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Review

The Recycling and Reuse of High-Value Abrasively Machined Feedstock Materials: A Review

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Abstract

Due to recent developments across the aerospace, power generation and defense sectors, the demand for flat-surfaced components with extremely high surface quality is rapidly increasing. In this regard, although abrasive machining processes often produce fine, contaminated swarf that is frequently relegated to landfill, these processes remain critical for the engineering sector. Motivated by increasing sustainability and circularity pressures, this narrative review examines the current state of the art in recycling and repurposing the chips, tooling and cutting fluids that are typically generated or consumed within grinding processes. In doing so, a number of methodologies for extracting useful materials from swarf slurries are identified, including pyrometallurgical routes (applied successfully to Ni–Co alloys, for example), hydrometallurgical strategies (e.g., iron leaching from ferrous swarf) and, in the case of non-metallic materials such as CMCs and CFRPs, chemical processing methods. Various means of separating abrasive constituents and removing contaminants from grinding swarf are also highlighted, within which centrifugation and heat treatment are found to be particularly useful for non-ferrous materials such as titanium alloys or composites, whilst ferrous materials are largely magnetically separated. Prospective applications for spent abrasive tooling are also explored, including reuse as shot, waterjet machining feedstock, road surface additives, or mortar in the context of cement production. Likewise, heat- and radiation-based strategies for prolonging cutting-fluid life are highlighted, and their associated sustainability benefits and limitations discussed, despite ultimate disposal still being relegated to fuel usage or landfill. Ultimately, this review identifies the scarcity of grinding-specific recycling process data and highlights the need for robust, publicly accessible recycling strategies for novel material systems.

Keywords: grinding; abrasives; HRSA; steel; composites; CFRP; CMC; recycling; sustainability; swarf; tooling

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1. Introduction

In scenarios where conventional subtractive processes are unsuitable, or extremely tight surface and geometric tolerances are required [1], abrasive machining strategies remain of critical importance. In industrialised countries, abrasive processes now account for approximately 20–25% of total machining expenditure [2], which is set only to increase over the coming decade, as the grinding market appreciates at a compound annual growth rate (CAGR) of 5.7%/5.8% [3,4]. One application that is expected to become increasingly reliant on these processes is that of small modular reactors. As the small modular reactor market rapidly grows [5], high-temperature material species such as ceramic matrix composites (CMCs) are increasingly necessitated. Because these materials are highly abrasive, have poor ductility and are susceptible to both chipping (fracture) and delamination, they are generally not suited to a conventional subtractive processing route, frequently making abrasive manufacturing necessary.

Elsewhere in industry, abrasive manufacturing processes are essential across a range of precision engineering scenarios wherein surface quality and flatness are critical; however, these approaches are not without their limitations. In contrast with defined-edge subtractive processes (i.e., turning or milling), material removal rate (MRR) is generally lower (although creep feed grinding is markedly more competitive [6]), heat generation is often higher, and part access can be difficult. Whilst these limitations can often be addressed by proper selection of cutting parameters, adequate cooling application and well-considered CAM strategies (respectively), the challenge of recycling grinding swarf, cutting fluid and spent abrasive wheels remains a persistent issue for the manufacturing sector.

For this reason, the present review outlines the current state of the art, as it pertains to the recycling of various high-value grinding feedstock materials, in addition to identifying prospective opportunities for future research in both metallic and non-metallic grinding applications.

2. Methods and Structure

As a consequence of the ambitious sustainability targets set by the UN's Intergovernmental Panel on Climate Change (IPCC), and the subsequent driving force that has been created for industrial symbiosis [7], recyclability is the focus of significant interest and research effort. Despite this interest, due to the variety of materials that can be recycled and the various means of doing so, a broad recyclability review, without process specificity, would necessarily be superficial. Given this observation, this study focuses specifically upon the recycling of subtractive-process waste, with a particular emphasis on abrasive feedstock materials. In this regard, as a non-systematic narrative scoping review, this study summarizes current best-practice methodologies, emerging publicly accessible methods and areas of low technology readiness.

In order to find relevant resources, an iterative search of Google Scholar, Web of Science and Scopus was conducted, in addition to searches of Google Patent and other patent databases. The decision to include the patent literature was made due to the proprietary nature of many emerging swarf recycling strategies, and the lack of process-specific works in the academic literature, such that patents often provide the only publicly accessible technical details. Sources were considered up to September 2025, with older studies analysed in contexts where foundational knowledge would serve an important explanatory role, or where more recent evidence was sparse. Throughout the study the following search terms were used: "recycling", "grinding", "abrasive machining", "reuse", "swarf", "metalworking fluid", "cutting fluid", "coolant" and "processing". These were utilized in conjunction with various Boolean operators.

Following initial retrieval, titles, abstracts and conclusions of works in the literature were screened qualitatively for relevance, limiting inclusion to works that directly or indirectly pertained to subtractive process-derived waste. Articles and patent literature with insufficient technical detail, in addition to works focused on primary manufacturing and end-of-life recycling processes, were excluded from consideration. Studies focused on conventional machining processes (e.g., turning, milling, and drilling) were selectively retained if they were deemed to play an important narrative role, or if transferability to

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abrasive machining waste might be possible. In total, approximately 70–80 publications, patents and standards were examined, with 40–60 retained for detailed analysis.

In pursuit of these objectives, the review begins with a background on abrasive machining (Section 3), covering the chronology of the technology (Section 3.1), mechanisms of action (Section 3.2), the recycling methodologies that are employed elsewhere in subtractive manufacturing (Section 3.3) and the waste products that are generated during abrasive processes (Section 3.4). Thereafter, the main body of the document focuses on the recycling and reuse methodologies (Section 4) that have so far been applied to grinding technologies; this is followed by a sustainability assessment (Section 5) that explores both abrasive machining as a whole, and the upside of the recycling and reuse strategies discussed in the prior chapter. Finally, the document is concluded, and future research recommendations are made (Section 6).

3. Background: Abrasive Machining

3.1. History of Abrasives

In a sense, abrasive manufacturing processes have been employed for almost as long as humans have used tools. Whilst examples of polished stone utensils dating from tens of thousands of years ago have recently been discovered in Japan (Figure 1) [8], polished/abraded surfaces and holes have been commonplace for much of modern history. The Egyptian pyramids were flattened via sandstone, ancient Greek sculptures were smoothed with abrasive powders, and cutting tools have been sharpened with stones for millennia. Historically, these processes were heavily reliant upon natural resources and human labour, with highly prized sharpening implements (such as whetstones) being sourced from quarries around the world.

Figure 1. Example of a Japanese Neolithic polished stone axe [8]. Open source.

Despite this long history of abrasive processes, the grinding apparatus of the sort that is reminiscent of modern machinery, though influenced by early pioneers such as Leonardo Da Vinci [9], was not realised until (comparatively) very recently. In 1876, The Brown and Sharpe Company (now named Brown & Sharpe) developed the first cylindrical grinding machine by retrofitting a small lathe with a grinding wheel attachment [10]. The design of Browne & Sharpe was later refined by Norton, who increased the power of the machine tool and improved the accuracy with which the machine could operate [11], and thereafter by Parsons' invention of computer numerical control (CNC), which, for the first time, allowed for efficient, high-throughput precision grinding of the sort seen today [12].

Currently there exists a vast range of CNC abrasive machining centres capable of offering a multiplicity of different subtractive manufacturing processes (i.e., cylindrical grinding, gear grinders, lapping machines, thread grinders, etc.), and likewise, an expansive range of abrasive tools. The sandstone wheels (historically sourced from quarries in Sheffield and the surrounding areas), which were commonplace throughout the latter portion of the 19th century, have now largely been replaced by higher-performing composite wheels. These modern wheels typically feature synthetic or natural abrasives such as alumina, silicon carbide or diamond, bonded with a glass, resin, silicate or a metallic matrix phase, and, unlike much of the tooling that was used in the past, these exist in a range of complex geometries (which are often dressed, crushed, or electrical-discharge machined into blank wheels) [13].

