

Ferrous metal waste that is generated in the form of oxide scales, chips, flashes and grinding sludge is often recycled using various processing techniques that are summarised below.

Table 3. Non-ferrous metallic waste generation and recycling methods.

Material	Process	Wastage and Form	Recycling Aids
Aluminum (smelting and refining)	Refining process for bauxite	Particulates (solid)	Smelting and refining
	Aluminum calcination Electrolytic smelting of Al Secondary Al smelting	Particulates (solid)	
		Particulates (solid)	
		Particulates (solid), slag (solid)	
Aluminum (forming and finishing)	Continuous/Direct/stationary/Die casting	Particulates, slag (solid),	Smelting and refining,
	Rolling	slag (solid)	Solid state recycling using Billet compaction and extrusion
	Extrusion	- - - -	
	Forging	Dead Stock (solid)	
	Drawing	Flashes (solid)	
	Machine/finishing	- - - -	
		Chips, sludge (solid)	
Copper (smelting and refining)	Copper concentration	Tailing having minerals (solid)	Smelting and refining
	Copper smelting	Slag (solid)	
	Copper conversion/scrap smelting	Slag, particulates (solid)	
	Electrolytic refining of copper	Slimes (solid)	
Copper (forming and finishing)	Casting	Slag (solid)	Smelting and refining
	Rolling	- - - -	Electrolyte recovery
	Extrusion	Dad stock (solid)	
	Machining and finishing	Chips, sludge (solid)	
Lead	Lead smelting	Slag (solid)	
	Lead drossing	Slag (solid)	
	Lead refining	- - - -	
	Secondary lead smelting	Dust (particulates), Slag (solid)	
Nickel	Smelting	Slag (solid)	Smelting and refining
	Refining	Slag (solid)	Electrolyte recovery
	Secondary smelting	Slag (solid)	
	Ni/Cr plating	Dust/particulates (solid)	
Zinc/Cadmium	Leaching and purification	Copper cake/cadmium (solid)	Electrolyte recovery
	Electrowinning	Slimes/sludge (solid)	
	Secondary smelting	Particulates, Slag (solid)	
	Reduction and distillation	Fumes, Slag (solid)	
Titanium	Smelting and refining	Slag (solid)	Smelting and refining
	Forming	- - - -	TiH_2 recycling
	Machining and finishing	Chips, sludge (solid)	

3.1. Melting/sintering in steel plants

In the steel making process, iron scrap in the form of oxide scale is used as the secondary raw material. An electric arc furnace is used for processing of the scrap metal wherein the 'virgin' metal together with scrap is charged with both the flux and reducing agents for the purpose of purification and alloying. One ton of scrap iron requires about 1.2 tons of iron ore, 0.7 tons of coal, and 0.5 tons of limestone along with an enormous amount of energy [48].

3.2. Recycling by hot compaction

Flash and chips generated during the trimming and machining of ferrous forgings are also used as a secondary raw material for the steel making process. This process is mostly applied where tons of chips are produced per day. Recently, the hot compaction technique, as a solid-state recycling process, has been used for compacting the chips and forming blocks. The blocks and billets obtained after compaction are used as raw material for the extrusion process [49].

3.3. Paint industry (red oxide paints)

One of the beneficiaries of recycled iron oxide grinding waste is the paint industry. Researchers have synthesised iron, chromium and ceramic pigments using the grinding waste that is collected from a cast iron foundry as both an iron source and low-cost chromium oxide (Cr_2O_3). Firstly, the grinding waste and chromite mixture is ball-milled in water for a substantial period of time. Subsequent to drying of the mixture, it is

(a) Calcinated for 3 h at 1250°C, followed by
(b) Ball-milling in water for one full hour, and
(c) Washed, filtered and then dried to obtain colour pigments.

Thus, the grinding waste can be treated as a source of iron for the making of both brown colour pigment and black colour pigment, which can be successfully used for transparent glazes [50].

3.4. Recycling using powder technology

The powder metallurgy (PM) process has several benefits to offer when used for the purpose of recycling and the manufacturing of porous parts for use in a spectrum of diverse applications. However, the few disadvantages tend to curtail its application. For instance, for the particulate raw material (powders), (i) an overall inability to manufacture both large-shaped parts and complex-shaped parts, coupled with (ii) having ductility and strength of the parts, and (iii) health hazards due to atmospheric contamination of the powder/dust and emission from furnaces are the commonly faced challenges [51,52].

The parts produced by powder metallurgy (PM)-based recycling have limited applications. The powder metallurgy (PM)-based recycling technique results in parts having limited strength due essentially because of a high level of porosity. Thus, these parts are suitable for applications where porosity is desirable and limited structural strength is desired [53,54].

The metal injection moulding (MIM) process has four basic steps and characteristics of the part following the different processing steps are governed by their respective parametric effects. One of the essential steps in the Metal Injection Moulding (MIM) process is preparation of the feedstock. It consists of mixing the powder with a binder system comprising a mixture of plastics of different molecular weight and having different melting point [58,59]. The entire surface area of the hard metallic powder particle is expected to be covered by the binder as well as lubricating additives like graphite. Rheology of the feedstock is influenced by the following [60]:

(a) Inter-particle friction, which depends on the nature, size and shape of the metal particle or ceramic particle, and
(b) The presence of additives like graphite.

Rheology of the feedstock is different from that of plastic injection moulding due to significantly higher metallic content [61]. The injection moulding feedstock should have time independent homogeneous melt flow properties without segregation (powder binder separation). Irregular flow of the melt causes defects like (i) air entrapment, (ii) weld lines, (iii) flow lines, (iv) cracking, (v) warpage in green parts, and (vi) poor mechanical strength during debinding and subsequent to sintering [62,63]. Aside from frictional effects, the flow of feedstock is governed by both the temperature and pressure of the injection system. Characterization of rheological properties, such as (i) shear rate, (ii) wall shear stress, and (iii) viscosity at varying temperature and pressure, can clarify the rheology that is required for reducing defects in both the green parts and sintered parts. The viscosity must be controlled within a narrow range to get a homogenous mould filling, which improves the overall quality of the components [64]. A careful review of published literature reveals only few studies on rheological properties of the feedstock of different metal/ceramic powder particles showing different degree of sphericity, different binder systems, and different degree of powder loading [61–64].

However, the feedstock that is made for in-process recycling in metal injection moulding (MIM) from powders of irregular shape and size, like the iron oxides or mixture of oxides containing graphite powder and varying binder constituents, has not as yet been studied for rheological properties. The solvent debinding is often sluggish and the solvents used for debinding (such as n-Heptane) are expensive. Controlled solvent debinding is essential to ensure overall consistency in the extent of solvent debinding. Moreover, the occurrence of spatially non-uniform debinding tends to impair the following: (i) properties of the finished part [65,66], and (ii) the sintered quality [67,68].

The effect of solvent debinding process variables, such as (i) solvent temperature, (ii) time of immersion in the solvent, the (iii) ratio of solvent volume per unit part volume, on the extent of debinding of parts made from feedstock-containing particles of irregular shape and size, has not as yet been studied. The details available in the published literature do not contribute much to the existing knowledge on the effect of debinding. For analysing recyclability of the metallic scrap by the metal injection moulding (MIM) process, feedstock preparation, solvent debinding, thermal debinding and sintering need to be thoroughly studied for best results.

Cast iron chips obtained from dry machining of car engine components are pulverised using the techniques of (i) target jet milling, (ii) high energy ball milling, and (iii) vibratory milling. The scrap powder that is obtained after ball milling has grains of irregular shape and having smooth edges while grains of irregular shape and sharp edges were obtained after target jet milling. Subsequent to compaction of the powders, the jet-milled powder had improved green strength (58% higher) and density (5.7% higher) than the ball milled powder. This is essentially because of increased mechanical interlocking of the cast iron particles obtained using the technique of jet milling [69]. The powder that is obtained after ball milling of the chips is mixed with pure iron to get better consolidation subsequent to sintering. Depending on application requirements, the compaction pressure can be modified. A low compaction pressure is suitable for applications, such as bearings. This kind of recycling technique is also suitable for the production of powders the following:

(a) Ultra-high-strength dual phase steels,
(b) Micro-alloyed steels, and
(c) High strength low alloyed steel obtained from forging plants [70,71].

The cast iron powder for recycling swarf (chips) was produced by mechanical processing (ball milling). The efficiency of ball milling was determined using the amount of powder that is below 100 mesh size for different time periods of milling. This study concludes that after 25 h of ball milling time there was an insignificant increase in efficiency, and it seems to have an optimum ball milling time of 25 h for a given system. The powder obtained after ball milling of the chips was mixed with pure iron so as to get better consolidation subsequent to sintering [55,72].

The grey cast iron scrap is processed by vibratory milling followed by powder metallurgy processing. From the investigations of Karandikar and co-workers, it was confirmed that cast iron scrap can be readily pulverised to industrial grade powders using a vibratory mill within a duration of 1 h. The powder annealing treatment was at 600°C for 60 min in an atmosphere of hydrogen that caused an improvement in the physical properties, such as (i) tap/apparent density, (ii) flow rate, and (iii) overall compressibility of the powder particles. An optimal compacting pressure of 415 MPa gives a combination of good green strength and maximum density following sintering. After sintering at 1075°C for 60 min, a tensile strength of 320 MPa and hardness level of 280 H_V was obtained. This kind of powder processing technique is also suitable for the recycling of ultra-high-strength dual phase steels, which has a low carbon content and alloying elements, such as chromium, vanadium, tungsten and molybdenum [56,73].

Machined scrap of medium carbon steel (Fe-0.45%C) requires annealing (1430°C) in an argon atmosphere for one full hour followed by normalising so as to relieve the stresses caused by machining. The sintered compacts were analysed for compressive strength and then correlated with solid state diffusion bonding. For the fine-grained materials, grain boundary diffusion was the dominant mechanism, whereas for the case of scrap bonding, grain size was not small, and both lattice and dislocation core diffusion help in bonding. The effective diffusion coefficient of steel for machining scrap is twice as high as that for the annealed scrap. This is essentially because machined scrap exhibits higher energy absorption than the annealed scrap. Thus, the ratio of high dislocation density to internal energy of the machined scrap will determine the following: (i) coefficient of diffusion, and (ii) resultant degree of solid-state bonding [57,74].

Grinding swarf is a mixture of small metallic particles, coolant, lubricants, and residuals from the grinding media. To reduce the consumption of cutting fluids, lubricants and quantity of solid waste, many manufacturers have installed oil filtration and recycling systems during the last 15 years. Grinding swarf obtained from the high-speed steel (HSS) industry can be recycled using a separation technique to get both the steel and oil (lubricants and coolants) separated. The steel that is obtained after recycling can be utilised in the production of wires, rods, and bars. A flow diagram proposed by Hong Fu and co-workers is shown in Figure 2.