3.2. Mechanism of Action

In a conventional machining process, a stationary (i.e., turning) or rotary (i.e., milling or drilling) cutting tool of defined geometry is plunged into a stationary or rotary billet of workpiece material. When this occurs, the relative motion between the leading edge of the cutting tool and the workpiece material leads to shearing and the ultimate removal, shaping or burnishing of said material. In this regard, grinding shares a number of similarities with conventional machining processes. Modern grinding strategies typically make use of a rotary cutting tool and a stationary workpiece and remove material by means of shear-driven plastic deformation, and in some cases, brittle fracture. Nonetheless, abrasive cutting tools, despite likewise being composite materials that have properties similar to those of conventional cutting tools (i.e., high hot hardness, chemical stability etc.), are markedly different in a number of key ways [13,2]:

- Grinding tools feature many thousands of cutting surfaces, compared to the far fewer cutting edges present on conventional defined-edge tools.
- The cutting surfaces that are present on a grinding tool are of irregular size and geometry.
- Abrasive grains may exhibit locally positive rake angles, which can lead to elevated cutting forces and temperatures.
- In terms of usable tool life, grinding wheels often last much longer than typical cutting tools, although they require frequent dressing to clear loaded chip material and to maintain an effective cutting surface.
- Grinding generates small chips of irregular thickness.

3.3. Waste Production and Recycling in Conventional Machining Processes

Due to the subtractive nature of machining operations, superfluous material is removed, typically via shearing, in the form of chips/swarf. This waste material typically passes through the machining centre via a conveyor and is stored in an adjacent bin, either for ultimate recycling/reuse, or, in scenarios where recycling is not feasible, for landfill. This is a particular challenge for industry, given the large volumes of material that are in practice machined, and the low buy–fly ratios that are often observed in many precision engineering, safety-critical contexts (e.g., between 6:1 and 10:1 for many aeroengine components [14]).

For many metals, particularly titanium alloys and nickel-based superalloys, recycling of machining swarf is an established and technologically mature process. This maturity is driven in part by the high costs, complexity and energy burdens associated with primary metal extraction (e.g., via strategies such as the Kroll process). These factors create a significant financial driving force for secondary material recovery, which, when considered

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alongside the already existing environmental incentives, has contributed to the achievement of much lower levels of waste. Historically, heat-resistant superalloy (HRSA) swarf is cleaned, degreased, chemically matched, remelted in a crucible and cast into billets of (typically lower grade) material [15,16]. Whilst this approach remains far superior to landfill, the associated loss of material results in it falling short of the true material circularity now targeted across high-value manufacturing sectors.

Over recent years, a number of authors have proposed more direct re-use strategies for swarf generated through conventionally defined cutting-edge strategies. Primarily, these approaches are focused upon bypassing full remelting by making use of the swarf as an additive manufacturing feedstock material. Example processes within this space include extrusion-based wire formation from Ti-6Al-4V swarf (Conform™—Figure 2) [17], powder feedstock production from staged ball milling of Ti-6Al-4V swarf [18] and laser direct metal deposition of screened carbon steel chips [19]. These strategies demonstrate promising reductions in energy consumption (e.g., ball milling of powder feedstock led to a 59% lower energy consumption relative to gas atomization) and acceptable tensile properties; however, they generally do not implement controlled atmospheres and they remain limited by low levels of output (Conform™, for example, can only produce between 0.0047 and 0.0141 m^3 of titanium feedstock per hour), oxygen pickup, and porosity formation. For these reasons, their use remains restricted to non-safety-critical contexts.

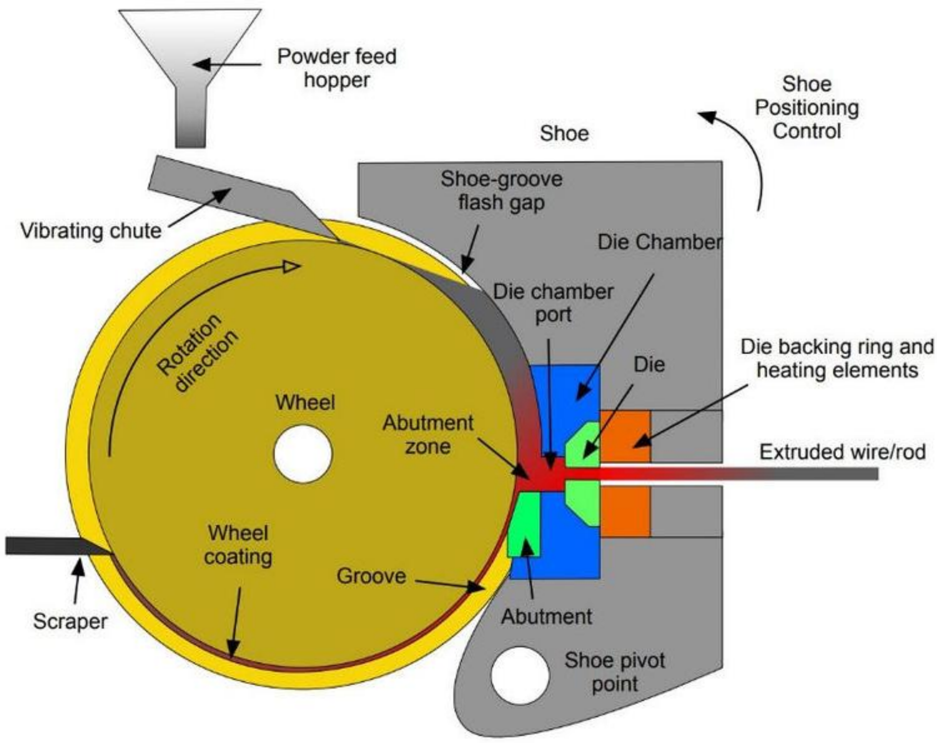

Figure 2. A schematic of the Conform™ extrusion process [18]. Open source.

Aside from the production of additive feedstock materials, novel swarf consolidation-based approaches have also been explored [20,21]. Typically, these processes seek to densify swarf without undertaking full-scale remelting via processes such as Field Assisted Sintering Technology (FAST) or other novel sintering methodologies (e.g., Equal Channel Angular Pressing [22,23]). These strategies are extremely promising ways to reduce processing steps between swarf generation and billet production, and as such offer a significant reduction in energy consumption. Unfortunately, however, many of these processes are currently still at low technology readiness level (TRL) and may be sensitive

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to many of the same shortcomings as the previously discussed additive strategies, i.e., porosity, oxygen ingress etc.

Hydrometallurgical routes have shown significant promise for the recycling of otherwise difficult, or uneconomical to recycle, ferrous materials. Ottink et al. [24] for example, proposed using a hydrochloric acid reagent to leach iron (amongst other elements) from steel swarf, with the outlook of generating ferric chloride (which is used in wastewater treatment/purification, as an etching agent for engraving circuit boards [25] and as an oxidant for metal extraction [26]). In their work, the authors noted that the leaching process under optimal conditions (60 °C, pH 4 and 1.20 g/mL HCl) was capable of generating a 99.3% pure iron-chloride solution wherein only 1% of the residual cutting fluid was dissolved into solution. Moreover, the leaching methodology has also been shown to extract magnesium, manganese, and (to a lesser extent) nickel.

There are of course a number of other non-metallic materials, i.e., ceramics, composites, etc., that are machined, but for which the discussed processes (remelting, additive feedstock production, and hydrometallurgical processes) are not suitable. Often, either these material systems are not frequently recycled, or the recycling processes that are available for these materials are not appropriate for machining waste. These effects are particularly heightened in material systems such as CMCs, for which, due to their early developmental timeline, the body of publicly available data is extremely limited. Due to this lack of information, and the fact that abrasive machining processes are often more common in the contexts of these materials, the available case studies are reviewed in the following section.

3.4. Swarf Morphology and Circularity Challenges During Abrasive Machining

Unlike the defined macro-scale chips that are produced during conventional cutting processes, grinding waste differs significantly. Due to the numerous microscopic cutting edges that are present on abrasive tooling, the swarf produced during grinding is typically extremely fine and resembles a sludge-like agglomeration (Figure 3). Waste in this form is difficult to handle/process, and due to the combined effects of its high surface area and the presence of remelted material, it often absorbs substantially more oxygen than other subtractive waste streams. This increased contamination is often prohibitive as to re-use in safety-critical sectors in which material purity is tightly governed. The ASTM, for example, state that Grade 5 Ti-6Al-4V has a maximum allowable oxygen content of 2000 ppm [27], as oxygen levels in excess of this threshold are shown to cause significant embrittlement [28].