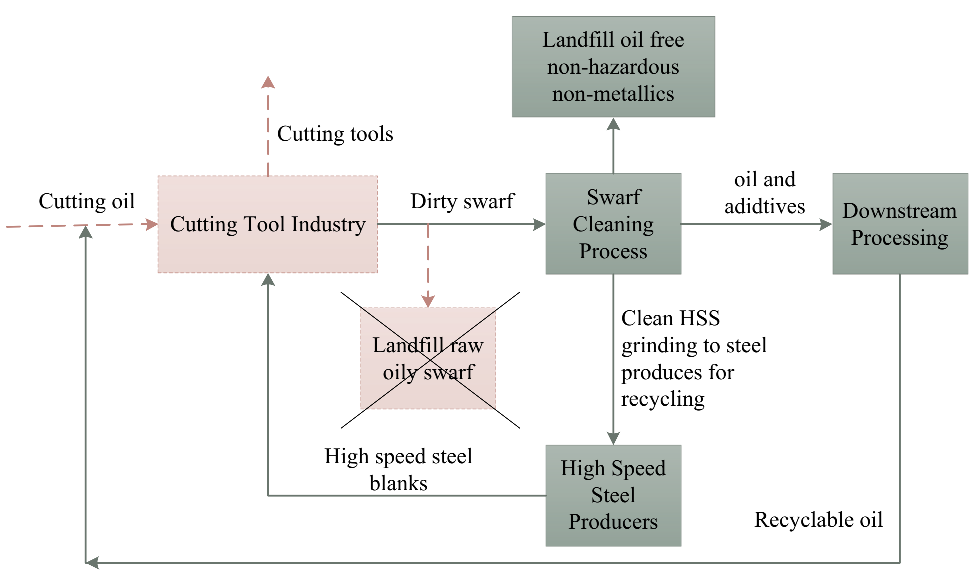

Figure 2. Recycling of grinding swarf [58].

The dashed line in Figure 2 indicates an environmentally unsound landfilling process of an oily grinding swarf, while the solid line indicates the recycling process. Recycling will eliminate the direct landfilling of raw swarf and will consequently produce three streams:

(a) Clean HSS grindings to be re-melted by steel producers,
(b) Cutting oil and additives to be treated and separated before reusing, and
(c) Greatly reduced volume of non-metallic, non-oily components to be landfilled as solid waste.

There are two processes for the cleaning of swarf. These are the following:

(a) Aqueous surfactant washing, and
(b) Super critical carbon dioxide (CO_2) ($SCCO_2$) extraction.

Aqueous washing is a low-pressure cleaning process involving the use of an expensive surfactant. Recovery of water and surfactant are important considerations in this procedure. Super critical carbon dioxide ($SCCO_2$) extraction is not a widely applied and used technique. It utilises the increased solvating power of CO_2 at the temperatures and pressures above its critical point (T_c = 31.1°C, P_c = 78.0 atmosphere). The operating pressure is usually higher than 100 atmospheres. Therefore, this necessitates the need for high-pressure equipment. In this technique, the carbon dioxide (CO_2) leaves no residue on the processed solid, and no waste water. The isolation and recovery of both solute and solvent for reuse can be fulfilled upon a simple mechanical expansion to atmospheric pressure [75–77].

The chemical and physicochemical transformation of substances during the mechanically caused aggregation is referred to as Mechanochemistry. Mechanochemical technology offers the advantages of ecological safety and the possibility of obtaining a product in the metastable state. Metals present in the waste are often in the form of oxide and oxidised compounds rather than as sulphide (one of the naturally occurring forms of a metal compound found in ores). Many chemical techniques are currently available for converting the sulphides to pure metal. Methods to sulfurize the metals present in the waste has been tried elsewhere with the intent of economically adopting mineral processing and metallurgical technologies for sulfurized metals for the purpose of recycling [78–80].

One of the applications of iron oxide in the recycled grinding waste can be the paint industry. The possibilities of recycling iron oxide for the manufacture of pigments were explored by S. Turan and co-workers [81]. They synthesised iron chromium ceramic pigments using the grinding waste that was collected from a cast iron foundry as a source of iron and chromium oxide (Cr_2O_3). The procedure for recycling is as follows:

(a) Grinding waste and chromite mixture was ball-milled in water for a long time.
(b) Subsequent to drying the mixture, it was then calcinated for 3 h at 1250°C followed by ball-milling in water for one full hour, washed, filtered and then dried.
(c) After processing, the pigments were characterised for both particle size and colour, with the prime objective of assessing quality of the mixture.

Similarly, use of grinding waste as a source of iron for the synthesis of brown colour pigment and black colour pigment is feasible for the transparent glazes [81].

4. Recycling of nonferrous metallic scrap

The aluminium scrap is first sorted according to composition and type of scrap and then melted and processed for the purpose of refining by chlorination. Dross processing is another method that can be used for the recovery of secondary aluminium, wherein recycled aluminium alloys are obtained subsequent to refining and alloying with titanium, copper and silicon [82–84]. Recent developments in aluminium recycling are summarised in Table 4.

The conventional method consists of pre-compacting, melting, casting, cutting the ingot and hot extrusion. However, obtaining raw material from the scrap is not a feasible process primarily because of the following:

(a) Large amount of metal is lost due to oxidation.
(b) Large energy consumption
(c) A sizeable number of labourers are required.
(d) Progressive release of hazardous gases into the environment

There is a direct way to convert aluminium scrap into useful product. This method essentially involves the following: (i) an initial compaction of the granulated chips followed by (ii) plastic working called solid state recycling (Table 4). The plastic working processes, such as (i) hot extrusion, (ii) hot rolling, (iii) high-pressure torsion (HPT), and (iv) equal channel angular pressing (ECAP), have been thus far been used. In this manner, the

Table 4. Advanced aluminum recycling techniques.

Technique	Advantages	Method
Fluidized Bed Reactor [85,86]	Remove paints, plastic coating, and organic contents	Fluidized bed of alumina heats scrap (<500 °C) and oxidizes organic components
Vacuum Treatment [87,88]	Eliminates chlorination and use of magnesium for refining, with environmental benefits	Application of vacuum to remove hydrogen and non-metallic inclusions from molten aluminum
Plasma torch for dross treatment process [89]	Eliminates salt fluxes use for dress treatment and improved recovery efficiency to 85–95%	Use of water-cooled plasma gas arc heater in specially designed rotary furnace for dross treatment
Solid State Recycling [90]	Eliminates conventional melting method for secondary aluminum recycling and energy saving	Hot/Cold Compaction of aluminum scrap followed by plastic working process

melting process is eliminated. This type of recycling can be applied to other nonferrous materials.

A novel approach for optimising solid state recycling was proposed for the hot compaction of Mg–10Gd–2Y–0.5Zr alloy [91]. The blocks obtained after hot compaction of the machined chips were characterised for density. Multiple regression analysis was used to find σ (the stress, dependent variable) for the work requirement in compaction, based essentially on the two dependent variables during compaction, namely (i) temperature, and (ii) velocity of the ram. This optimisation approach did result in highly dense compacts but also minimum energy requirement during processing. The energy for hot compaction has two components. These are:

(a) The work that is required for deformation, and
(b) Heat required for raising the temperature.

Also, rheology of the powder does have a great influence on velocity of hot compaction than temperature, up to 400°C for the chosen alloy [91,92].

The lead scrap generated from lead acid batteries, sheets and pipes are often recycled in a scrap processing plant. A major source of lead scrap, i.e. lead acid batteries (75–80%) is first separated from free acid and plastics. Pyro-metallurgical smelting separates the secondary lead from feed material to eliminate the metallic elements and other oxidised impurities by the process of slagging. Molten lead is then refined to get the following: (i) soft lead, (ii) calcium lead, and (iii) antimony lead, which can be used for manufacturing new batteries. The hydro-metallurgy process and electro-metallurgical process replace the conventional pyro-metallurgy route for the purpose of processing secondary lead. This includes both the leaching process and the electrowinning process for a cost-effective elimination of the emission of atmospheric lead [91,92].

Secondary sources of zinc include galvanised sheets and brass scrap. The solid waste containing zinc is usually recycled using the techniques of (i) smelting, (ii) refining, (iii) leaching, and (iv) electrowinning [93]. The shredded copper scrap from automobiles and other sources contains metals like tin, lead, zinc, and nickel. The pyrometallurgical recycling route for both copper and alloys of copper is smelting in a primary smelter. This is followed by refining wherein the metallic impurities like zinc, aluminium, silicon and tin are progressively removed by oxidation [94,95]. Recent developments towards both economic feasibility and environmental safety for the purpose of recycling copper include the following:

(a) Direct electrorefining of the scrap in a sulphate solution, and
(b) Direct electrowinning technologies.

4.1. Solid state recycling

Three major solid-state recycling processes have been reported in recent years to process aluminium and aluminium waste and include the following:

(a) Powder metallurgy method [96]
(b) Severe plastic deformation methods (SPD) [97]
(c) Hard facing or cladding method [98]

Solid State recycling is a process of recovering the metal chips through direct conversion by means of plastic deformation followed by sintering of the final product without melting. The key steps involved in solid state recycling are the following: (i) pulverizing the metal chips, (ii) cleaning, (iii) drying, (iv) heat treatment, (v) cold/hot compaction, and finally (vi) sintering or cold/hot plastic working. This is then followed by cutting to the desired size and shape [98]. A flow chart depicting the solid-state recycling methods is as shown in Figure 3.

4.1.1. Recycling by hot extrusion

Extrusion is essentially a plastic deformation process. In this process, the compacted nonferrous scrap in the form of billet is applied with a compressive load and forced to flow through a die opening of smaller cross-sectional area than the billet. Extrusion at an elevated temperature tends to produce both compressive forces and shear forces, and along with temperature are the driving components for diffusion to occur among the