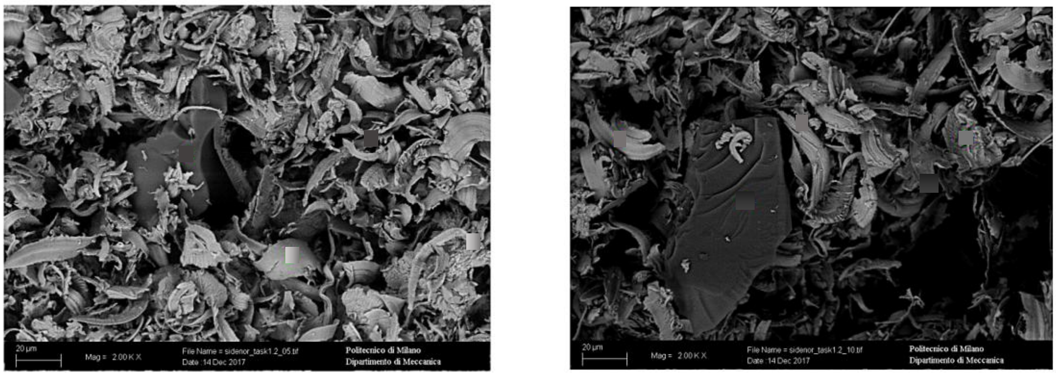

Figure 3. Example micrographs of iron grinding sludge [29]. Open source.

Aside from the handling and contamination issues associated with grinding swarf, its fine geometry also creates challenges when separating the swarf from the cutting fluid. If grinding debris is not adequately removed from the media, it will be recirculated within

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the machine tool, often leading to accelerated wear throughout the grinding centre, reduced cooling/lubrication performance, and, potentially, in severe cases, part scrappage. These issues are of particular concern during the grinding of brittle materials that generate powder-like debris during machining (e.g., carbon-based materials, ceramics, and glass fibre composites), leading to hydrocyclonic or centrifugal filtration systems (e.g., RBM's IFDR system) rapidly being adopted in place of conventional physical filtration modalities (which are prone to clogging and require frequent maintenance input).

In addition to these difficulties, a further challenge that is associated with abrasive processes is the fact that the grinding wheel breaks down during use (more often than with typical cutting tools) in order to self-sharpen and is generally dressed inside the machining centre. As a result, the recovered swarf is not only contaminated by the machining atmosphere and cutting fluid, but also by both the abrasive grains and the matrix phase of the grinding wheel/dressing role. As such, should the ground swarf be recycled into a billet or section resembling the original feedstock material, the tooling constituents would likely need to be separated from the swarf.

In this regard, although some specific contamination governance exists [27], and isolated thresholds are occasionally reported in particular grinding waste handling and disposal contexts [30], systematic, quantitative descriptions of specific factors relative to abrasive machining, such as permissible particulate entrainment levels in swarf, or acceptable residual cutting-fluid content in recovered feedstock materials, remain poorly consolidated, across both the academic and the standards-focused literature. As such, qualitative blanket omission of contaminated materials from safety-critical contexts is likely necessary until technologically mature processes can be established and broad application-specific guidance provided.

4. Recycling and Reuse in Grinding

Whilst the swarf that is generated in conventional subtractive machining processes is typically relatively clean or cleanable, and generally of consistent geometry, grinding swarf or sludge is often much more difficult to clean and process. The sludge that is generated in many grinding applications is often regarded as a secondary recyclable stream because its value, as a commodity, is significantly reduced relative to "clean" swarf. For "clean" swarf, separation and washing is much easier (and more cost-effective), and the recycled material that is ultimately generated is of higher purity (and thus value). In this sense, whilst there are marked differences in the recyclability of different material systems (hence the available research within this chapter is categorised by material), there are also procedures and procedural developments that are applicable to the abrasive machining of a wide range of materials.

As an example, in almost all scenarios wherein a metal is ground, post-process cleaning of the swarf to remove cutting fluid and other impurities is generally necessitated. Historically, there have been a number of developments in this area, such as the 1976 patent of Carman [30], who sought to protect a proprietary means of washing swarf with an "aqueous detergent solution" in order to emulsify any residues, entrain the contaminants in the fluid stream, and ultimately evaporate the impurities. In a similar patent, Dankoff et al. [31] sought to protect a process by which recyclable workpiece material could be recovered from grinding sludge. The process involved screening of the swarf, followed by a multistage cleaning process with two distinct solvents, a heating stage to vaporise said solvent, and finally a magnetic separation stage. It should be noted that the utility of the final separation stage will be dependent upon the ferromagnetism of the swarf that is to be recovered; however, the stages preceding said magnetic separation are applicable to a number of material species.

Ultimately, whilst there are a number of generic salvage strategies that are commonplace within grinding, there are likewise a multitude of recycling methodologies and reuse cases that are unique to a given material species. With this in mind, the following chapter first examines recycling and reuse practices by the material that is to be recovered and thereafter explores the strategies that allow abrasive tools and cutting fluids to be reused.

4.1. Heat-Resistant Superalloys

Given the high cost of HRSA materials and the scarcity of many of the alloy additions that they make use of, there is a clear driving force for swarf recovery. Despite this, for many HRSA materials, there is a very limited amount of research available within the public domain. In titanium alloy grinding for example, there are a small number of companies who are willing to pay for titanium sludge (e.g., Globe Metals Inc. Quebec, Canada [32]); however, the exact methodologies that those companies employ to extract titanium from the grinding sludge are generally not accessible in the public domain. In concert with the previously discussed swarf-processing patents (Section 4), it is likely that the process will involve some combination of screening, cleaning with solvent (or spinning in a centrifuge for example) and a final separation stage to isolate the titanium swarf from the abrasives, although exactly how this would be accomplished (given that titanium is not ferromagnetic) is difficult to say. It is possible that either the abrasives or the titanium could be preferentially dissolved; however, this is conjecture.

One prospective titanium recovery methodology that is available in the public domain can be found in a 1996 US patent [33]. In that patent, Gerdemann and White identify a titanium grinding sludge recovery strategy (Figure 4) that involves sieving to remove coarse contaminants/wheel fragments, pelletizing with an un-specified binder (i.e., sugar, hydrolysed starch etc.), and smelting in an electric arc furnace with an iron source (i.e., scrap or sponge iron). In doing so, ferrotitanium and titanium slag is produced; the former is frequently used during steelmaking for deoxidization, desulfurization and denitrogenation whilst the latter is often used as a pigment. Ultimately, the utility of this process lies in the ability to produce ferrotitanium from titanium swarf whilst avoiding contamination. In this sense, the success or lack thereof of this process seems to hinge upon the quality of the supplied swarf, and the efficacy of the sieving process.

The use of titanium grinding swarf as a feedstock material for the production of ferrotitanium is a relatively novel concept. The notion of compacting swarf into pellets is comparatively much more commonplace. In this regard, a number of companies currently offer titanium alloy briquetting solutions to industry, i.e., [34,35]. These compacting processes have a number of key benefits relative to loose swarf processing, which include

- Improved swarf handling;
- Increased resale value;
- Mechanical extraction of cutting fluids (which can then be used in multi-fuel heaters, refined or resold—Section 4.4);
- Reduced freight cost;
- Reduced fire risk (due to the lower surface area of a compacted briquette relative to loose swarf).

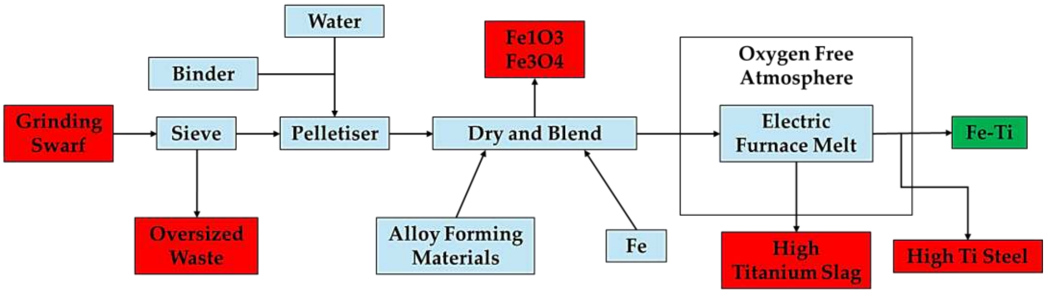

Figure 4. Titanium grinding swarf recovery methodology, adapted from [35]. Public domain.

Of course, as with any recycling process, the opportunity cost of briquetting must be considered on a case-by-case basis. In production, where large volumes of material are machined, the incentives for briquetting are well-pronounced; however, in a research and development or prototyping environment, the benefits may not be sufficient to offset the associated initial capital outlay.