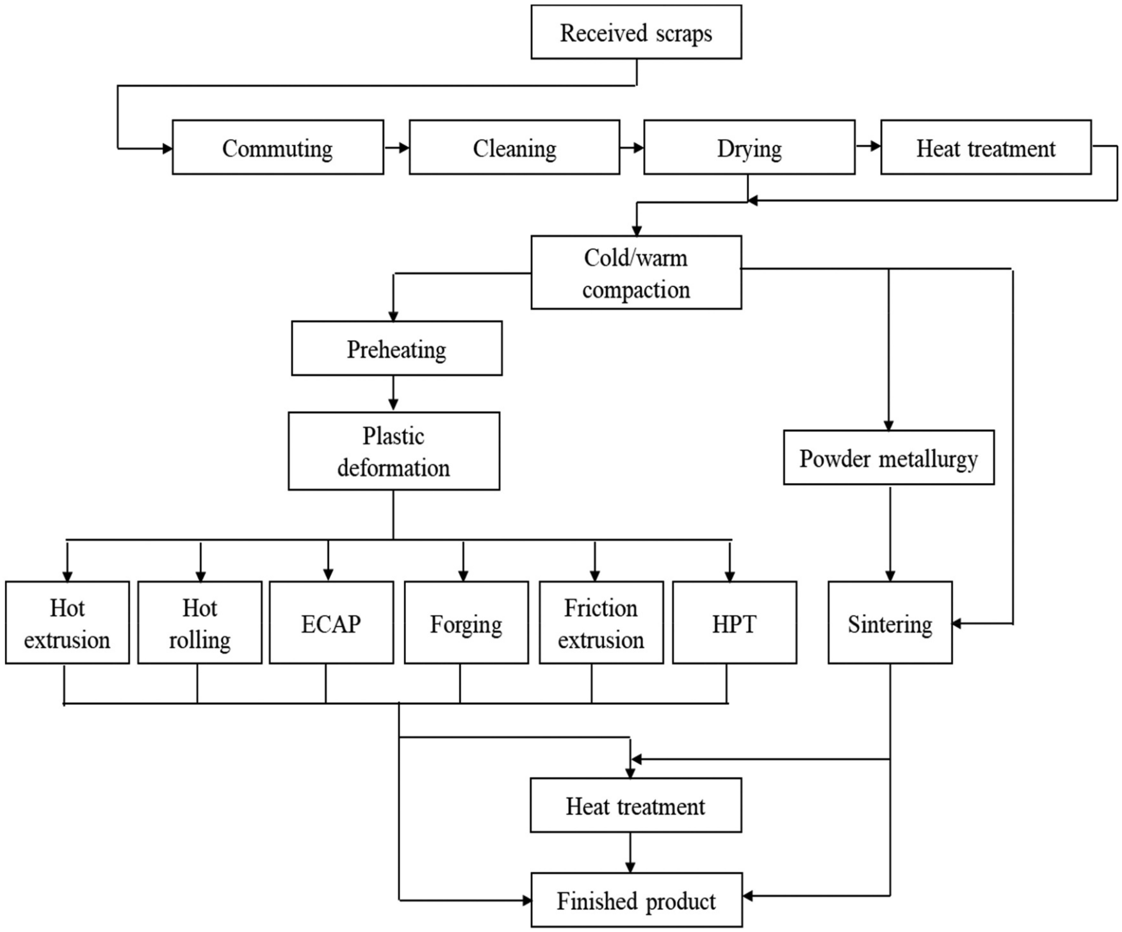

Figure 3. Flow chart depicting solid-state recycling of nonferrous scrap.

scarp particulates that are used to form a solid part. In addition, high reaction compressive forces are developed by restriction at the interfaces of the billet-container. This essentially results in compressive stress that is adequate enough to prevent cracking of the material.

The oxide layer breaks down under the influence of shear forces acting during the extrusion process. The material flows into the die in the form of elongated grains. The thin and brittle oxide layers do not tend to elongate with the chips. In order to break these oxide layers, large plastic strains are necessary along with high pressure and temperature. Thus, fracture of the oxide layer takes place due to a combination of shear force and friction between the oxide layers and the base metal that enables in combination diffusion to take place [99].

Few researchers have worked on the solid-state recycling of aluminium and aluminium alloy chips. A summary of the most relevant contributions is the following:

(A) Stern (1945) first presented and patented direct conversion of the aluminium alloy machining chips into both finished products and semi-finished products using hot extrusion.
(B) Gronostajski and co-workers [100] produced composites by direct conversion of aluminium and the $AlMg_2$ alloy granulated chips along with tungsten powder into final products using the technique of hot extrusion. They observed the hardness and mechanical properties of aluminium and $AlMg_2$ base composites to be slightly lower than that of the parent composite. The material that was produced could be further processed by other plastic working methods, such as (i) forging, and (ii) rolling, to improve its mechanical properties.
(C) Gronostajski and Matuszak [101] developed a method for the direct conversion of chips into a finished product using the powder metallurgy technique and followed by extrusion. Pre-sintering was used to set in motion the diffusion

transport of matter between the aluminium particles and the aluminium alloy particles. They observed the extent of diffusion transport during pre-sintering to be very limited due essentially because of a small number of contact bridges between the particles and high oxidation of their surfaces.

Fogagnolo and co-workers [102] studied the method of cold pressing and hot pressing followed by hot extrusion and the possibility of using this method to recycle the chips of an aluminium alloy matrix composite. They observed the hot extrusion of cold pressed sample or hot-pressed sample to promote in the consolidation of the chips. However, hot extrusion of the hot-pressed samples was the best route. For chips of the aluminium alloy matrix composite, the ultimate tensile strength (UTS) and hardness were higher for the recycled material than for the starting or initial composite essentially because of a noticeable refinement in the microstructure coupled with a healthy dispersion of the aluminium oxide particles made possible by the extrusion process.

Allwood and co-workers [103] studied recycling of aluminium 1050A-H14 scrap using the operations of (i) compaction, (ii) flat rolling, and (iii) forward extrusion. All operations being performed separately. They observed bonding of the chips to increase with an increase in extrusion ratio. An extrusion ratio above 4 and a die angle of 200° was necessary to achieve bonding of the chips. The deformed sheet metal using flat rolling was unstable with the occurrence of severe edge cracking and the occurrence of only little bonding. Suzuki and co-workers [104] proposed a method for the recycling of aluminium alloy chips using both hot extrusion and hot rolling. The hot rolling was performed in two conditions:

(a) Normal roiling, and
(ii) Differential speed rolling (DSR).

Tensile strength of the recycled material obtained after 580 K heat treatment was superior to the non-recycled material. The differential speed rolling (DSR)-based chip consolidation was found to be better than the normal-based rolling for a large rolling reduction per pass.

Mani and Paydar [105] worked on equal channel angular pressing – forward extrusion (ECAPFE) consolidation of aluminium particles. They observed the mechanical properties and physical properties of the ECAPFE recycled material to be better when compared to the extruded profiles resulting from forward extrusion. The key reasons were the following:

(a) A refinement in the grain size due to dynamic recrystallisation and shear deformation in the die, and
(ii) A uniform dispersion of the oxide contaminant during equal channel angular processing (ECAP).

The concept of ECAP-FE die is shown in Figure 1. Chiba and co-workers [106] investigated the possibility of solid-state recycling of aluminium alloy machining swarf using both cold profile extrusion and cold rolling process. The cast aluminium-silicon (Al-Si) alloy swarf was cold compacted into billets and the cold profile was then extruded into square bars using an extrusion ratio greater than 4 or equal to 4. After annealing, the extruded bars were multi-pass cold rolled to get 1-mm thick strips and a total reduction of 85%. They observed coarse residual voids to exist in regions where an insufficient amount of plastic strain was introduced in the material that was recycled using the extrusion process. Both strength and density of the material that was recycled through extrusion and an additional rolling process were found to be superior to the material that was recycled using only the extrusion process coupled with a marginal reduction in ductility.

Haase and Tekkaya [107] investigated direct conversion of aluminium alloy AA6061 chips into finished products by using hot extrusion followed by cold extrusion. For hot extrusion, a conventional flat face die and an ECAP-FE die were used. The chip-based extrudates were then machined to produce chip-based preforms for the purpose of cold extrusion. These preforms are then (i) forward extruded to get rods, and (ii) backward extruded to get cans. They observed the quality of the chip-based finished parts to be strongly dependent on quality of the bonding between the individual chips.

Mashhadi, and co-workers [108] studied recycling of aluminium scrap using cold pressing and melting by using a salt flux. Based upon this optimum process, Wojciech and co-workers [109] and Tekkaya and co-workers [110] investigated cold compaction followed by hot profile extrusion of (i) aluminium alloy 6060 (AA6060) chips, and (ii) an alloy mixture of aluminium and silicon carbide (SiC) particles. They characterised the extrudates to have a large number of seam welds at all the chip boundaries. In a continuing study, Güley and co-workers [111,112] presented the influence of die design, heat treatment and chip type on the solid bonding of aluminium alloy 6060 [i.e. AA6060] and aluminium alloy 7175 [i.e. AA7175]. They found the AA6060 chips when extruded through a porthole die produced an extrudate that essentially had twice the ductility of a corresponding extrudate that was made using a flat die. Gronostajski and co-workers [113,114] performed the direct recycling of aluminium chips into extruded products. They mixed the aluminium scrap with reinforcing phases like tungsten and found strength of the composite material without the reinforcing phases to differ marginally from those of the solid material. The strength was improved following the addition of reinforcing phases at a high temperature. Samuel [115] studied the extrusion of aluminium scrap reinforced with Saffil ceramic fibres. He found the relative strengthening of the composite material at both ambient temperature and elevated temperature to be significantly higher when compared to the conventional alloy. Furthermore, he showed the ultimate tensile strength, yield strength and hardness to be considerably increased due to the addition. Puga and co-workers [116] investigated the recycling of aluminium swarf by direct incorporation in aluminium melts. Mao-liang and co-workers [117] studied the effect of extrusion ratio on microstructure and mechanical properties of the AZ91D magnesium alloy that was recycled from scrap using the technique of hot extrusion. Tang and Reynolds [118] produced a wire using friction extrusion of the machining chips of an aluminium alloy. By using the friction extrusion process, they produced defect-free wire of aluminium alloy 2050 and aluminium alloy 2195.

4.1.2. Recycling by hot rolling

Solid-state recycling by the hot rolling of nonferrous scrap in the form of machined chips can be performed. Very few manuscripts are available in the published literature on recycling using hot rolling. A basic sequence involved in the solid-state recycling using hot rolling of the aluminium alloy chips to achieve a sound sheet is shown in Figure 4. Chips of a commercially available aluminium alloy belonging to the 6000 series [i.e. Al 6082] were used as the raw material for solid state recycling by Kore and co-workers [119]. The cold compacted and hot rolled sheets showed better properties in (a) the annealed condition [UTS = 146.7 MPa, Elongation = 24.2%], and (b) the T6 heat treated condition [UTS = 279.31 MPa, Elongation = 12.06%]. For an intermediate annealing heat treatment during hot rolling does help in softening as well as diffusion bonding among the chip particles (Figure 4).

4.1.3. Recycling by super plastic deformation (SPD)

With only light pre-processing, significant plastic deformation can result from widespread reuse of scrap metal pieces. The SPD technique, known as high-pressure torsion (HPT), has been used to consolidate metals [120,121]. Recently, high pressure torsion (HPT) has been used in the field of recycling scrap metal. However, limited literature can be found on recycling nonferrous metal using the high-pressure torsion (HPT) process. The chips that were machined from copper that had undergone both equal channel angular pressing (ECAP) and coarse-grained processing were combined using the technique of high-pressure torsion (HPT) [121]. The measurements reveal the consolidated discs to have an extremely fine microstructure and a high value for microhardness.