In accordance with the limited public domain information pertaining to the recycling of titanium alloy grinding sludge, the recovery of nickel- and cobalt-based superalloy swarf is likewise often proprietarily conducted [36] by the superalloy supplier, and as such, is seldom considered within the academic literature. Of the limited work that exists in this area, the pyrometallurgical (and electrochemical) efforts of Holman et al. [37,38] is some of the most promising. In their work, the authors manufactured electrolytic anodes from the turning and grinding swarf of two Ni–Co alloys, which were cast into preheated mild steel book moulds coated in zirconium oxide. Thereafter the authors placed the anodes in a glass bath and, via the use of an acidic sulphate–chloride electrolyte, produced an electrolytic cell for carbon reduction, and, ultimately, melt oxidation. In doing so, Holman and colleagues were able to recover in excess of 90% by weight of the cobalt and nickel from the anodes.

Clearly, this process is, at a surface level, extremely promising; however, considering the age of these reports, and more importantly, the lack of research that has built upon these precedents (although other electrolytic processes have been explored [39]), it appears that the pyrometallurgical process highlighted either does not reflect current industrial interests, or any developments in this area have remained proprietary. Whilst it is difficult to say with any certainty why this is the case, it is possible that the lack of uptake is a consequence of the high loss to slag of both molybdenum and tungsten. The concern thus may be that highly alloyed nickel-based superalloys, namely, those that contain expensive alloy additions, e.g., rhenium, would equally suffer with a high loss to slag of said alloy additions, making the process economically inefficient.

Aside from the work of Holman et al., there is a growing body of literature focused upon the recycling of HRSA scrap materials [40], much of which focused upon pyrometallurgical (i.e., direct remelting, or re-melting with fresh material); hyrdrometallurgical; or hybridised, pyro/hydrometallurgical strategies; however, little of the work available directly references the use of grinding sludge as a feedstock. In this regard, there is significant scope to develop resource-efficient recycling strategies for these materials.

4.2. Steel and Cast Iron

In contrast with the limited body of research that considers the recycling of HRSA grinding swarf, steels, and to a lesser extent, cast irons, are, at least from the perspective of typical separation and remelting protocols, relatively well-researched. This is likely a consequence of both the extremely long lineage of steel and cast-iron usage, and equally, their scope for magnetic separation from contaminants. In a sense, the ferromagnetism of these materials allows for a marked reduction in the cost associated with the processing

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of steel-grinding swarf, wherein the necessity of processes such as centrifugation and chemical dissolution of contaminants, though still of utility, is often of lower importance.

Despite this relatively established chronology of steel/iron grinding swarf recycling, there are nonetheless a number of more recent technological developments within the field that offer unique benefits. One such example of a recent development is (similar to the titanium related research of Smyth, Dhiman and others) the work of Großwendt et al. [41], who made use of X153CrMoV12 (DIN 1.2379, AISI D2) tool steel-grinding sludge as a feedstock material for electrical discharge sintering (EDS).

In direct contrast with other recent work that embraces the (cutting disk application specific) abrasivity benefits of ceramic tooling contaminants during steel swarf recycling [42], the process outlined by Großwendt et al. first involves rigorous cleaning to remove both abrasive constituents (SiC and Al_2O_3, in this case) and residual cutting fluid from the swarf. This begins with magnetically separating the swarf from the abrasive particulates via repeated exposure to a neodymium magnet, followed by supercritical CO_2 extraction of residual oil.

Thereafter, the EDS process employed by the authors involved pre-compacting the grinding waste via the use of Cu-alloy stamps and a ceramic die. Next the samples are sintered via electrical discharge from a local capacitor (wherein the joule heating effect sinters the swarf), austenitized at 1080 °C, quenched in oil and tempered. Finally, the generated cylindrical billets were compression- and hardness-tested relative to a baseline of a conventionally manufactured cast and hot-rolled ingot. In doing so, the authors noted that the recycled coupons were subject to a significant reduction in compressive strength, and likewise that, prior to tempering, the hardness of the recycled ingots was also markedly worse (by approximately half) than that of the conventionally manufactured material. Despite this, Großwendt and colleagues did note that hardness increased significantly after tempering, wherein peak hardness occurred at a temperature of approximately 500 °C.

Ultimately, reduction in the compressive strength of the recycled material is an intuitive consequence of

- The improper consolidation of the swarf material.
- Contamination of the feedstock i.e., via the oxidation of the swarf during the grinding operation.
- Insufficient electrical discharge energy during sintering.
- The presence of pre-generated cracking by the EDS process.

The inability to generate material properties that are comparable to those that can be obtained via a traditional processing route remains a cause for concern for adopters of the technology. Nonetheless, given minor refinement, it is very likely that the process identified by Großwendt et al. retains a great deal of promise. For one thing, due to the reduced energy consumption of EDS relative to conventionally manufactured material, it remains a valuable tool for swarf consolidation. However, even omitting the EDS process, cleaning the swarf material via the use of supercritical fluid is likely of significant utility. Nonetheless, it is important to note that whilst the work of Großwendt and colleagues serves as a case study for the supercritical fluid-assisted recycling of steel-grinding swarf, the authors did not define the precedent of using supercritical fluid to clean cutting fluid from swarf material, and in fact, significant research exists within this field (most prominently the early work of Dahmen et al. [43], in addition to the steel swarf recycling of Fu et al. [44]).

Similar to the research of Großwendt et al., Singh et al. [45] proposed direct compacting/sintering of steel-grinding swarf, with the outlook of generating a metal matrix composite (MMC) of both the bulk (largely uncontaminated) steel sludge, and the fine oxidised steel particulates generated (which occur as a consequence of the high heat, cutting fluid-free environment) during the material removal process. To do so, the authors first magnetically separated the swarf from contaminants, and then cleaned it with acetone, heated it (to evaporate any volatile residues) and finally sieved it through a 425 μm opening. Thereafter, the resulting swarf feedstock was pelletised via a hydraulic press, sintered in an argon environment (at 1150 °C for 90 min) and left to cool inside the furnace, generating a composite material composed of a steel matrix phase with fine iron-oxide precipitates.

After sintering, the authors went on to test the microhardness of the ultimate steel/iron oxide MMC, noting marked variations in the observed hardness as the microindenter traversed from the comparatively soft (~130 $Hv_{0.5}$) mild steel chips towards the much harder oxide particles (~540 $Hv_{0.5}$). Whilst this inhomogeneity is typical of composite materials, Singh and colleagues also noted significant periodic reduction in microhardness as areas of increased porosity were indented, which, in safety-critical/load-bearing scenarios, is a cause for concern. As such, if this strategy is to be developed for future applications it would be crucial to conduct significant structural/mechanical testing and microscopy in order to characterise the impact of aforementioned porosity on the broader mechanical properties of the component, in addition to gaining an improved understanding as to the extent to which the composite material is properly consolidated, and further, the strength of the steel/iron-oxide interfaces.

Aside from direct compacting/sintering, another novel means of recycling ferrous grinding swarf was identified by Takagi et al. [46], who proposed the use of high-carbon chrome bearing steel as an alternative to iron powder for the manufacture of disposable body warmers. As part of their research, the authors measured the heat generation (via a type K thermocouple) of body warmers composed of both dried (via oven at 110 °C) and dried and washed steel-grinding sludge to that of conventional, iron powder-based body warmers. In doing so, the authors noted that the obtained peak temperature of the body warmers was comparable, and further, that whilst the iron powder body warmers generated superior heating duration relative to that of the grinding sludge-based body warmers, the heating duration that was obtained by the grinding sludge was, nonetheless sufficient for the application (approximately 5–25 h). Moreover, the heating characteristics of the grinding sludge-based body warmers aligned with those defined by the Japanese industrial standard (JIS) S 4100-1996 [47], further emphasizing the use case.

In this regard, whilst the results of Takagi and colleagues are promising, it is of course important to note that disposable body warmers are generally regarded as an unsustainable commodity. This is largely a consequence of the reacted heating pad waste (HPW) not being suited to conventional recycling modalities, which thus often necessitates disposal in a landfill. In response to these concerns, a small number of prospective applications for HPW have been proposed, most prominently for use in inorganic arsenic absorption [48] and water purification; however, as these recycling technologies are designed for iron powder-based HPW, it remains to be seen whether grinding sludge-based body warmers would likewise be able to make use of the same recycling processes.

Ultimately, whilst conventional means of recycling ferrous grinding material are relatively ubiquitous, they often lack the cost efficiency necessary to find large scale use. As such, despite the growing body of novel, increasingly cost-effective strategies that are being considered within the literature, there remains significant novelty within the field, an area that warrants further pursuit.

4.3. Composites

Whilst there are exceptions, typically, composite materials have poor recyclability. This is in part because composites do not typically fit into any one material species category, and as such, are often not suited to conventional recycling processes. When

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considering carbon fibre reinforced polymers (CFRPs), or glass fibre composites, for example, some of the challenges are as follows:

- CFRP and glass fibre composites generally employ the use of a materially dissimilar matrix phase, necessitating a staged approach to recycling.
- During these processes it is often difficult to liberate the reinforcement phase from the matrix phase.
- Liberation of the reinforcement phase can be deleterious to the reinforcement phase, preventing direct reuse of fibres.
- Thermosetting resins cannot be remelted and are frequently used as a matrix phase.
- The reinforcement phases that are used in composite materials are often extremely hard and are thus capable of rapidly abrading the tooling used during recycling process.

Despite these difficulties, it is worthwhile to remark that many modern composite materials do not make use of polymers, and further, in the case of CMC materials for example, the reinforcement and matrix phases are often materially consistent with one another (i.e., SiC–SiC or C–C composites). In these scenarios, assuming that there exists an adequate means of recycling the material in question, the additional challenges of inhomogeneity may not be particularly relevant. Nonetheless, CMC recycling faces unique challenges that are generally not faced by more conventional composite materials. Most fundamentally, CMCs, as high-temperature materials, are generally not suited to recycling processes that require melting or burning, and likewise, are a challenging material to pulverise, not because of their impact strength, but rather because of the wear that they elicit on dies/tooling implements, as a consequence of their extremely high hardness.

Notwithstanding these restrictions, CMC recycling remains a field of significant interest. However, as CMC machining is very much in its infancy, relevant recyclability research often does not focus specifically on abrasively machined swarf. Nonetheless, many prospective methodologies that are viable means of recycling CMC components may equally be applicable to the recycling of swarf. As an example, one paper describing a recycling feedstock that shares similarities with grinding swarf was written by Wang et al. [49].

In their paper, the authors explored a multi-stage chemical/physical methodology of extracting pure silicon (Figure 5) from a slurry of silicon, SiC, residual cutting fluid and tooling-related contaminants created during the sawing of silicon ingots (for photovoltaic cell production). In their paper, Wang et al. utilised a process of

- Initial centrifugal separation—This is in order to remove large SiC particles.
- Chemical treatment—This is first performed with acetone to remove any contaminant oils, and then with nitric acid to dissolve residual metals.
- Multi-stage high-gravity centrifugation—This is via the use of an unspecified fluid of a specific gravity between those of silicon (2.33) and SiC (3.2).
- Secondary chemical treatment—The floating material (primarily silicon, with a small volume of residual SiC) is cleaned with both acetone and deionized water.
- High-temperature precipitation—The floating material is then pelletized and heated (to 1470 °C) for "several hours" in an argon atmosphere, causing the separation of the silicon and the SiC.
- Cleaning—The crucible contents are cleaned with water to separate the non-adherent Si clusters from the mixture.
- Ternary chemical treatment—The silicon clusters are washed with hydrofluoric acid to remove impurities (which rise to the surface during heat treatment) and washed with deionized water.
- Directional solidification—New ingots of silicon are produced.

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Ultimately, the recycling process identified by Wang and colleagues is rigorous and highlights a range of important strategies that can be employed in isolation, or in concert, during the recycling of a range of ceramic materials. In this sense, it is foreseeable that aspects of this process could be employed as a means of recycling SiC grinding swarf; however, there are a range of prospective unique limitations that the process may face if applied to the grinding of SiC–SiC CMCs. Perhaps most pertinently, the fact that diamond (which is generally the abrasive of choice for grinding SiC) has a specific gravity of 3.52, which is markedly closer to SiC (3.2) than silicon (2.33). This similarity may make centrifugal separation non-viable; however, as diamond begins to burn (in air) at approximately 900 °C [50], if centrifugation and chemical treatment can remove other contaminants, heat treatment may suffice as a means of removing any diamond abrasive constituents from the mixture.

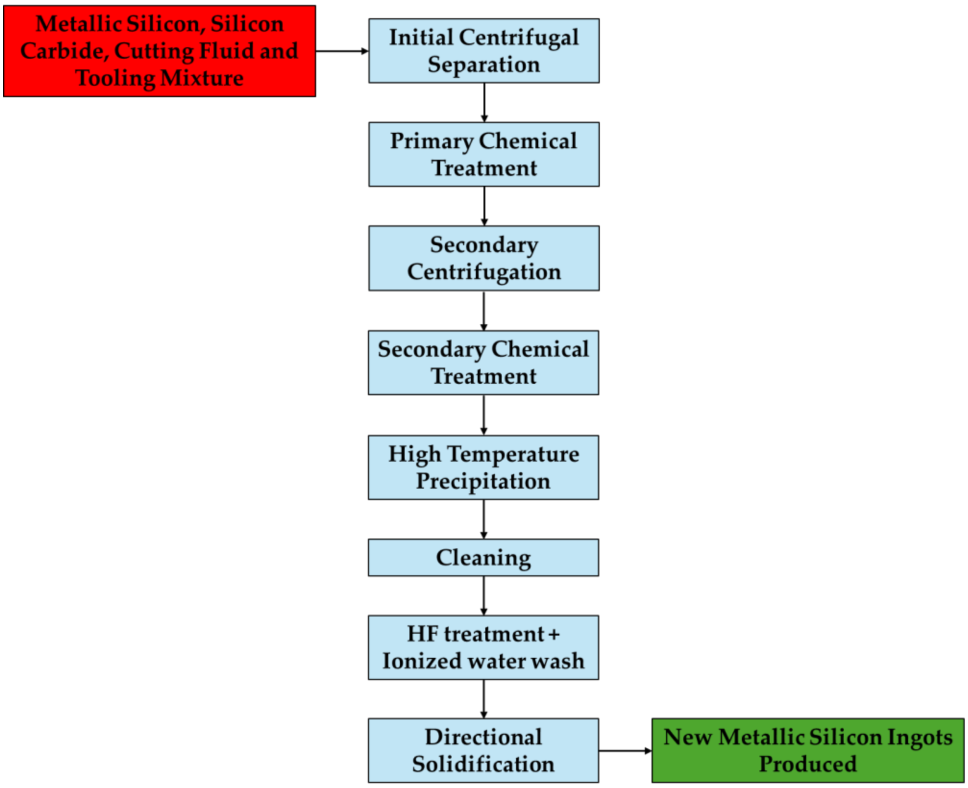

Figure 5. Multi-stage silicon recycling process, adapted from [49].

Whilst the procedures outlined by Wang and colleagues, in addition to those of Tian and Ge [51] (amongst others), provide a strong basis for the reclamation of SiC from waste material, they are not particularly informative as to the recyclability of other CMC formulations (i.e., Al_2O_3/Al_2O_3). Nonetheless, if ground CMC abrasive constituents can be directly reused, i.e., in shot blasting, chemical processing, metallurgy etc., then the recyclability of said CMC material is derived solely from the capacity of the abraded CMC material to be extracted out from other contaminants. In this sense (assuming particle rather than whisker or fibre-reinforced CMCs), the screening processes outlined by Wang et al., (i.e., centrifugation and chemical and heat treatments), in addition to the precedent that has been set by industry [52,53], would likely be sufficient to extract a range of ceramics from their respective grinding swarfs.

In any case, it is nonetheless true that CMC materials are, due to their relatively recent industrial adoption, the subject of far less recyclability research than other more established composite systems, i.e., CFRP or GFRP. However, whilst the broader recycling of carbon and glass fibre materials is well represented in the literature, research specifically dealing with the recycling of ground CFRP swarf is much more niche. Despite this, it follows that any recycling process that makes use of fine, mechanically pulverized CFRP particulates, assuming that the thermal effects of the abrasive machining process are not significant (and that there is no cutting-fluid ingress into the fibres), should be applicable to ground CFRP swarf. In this regard, an example of a prospective means for the recycling of CFRP grinding swarf would be as follows [54]:

- Collect clean CFRP grinding swarf (assure the machining centre is dry and any contaminating swarf is removed).
- Screen the CFRP swarf for any contaminants and categorise by fibre content (where a high fibre content would be inferred by coarser swarf).
- Blend the fine recyclate with new resin for reuse in the matrix phase of a new composite material system.
- Retain the coarse (fibre rich) recyclate.