Furthermore, the aluminium alloy chips can be consolidated sufficiently into a cylindrical specimen using the technique of compressive torsion processing (CPT) [122] by carefully controlling both the temperature and rotation time. The tensile strength of the specimen processed by compression torsion processing (CTP) technique was

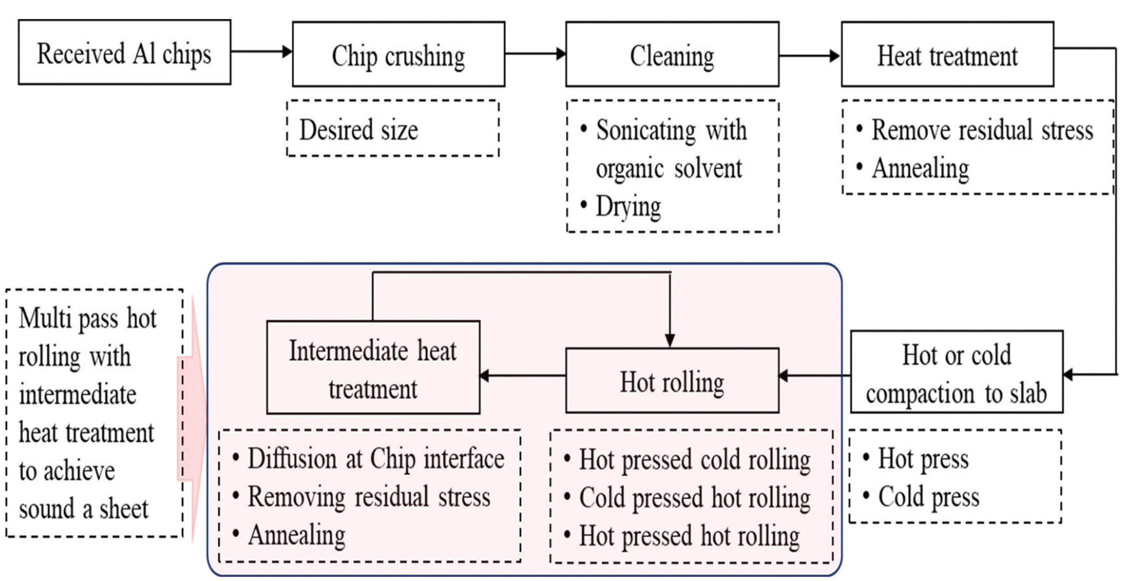

Figure 4. Basic sequence of hot rolling for solid-state recycling.

higher than that of an annealed alloy that was made using the traditional ingot metallurgy (IM) process [122]. Apart from the use of pure aluminium chips, the technique of high-pressure torsion (HPT) has been used for the consolidation of aluminium alloy chips [123]. Due to the smaller aluminium matrix grains and silicon particle size in an aluminium alloy, it was observed that the high-pressure torsion (HPT) method successfully produced fully dense bulk samples that had a greater microhardness. When compared to hot extrusion, or die compaction, the high-pressure torsion (HPT) technique is more effective in producing nanocrystalline/ultrafine grain (UFG) recycled bulk from the aluminium alloy chips [123]. Pandey and co-workers [124] used the high-pressure torsion (HPT) technique as a novel approach for the recycling of aluminium alloy 6082 to produce both a disc shape component and a bush-shaped component. They found that prior to the high-pressure torsion (HPT) process, annealing of the chips makes them pliable while concurrently improving product density. In addition to recycling of the aluminium alloy chips, the high-pressure torsion (HPT) technique was utilised to recycle aluminium chips with 20% Al_2O_3 and 20% SiC [125]. As a result, an ultrafine-grained (UFG) microstructure of both aluminium sample and aluminium composite sample having a relative density ranging from 99.7 to 98.3% was successfully produced using the high-pressure torsion (HPT) technique. The aluminium matrix and the reinforcing particles were successfully both refined and fractured during the high-pressure torsion (HPT) processing.

4.1.4. Recycling by sintering

Apart from different solid-state processing using the techniques of spark plasma deposition (SPD) and plastic deformation at an elevated temperature, there are direct sintering of the compacted nonferrous waste from a machine shop that is used for recycling. Recently, the technique of field activated assisted sintering (FAST) or pulse electric current assisted sintering (PECS) or spark plasma sintering (SPS) have been used to recycle the chips/swarf of pure aluminium, aluminium alloys and titanium alloys. Paraskevas and co-workers [126] used the process of spark plasma sintering (SPS) to consolidate chips of aluminium alloy 6061 and aluminium alloy 6082. They used a sintering temperature of 490°C and under 200MPa pressure for ~7 min. For this condition ~ 99.99% density was achieved. Further, this method was used to recycle scrap from aluminium sheet [51,127]. First, scrap from the aluminium sheet needs to make a desirable size by chopping prior to sintering. Aluminium alloy 5182 sheet was sintered using spark plasma sintering (SPS) by Paraskevas and co-workers [127]. Solid-state recycling using the SPS method was also explored for the magnesium alloys [128]. The FAST integrated forge technique was used by Weston, et al. [52] to recycle the Ti-6Al-4 V alloy. They claim that when compared to hot isostatic pressing, the FAST-forge technique offered greater mechanical qualities and is a faster manufacturing method. The FAST-forge technique uses titanium alloy swarf, a low-cost feedstock, which has completely altered the economics of titanium alloy components. Li and co-workers [53] investigated the solid-state recycling of rare earth materials (Mg – Gd – Y – Zn – Zr) using the techniques of spark plasma sintering (SPS). Different combinations of sintering temperature and sintering time, or duration, at a pressure of 40MPa were studied. The spark plasma sintering (SPS) condition of 500°C for 10 min did result in superior compression yield stress (217 MPa), ultimate compression strength (467 MPa) and compression failure strain [20.4%] for the recycled billets than for the cast billets [compressive yield stress = 181MPa, ultimate compressive strength = 405 MPa and compressive failure strain = 19.5%] [53].