Whilst this process has significant scope for use in the recycling of ground CFRP, there are a number of prospective limitations to this approach. Most fundamentally, it would be extremely difficult to remove abrasive particulates from the CFRP swarf. This means that the new composite material would contain some volume fraction of abrasives, which may have a deleterious effect on mechanical properties. Although, this may not be the case in all contexts, and further, these effects may not be restrictive for certain applications, this strategy remains limited, as it does not propose a means of reusing the coarse fibrous recyclate and as such, cannot facilitate full material circularity.

In this sense, whilst, at a surface level, the fibre-rich, coarse swarf may retain some function as a reinforcement phase, as the fibres within the swarf have been subject to an extreme thermal and mechanical loading regime, it is very likely their engineering value has worsened significantly. As such, given the geometric inconsistencies of these fibres, it remains to be seen whether they would retain any scope for reuse. Moreover, the chemical recycling technologies that are currently employed during CFRP recycling (i.e., solvolysis) serve the purpose of attacking the resin matrix phase with the outlook of extracting the fibre mat from the composite material [55,56], rather than dissolving the fibres themselves. With this in mind, whilst chemical processing strategies may be of utility in removing any adhered resin from the fibre-rich swarf, they remain of limited utility in this particular context. Ultimately, it would be worthwhile to devise prospective applications wherein the (comparatively) coarsely chopped CFRP swarf could be effectively employed, as, for example, a filler material.

4.4. Tooling and Cutting Fluid

Whilst large agglomerations of grinding sludge within a machining environment creates an immediate impulse to explore recycling strategies, the site of expired abrasive tooling, aesthetically, is much less alarming. Nonetheless, the manufacture of abrasive tooling is associated with a significant energy cost, and, as large volumes of abrasives are increasingly used, the burden on landfill is likewise consequential. Equally, spent cutting fluid often presents significant challenges to industrialists. Microbial spoilage, contamination and degradation, in addition to the difficulty that is often associated with separating grinding sludge from cooling and lubrication media, often necessitates complete disposal. Given these challenges, a number of authors have explored various strategies of recycling both abrasive tooling (i.e., grinding wheels) and spent cutting fluids, ranging from re-use cases for abrasive particulates to strategies to prolong fluid use.

Sabarinathan et al. [57], for example, explored the potential scope for recycling alumina grinding wheel waste (Figure 6) for use as a waterjet machining (WJM) abrasive during the cutting of both aluminium and marble. In their research, the authors collected wheel scraps, mechanically crushed them via a Rajco jaw crusher, and sieved them to collect ASTM 80 grit particulates. Thereafter the authors compared both the grain morphology and the cutting performance of the recycled alumina abrasives relative to a garnet abrasive (which is commonplace in WJM). In doing so, they observed that, whilst the recycled alumina generated increased both surface roughness and kerf width relative to that of the garnet abrasive (prohibiting use during finishing operations), it was likewise able to generate marked improvements to material removal rate (MRR), making it a viable choice for roughing operations.

Similarly, Mizobuchi et al. [58] explored the prospect of generating a recycled grinding wheel from reconstituted wheel scrap for use in the polishing of large austenitic stainless-steel sheets. In order to do so, the authors sourced the irregular scrap abrasive sheets from which round grinding wheels are cut, crushed them first into 2 cm^2 pieces, and then placed approximately 20 g of the crushed material into a mechanical crushing machine and pulverised it to generate a fine powder (removing any material not easily crushed). Thereafter the authors generated an aqueous polyvinyl acetate (PVA) solution (primarily PVA, a preservative, and in some cases, titanium lactate) via a process of rigorous stirring and heating followed by a cooling stage. Having generated the PVA solution, the alumina abrasives were kneaded into the mixture, formed into a mould, consolidated under pressure and dried in a furnace. As part of the process, the authors noted that when the volume fraction of abrasive grains exceeded 50%, bonding became impossible.

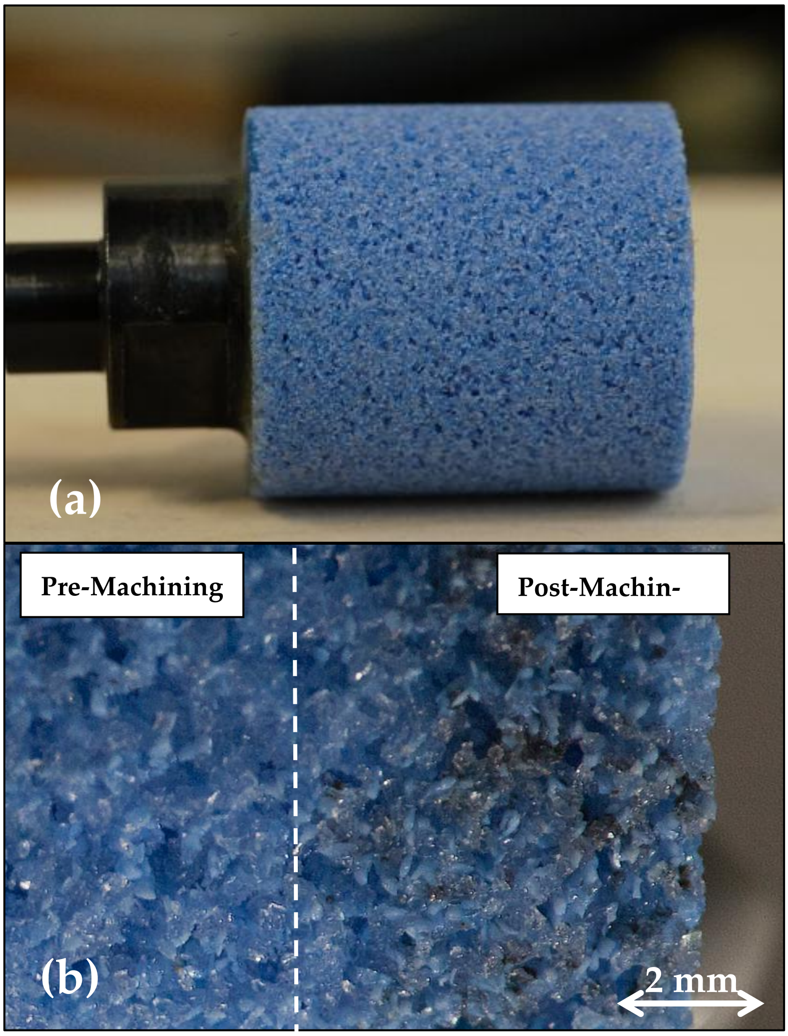

Figure 6. Example (**a**) macroscale image and (**b**) closeup of an alumina grinding wheel, pre- and post-machining.

Having manufactured a grinding wheel from the recycled abrasive grains, Mizobuchi and colleagues went on to test the hardness and water resistance of the recycled wheel, in addition to in-context polishing performance metrics such as surface roughness and a tool-wear-related loss ratio. In their work, the authors observed that both the hardness and the water resistance of the recycled wheels improved as the volume fraction of abrasive material increased, despite still not being comparable to those of a conventionally manufactured abrasive wheel (in this context). Nonetheless, although tool wear was only compared across recycled wheel types (not relative to a standard grinding wheel), and surface scratching was noted during a number of trials, the recycled tools were able to successfully polish the steel workpiece material, and under specific wet polishing conditions, surface roughness was found to be comparable to that of a standard polishing wheel.

Aside from attempts to retain old abrasive tools for other (non-typical) grinding applications [59], or to reconstitute grinding wheels from waste products [60–62], spent abrasive tools have also found industrial applications as aggregate in road surfaces [63] and as mortar in cement [64]. Moreover, many hobbyists repurpose old grinding wheels (which are retired due to loss, rather than defects) for use as stationary benchtop grinding stones, as a source of abrasive media for hand-deburring operations, or for use in rock tumbling. Likewise, whilst there are a very limited number of research articles focused upon chemical recycling processes for abrasive tooling, there may be scope to explore dissolution-based processes in the future (e.g., for metal bonded wheels); however, further work is needed to determine both technical and economic feasibility.

In addition to the recycling of tooling, research into the recyclability of spent grinding cutting fluids is similarly the topic of a great deal of recent discussion, primarily as a result of the litany of negative sustainability implications that are associated with the improper manufacture, management and disposal of cooling and lubrication media [65]. These limitations create an interest in the exploration of means by which the volume of consumed cutting fluid can be reduced, in addition to methodologies that can be applied to retain the quality of the fluid that is currently recirculating within the machining centre. In this regard, both on-machine filtration systems and the aforementioned briquetting processes retain a great deal of value within this domain. Briquetting is of a particularly unique value to the grinding process, largely because mechanically squeezing the grinding sludge is one of the only ways to separate the swarf material from the cutting fluid without destroying the latter.