Iron impurities significantly impact the mechanical properties and processing behaviour of aluminium alloys, particularly influencing their ductility, toughness, and overall performance. The increased iron content in recycled aluminium-silicon alloys does lead to a notable reduction in tensile strength and elongation due to the formation and presence of brittle Al-Fe-Si intermetallic [67]. Similarly, iron impurities promote the formation of β-Al_5FeSi intermetallic in Al-Si alloys, which tends to only degrade the mechanical properties [68]. The challenges of high iron content in recycled aluminium can be managed through alloy design and processing techniques. To mitigate these adverse effects, researchers have explored the following:

(a) Alloy design strategies that incorporate elements like manganese or chromium to modify the iron-rich phases,
(b) Advanced casting and heat treatment techniques to control microstructure, and
(c) Refinement methods, such as electromagnetic filtration and ceramic foam filtration to reduce the iron content [129].

These efforts are crucial for improving the performance and sustainability of aluminium alloys.

5. Metallic powders and their recycling in additive manufacturing processes

Powder recycling in additive manufacturing (AM) processes, such as (i) Laser Powder Bed Fusion (LPBF), (ii) Direct Energy Deposition (DED), and (iii) Cold Spray (CS) presents several challenges that can impact both the quality and performance of final components. In the technique of laser powder bed fusion (LPBF), the recycled powders like Ti-6Al-4 V and stainless steel 316 L undergo changes in particle size distribution (PSD), flowability, and morphology due to repeated thermal cycles and oxidation. For instance, Ti-6Al-4 V powders exhibit changes in particle size distribution (PSD) and a slight increase in the oxygen content. These changes were controlled with a recycling index to maintain part integrity [130]. A recent study reported that recycled stainless steel 316 L powders increased porosity by 10% along with a minor reduction in mechanical performance, thereby highlighting the need for stringent process controls [131].

In direct energy deposition (DED), reduced powder flowability and microstructural inconsistencies can lead to the presence of defects in the deposited material and degradation of mechanical properties. The Ti-6Al-4 V powders in the DED process exhibit reduced flow characteristics, resulting thereby in inconsistencies in the deposited layers [132]. Aluminium powders, after several recycling cycles, did reveal the following: (i) a 15% decrease in tensile strength, and (ii) a 10% reduction in fatigue life due to microstructural changes [133].

Cold Spray (CS) faces issues, such as particle deformation and contamination, which can hinder bonding quality and coating performance. Aluminum powders experienced significant particle deformation during high-velocity impact, thereby altering the particle size distribution (PSD) and reducing recycling efficiency [134]. The titanium alloy powders in cold spray (CS) did reveal increased oxidation levels after recycling, thereby affecting and/or influencing the mechanical properties of the coatings.

Despite these challenges, rigorous monitoring, proper process control, and appropriate handling strategies can mitigate these issues, making powder recycling a viable and sustainable approach emphasising the importance of maintaining strict chemical and physical property standards for the recycled powders to ensure consistent part quality. Regular equipment maintenance and environmental control is very essential to prevent contamination and preserve powder integrity. Overall, effective powder recycling strategies can significantly reduce production costs and material waste while concurrently maintaining quality of the final components.

6. Key highlights and conclusions

From a careful, cautious and complete review of the published scientific literature on recycling, the following points deserve special attention:

(1) Manufacturing industries generate a diverse range of metallic scrap, to include chips, powders, scales, dust, and sludge. Each type of scrap has unique recycling challenges and potential, making the development of tailored recycling processes crucial for maximising both material recovery and reuse.

(2) Most iron scrap is recycled through secondary steel smelting, which while being effective, is observably energy intensive. This method highlights the need for more energy-efficient recycling techniques to reduce both the environmental impact and operational costs associated with metal recycling.

(3) Powder processes like additive manufacturing (powder bed fusion, direct energy deposition, cold spray), powder metallurgy and metal injection moulding enable the scrap to be directly shaped into a product and subsequently sintered.

(4) In order to achieve high-quality recycled parts, it is essential to optimise multiple processing stages and control parameters. This essentially involves the following: (i) meticulous monitoring of powder properties, (ii) maintaining strict environmental conditions, and (iii) ensuring proper equipment maintenance. Such optimisation efforts can mitigate the adverse effects of recycling, such as (i) changes in particle size distribution, (ii) flowability, and (iii) contamination, thereby maintaining the integrity and performance of the final components.

(5) While the recycling of metal powders in additive manufacturing and other powder processes presents several challenges, the potential benefits in terms of material efficiency, cost reduction, and sustainability make it a promising area for continued research and development. Continued advancements in process control, material science and materials engineering are essential to fully realise the potential of solid-state recycling of metal powders.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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