Nonetheless, even when extremely effective management systems are employed, spent cutting fluids are still ultimately created (though at much lower volumes), and, likewise, the issue of reclaiming (and cleaning [66]) residual cooling and lubrication media from the generated swarf remains a cause for concern. In this regard, one frequently employed means of disposing of emulsion-based fluids is to evaporate the water content of the emulsion (which is often over 90% of the volume) and to make use of the retained oil as a fuel for combustors (or, if still of an acceptable standard, reuse as a coolant or lubricant), either with the outlook of generating ambient heating or in order to produce electrical power. Nonetheless, whilst this process is an efficient means of creating value from a waste product, there are a number of pertinent challenges associated with this re-use methodology. These include:

- Difficulties extracting fine ground swarf from the waste cutting fluid.
- Health risks associated with mobilising harmful microorganisms during evaporation.
- Poor cost-efficiency given the energy burden of heating the spent fluid, in addition to the labour costs associated with the process.

- Carbon dioxide emissions during the combustion of lubricating oil (i.e., as a consequence of the hydrocarbon groups found in esters).

Given these limitations, cost effective, sustainable means of recycling spent cutting fluids are in great demand, though short supply. Despite this, the early work of Schenach [67] remains pertinent within the domain of waste cutting-fluid recycling. In their research, Schenach outlines a process of allowing the fluid to settle, filtering out any solidus contaminants (i.e., swarf material), injecting said fluid with low-pressure stream both to kill bacteria/fungi and to separate out the "tramp" oil, and finally replenishing the emulsion with an additive concentrate. This process is of particular interest for two primary reasons: for one, and perhaps most importantly, it allows the lifecycle of the fluid to be prolonged significantly, while equally, maintenance can be accomplished within the machining centre itself, rather than via external machinery.

More recently a number of proprietary filtration and cutting-fluid management processes have been designed to both remove solid waste from the spent fluid and rid it of bacterial/fungal contaminants. In this regard, the former is often accomplished via a high-pressure, cartridge, bag or cyclonic filter [68], whilst the latter is accomplished via the use of ultraviolet (UV) lighting, or via heating of the media. Unfortunately, however, whilst these developments are promising for the future of fluid management, many of the currently available systems require significant refinement in order for them to be truly efficacious. Whilst this is in part a consequence of inefficiency in the process design (i.e., insufficient heating temperature/dwell time, or UV light intensity), many of these processes are likewise limited due to their sole focus upon the machining sump. This is due to the fact that the associated intermediary pipe network between the sump and the ultimate cutting-fluid delivery site is often likewise contaminated with bacteria/fungus, and as such, this leads to the spoilage of the otherwise clean fluid within the sump.

Ultimately these limitations make a strong case for exploring alternative cooling and lubrication media such as supercritical CO_2 ($scCO_2$) [69], minimum quantity lubrication (MQL) [70], or ionized air-based cooling/lubrication [71] strategies. In each of these scenarios, the necessity of a large machine sump filled with significant volumes of recirculating fluid is mitigated, and in doing so, the burden of ultimate disposal (in addition to the challenge of sustainable fluid usage) is likewise removed. Needless to say, many of these technologies remain in their developmental infancy, and as such, further research exploring the recyclability of conventional cooling and lubrication media is warranted.

For clarity, a structured summary of key cutting-fluid failure modes and the corresponding remediation strategies used to mitigate them is provided in **Table** .

Table 1. Summary of cutting-fluid failure modalities and potential remediation processes.

Cutting-Fluid Failure Modality	Indicative Diagnostic Metrics	Discussed Remediation Processes
Microbial spoilage	Bacterial load, odour, pH stability, sump temperature.	UV treatment, heating, low-pressure steam injection.
Swarf and particulate contamination	Fluid performance, surface roughness degradation, part damage, filtration system loading.	Briquetting, cartridge or bag filtration, cyclonic filtration.
Tramp oil accumulation	Fluid performance, odour, surface oil slicks, discoloration, foaming.	Filtration, low-pressure steam injection, settling-based separation.
Emulsion quality or stability degradation	Fluid performance, concentration changes, fluid phase separation, discoloration, foaming.	Concentration replenishment, additive replacement, integrated fluid management processes.

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4.5. Recycling and Reuse Strategy Summary

As Sections 4.1–4.4 cover a broad range of distinct materials systems and processing strategies, Table 2 is provided to consolidate key findings in a concise, digestible format. The table outlines the typical waste forms generated during grinding for each of the previously considered material species, in addition to the various methodologies that have been discussed as means for their recycling and reuse. Thereafter, the electrical power and consumable resources associated with those processes are explored, in addition to the volume fraction of waste that they can recover. Finally, the readiness states of any proposed technologies are considered and any bottlenecks that could hinder effective implementation are explored.

Table 2. Reported recycling and reuse strategies for abrasive process waste.

Material System	Waste Form	Prospective Strategies	Resource Demand	Achievable Recovery/ Re-use	Indicative Technology Readiness	Implementation Bottlenecks
HRSAs	Fine sludge of metallic swarf, abrasive tooling constituents and cutting fluid.	Centrifugation, liquid or non-aqueous based solvent cleaning, compaction, sintering, remelting, additive feedstock usage, electrolytic recovery, chemical recovery.	High (for thermal, electrochemical or staged processes). Moderate–High (for ferrotitanium).	Partial recovery of downgraded alloy products or secondary chemical derivative products.	Low–Medium.	Challenges separating swarf and non-metallic contaminants, oxygen pickup during processing, porosity and contamination issues in additive and sintering processes.
Steel and Cast Iron	Fine sludge of metallic (magnetic) swarf, abrasive tooling constituents and cutting fluid.	Magnetic separation, liquid or non-aqueous based solvent cleaning, compaction, sintering, remelting, additive feedstock usage.	Moderate–High (lower separation energy consumption than HRSAs).	High recovery potential for lower quality material.	Medium.	Oxidation, porosity and contamination issues in additive and sintering processes.
CMCs and Ceramics	Fine ceramic particulates and fibre fragments, mixed with diamond abrasive constituents and cutting fluid.	Potential for centrifugation, staged screening processes, fibre reuse, potential chemical processing.	High (if multi-stage high temperature thermal, and chemical processing is required). Moderate (if reliant on mechanical pulverization, separation and screening).	Low recovery potential in low quality aggregate or non-structural contexts. Very low recovery potential for direct CMC reuse.	Very Low.	Significant resistance to thermal and chemical processing, brittle material system prone to defects that would persist in a recycled product, fibre-matrix consistency makes fibre mat separation difficult.
CFRP and GFRP	Carbon and glass dust, uncut fibres, thermally decomposed polymer, carbonaceous residue, diamond abrasive constituents and cutting fluid.	Screening, resin dissolution (solvolysis), fibre mat extraction, pulverization and recombination with fresh matrix.	Moderate–High (if multistage high temperature thermal, and chemical processing is required). Moderate (if reliant on direct reuse of mechanically	Moderate recovery potential as a feedstock material for a low-quality secondary composite.	Low–Medium	Difficulty removing thermosetting resins, matrix degradation, thermal and coolant related fibre degradation.

			pulverized material).			
Abrasive Tooling	Radially spent abrasive composite grinding wheels, metallic or polymer bond materials, individual abrasive constituents.	Mechanical crushing, screening and sieving for reuse as secondary abrasives or fillers.	Low–Moderate (dependent upon the degree of pulverization and sieving required).	Moderate reuse potential in recycled cutting tools, or as waterjet abrasive, otherwise high reuse potential when relegated to road surface and other non-safety-critical filler materials.	Medium.	Highly resistant to chemical and thermal processing methods, cost efficiency challenges, bonding degradation.
Cutting Fluids	Emulsions and neat oils contaminated with fine swarf, particulates, fibres, tooling constituents and microbes.	Filtration, replenishment, microbial treatments, extraction via compaction.	Moderate (pumping load, heating demands, consumption during filtration).	Significant opportunities to drastically prolong use given proper maintenance, however, ultimate disposal relegated to combustion or landfill.	Medium–High.	Biofouling, fine particulate removal, system-wide contamination.

5. Sustainability

The UN's Intergovernmental Panel on Climate Change (IPCC) has determined that, should global warming be held to a maximum of 1.5 °C (which is deemed necessary to prevent frequent extreme weather events, ecosystem degradation and risk to human well-being), CO_2 emissions must fall to net zero by 2050 [72]. In response to these concerns, the manufacturing sector is faced with the challenge of improving the long-term sustainability of their operations; in this context, subtractive technologies are, as a result of both low buy-to-fly ratios, and elevated power/resource consumption rates, a topic of particular interest.

In this regard, given the significant energy burden that is associated with the manufacture of virgin feedstock/tooling material, both energy efficient recycling/reuse methodologies and strategies used to prolong tooling and cutting-fluid life are of irrefutable value. This is of particular importance in abrasive machining contexts, as many of the materials that are suited to abrasive machining methodologies are extremely energy-intensive to produce. Often this is a consequence of the high processing temperatures that are necessitated during their manufacture, the multi-stage thermomechanical processing that they require (in order to generate the desired properties), or the significant energy demand that is associated with extracting the constituent materials from ore. In this regard, the Task and Finish group [73] (on behalf of the UK's High Value Manufacturing Catapult) identified nickel, cobalt and tantalum as three of the four minerals with the greatest environmental, social and governance (ESG) risk (platinum being the fourth). All of these are present in components that are frequently ground (i.e., aeroengine blades and medical implants).

Building upon this topic, it is likewise true that many of the materials that are often abrasively machined, e.g., tool steel, are constituted of feedstock metals which are, as a consequence of significant consumption, of rapidly decreasing supply. Mohr and colleagues [74], for example, estimate that, as the recoverable iron stores (346 Gt) are depleted, the supply of iron ore is likely to fall rapidly from 2050 onwards, and approach pre-industrial revolution levels by 2150. Likewise, a number of the elements that are used in alloy additions of HRSAs (for example, molybdenum or rhenium) are growing increasingly scarce, and can cause significant emissions of environmentally harmful waste products during processing.

Similarly, the extraction of many of the aforementioned materials is often detrimental to the health of the individuals involved in the extraction process. Prolonged exposure to airborne molybdenum particulates, for example, have been shown to contribute to downstream lung health complications [75], whilst many chromium compounds are cardiovascularly, gastrointestinally and renally toxic [76]. Moreover, it is often the case that the conditions within which many frequently abrasively machined materials are extracted from the earth are a significant cause for ethical concern. One particularly important case study in this regard is that of cobalt production.

In osseointegrative knee implants, cobalt chrome (Co–Cr) is frequently the material of choice (Figure 7). In scenarios where Co–Cr is used, the back surface of the patella is generally ground so as to generate a low wear interface between the implant and the polyethylene cushioning of the tibial component. Unfortunately, however, whilst being an excellent low-wear, high-hardness material, a fraction of the cobalt that is used in Co–Cr may be sourced (intentionally or otherwise) from "artisanal" Congolese mines [77], which are often extremely dangerous for workers. Frequently, mining will be conducted without the protection of any breathing apparatus or skin protection, and often, the tunnels that are dug within the mines will be constructed without any internal scaffolding, leading to repeated collapses, and the ultimate injury or death of the workers within them [78].

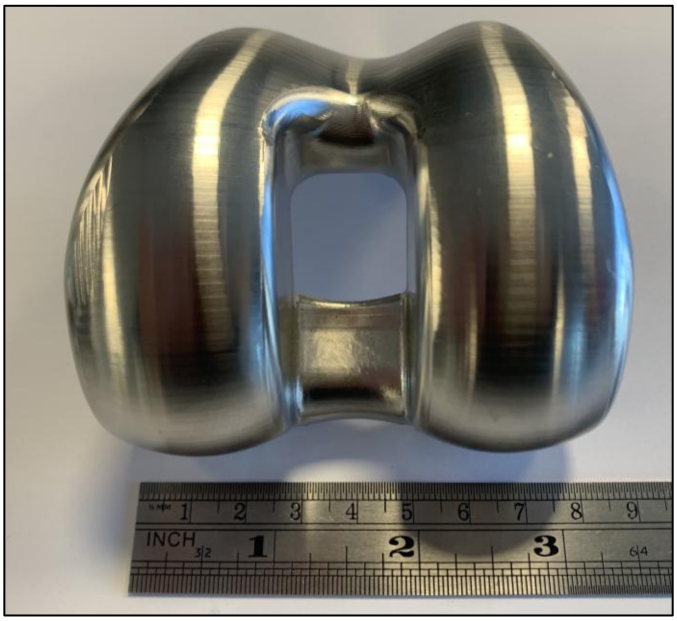

Figure 7. Example Co–Cr knee implant.

By recycling critical ground materials such as cobalt, industrialists are able to reduce the demand for new material, reducing the number of workers who are exposed to the often-hazardous mining processes, and thereby reducing the reach of the negative health implications associated with said processes. Clearly, this is a significant victory for sustainability; however, it is important to remember that reducing virgin material production is not an ethically perfect solution. Often the mining of critical minerals is one of the few viable career options in many impoverished regions, and as such, whilst the mines are a cause of significant suffering to workers, they also serve as a bulwark against poverty [79].

In this regard, if the demand for virgin material were to shrink as a consequence of increased material recovery, downward pressure on commodity prices could potentially reduce opportunity for the already deprived artisanal miners. This may be offset to some extent by the advent of new recycling processes and the associated creation of new employment opportunities; however, these jobs are not always accessible to economically deprived populations, and as such, the economic and social benefits associated with increased swarf recycling may not be fully realised.

In addition to recycling ground swarf, the availability of proper cutting-fluid recycling/management is likewise valuable. Adequate recycling protocol allows the useful life of the fluid to be prolonged, and in doing so reduces the volume of cooling and lubrication media that is either placed into landfill or combusted in a waste oil heater. Moreover, fluid management systems help to maintain quality, leading to superior long-term lubricity and cooling capacity of the fluid, which, in turn leads to lower power consumption within the machine tool and lower consumption of cutting tools, generating a significant both financial and environmental upside.

Equally, methodologies used to maintain cutting-fluid quality are likewise of significant benefit to the individuals working on the machine shop floor. By maintaining a clean fluid supply, operators are less likely to be exposed to microbially contaminated media, and thus, less likely to face the associated negative ocular, respiratory and dermatological implications of prolonged contact with spent cutting fluids [65]. Furthermore, even failing to acknowledge the immediate social and environmental implications of fluid management/recycling, the capacity to reduce the frequency with which industrialists require (often) expensive cooling and lubrication media disposal is a great financial incentive.

Ultimately, given the clear sustainability benefits of recycling and reuse strategies for abrasive machining, in concert with the (almost) £5bn governmental incentive structure for green industry [80], the recycling of abrasive machining waste clearly warrants further pursuit.

6. Conclusions and Future Work

The recycling and reuse of abrasive manufacturing waste is a topic of significant industrial and societal benefit. Nonetheless, analysis of the available scientific literature highlights the clear disparity between the volume of literature available on the recycling of conventionally machined swarf and that which is focused specifically on the unique challenges that are associated with grinding processes. Likewise, of the recycling methodologies that are documented, many are frequently proprietary to individual businesses (hence much of the available literature is in the form of patents), and as such, process specifics are often not available. As such, this review serves to highlight that the prospective growth of recyclability development has thus far been hampered by limited public domain access to established recycling methodologies.

In this sense, whilst the recycling of composites materials, for example, is, perhaps as a result of the extremely high degree of specificity of the subject matter, comparatively niche, the recycling of metallic grinding sludge remains a burgeoning field of increasing industrial interest. In this regard, a small number of scientific authors have explored chemical, hydro and pyrometallurgical means of recycling abrasive machining swarf, and although all processing variations have not been readily adapted for all material species, a precedent remains. Nonetheless, significant future work should be conducted to

- Characterise the viability of recycling processes previously developed for defined-edge cutting processes on grinding sludge (e.g., direct remelting).
- Explore chemical (e.g., dissolution-based) recycling processes for both non-metallic workpiece materials (e.g., monolithic ceramics, CMCs) and abrasive tooling.
- Undertake a cost–benefit analysis of current industrially available recycling processes.
- Further develop non-magnetic methods for separating swarf from abrasives in non-ferrous grinding sludge.

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- Assess the effectiveness of centrifugation as a means of removing non-alumina abrasive constituents (e.g., diamond) from grinding waste.
- Evaluate whether other non-alumina abrasive constituents (e.g., SiC or diamond) can likewise be re-used in shotblasting/waterjet machining applications, or, equally, whether they are suitable materials for road surface aggregates.
- Devise processing routes for coarsely ground CFRP swarf and, more broadly, pulverised carbon fibres in general.

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