safety

Review

Subtractive Manufacturing of Hazardous Materials: A Review

Leon Proud [1,*], Daniel Whitehead [1], Tom Slatter [2], Pete Crawforth [1] and David Curtis [1]

[1] Advanced Manufacturing Research Centre (AMRC), University of Sheffield, Catcliffe Way, Rotherham S60 5TZ, UK; d.whitehead@amrc.co.uk (D.W.); p.crawforth@amrc.co.uk (P.C.); d.curtis@amrc.co.uk (D.C.)

[2] Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Epinal Way Loughborough, Leicestershire LE11 3TU, UK; t.j.slatter@lboro.ac.uk

* Correspondence: l.proud@amrc.co.uk

Abstract

Whilst subtractive manufacturing has been de-risked significantly over recent decades, the emergence of new unfamiliar materials is proving to be a significant challenge for social sustainability. Given this rapidly evolving landscape, this review serves to outline the current available data on the occupational health implications of various existing and emerging material species, ranging from radioactive metals to composite materials. A structured search of sources up to January 2025 was conducted using databases such as Google Scholar, PubMed and Web of Science in addition to various authoritative occupational health reports, prioritising the literature directly pertaining or analogous to machining-related hazards. Evidence highlights the complexity of the machining environment, with occupational hazards ranging from toxicological factors to fire risks (i.e., due to swarf pyrophoricity). Case studies outline both relatively benign pathologies (e.g., dermatitis and sensitisation) and much more severe health complications (e.g., carcinogenicity, systemic organ damage and death), underscoring the need for continuous assessment and updating of exposure controls, even for materials traditionally regarded as safe.

Keywords: metals; beryllium; composites; ceramic-matrix composites; CMCs; irradiated materials; radioactive materials; machining; PPE; containment

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1. Introduction and Research Question

As new technologies are developed, advanced material species (e.g., fibre reinforced composites, titanium alloys, refractory metals and beryllium alloys) capable of tolerating (and thriving within) extremely challenging operational environments are increasingly necessitated. Whilst these materials are frequently indispensable, they are also often hazardous during handling, machining and disposal, posing risks to both machine tool operators and the broader natural environment. Recently, the occupational health literature has highlighted links between subtractive manufacturing process exposure and adverse health outcomes ranging from respiratory disease [1], cancer [2,3] and silicosis [4].

In beryllium-component manufacturing for example, machinists remain a particularly at-risk party for chronic beryllium disease (CBD) [5] and lung granuloma formation [6]. Comparable dangers exist when machining radioactive materials [7] which are only exaggerated by the compounding effects of pyrophoricity, criticality effects and broader radiological hazards. Whilst these cases are extreme examples, heightened concerns also exist when machining fibre-reinforced composite materials and ceramics, particularly due to the mobilisation of fine, often biopersistent, particulates/fibres [8]. If these concerns are to be mitigated additional manufacturing diligence must be applied.

Although this onus exists, many manufacturers remain ill-prepared for the challenges associated with the machining of hazardous materials. This often leads to either insufficient health and safety protocol being followed or an inability to support burgeoning technological workstreams. In the former case, this often places machine tool operators and the general public at risk; whilst the latter scenario frequently leads to bottlenecks within the manufacturing supply chain. These risks reflect a broader concern within the research literature that H&S readiness is not able to maintain pace with the changing technological landscape [9]. The European Agency for Safety and Health at Work (EU-OSHA) cautions that "new work situations bring with them new and emerging risks and challenges for workers and employers, which in turn demand political, administrative and technical approaches that ensure high levels of safety and health at work" [10].

Given these challenges, this work serves to review the existing literature available on hazardous materials, to establish which materials require additional diligence and, in those scenarios, to outline the prospective protocols necessary to facilitate their safe machining. In doing so, it seeks to address the overarching research question: "*What material-specific occupational hazards arise during subtractive manufacturing, and how can the available literature be employed to both characterise and inform the mitigation of residual risk?*"

In pursuit of this aim, this review provides new engineering-specific insights into how cutting parameters, material properties and process environments interact to determine risk. It highlights research gaps in the machining of irradiated materials and ceramic-matrix composites and proposes process-specific containment measures that extend beyond conventional OSH guidance, thereby bridging the gap between machining science and occupational health.

Overall, the research is intended to inform and contextualise occupational safety best practices rather than replace formal guidance. Accordingly, any specific interventions or control measures should be discussed with a qualified health and safety professional prior to implementation.

2. Methods and Structure

Building upon the overview and research question presented above, this section outlines the methodological approach and structural logic adopted for the review. The review itself is intended as both a preliminary tool to be used prior to onboarding new material species/manufacturing processes, and as a point of reference for continuous occupational health improvement. Within this framework, the methodology was designed to qualitatively assess the risk profile (i.e., nature, severity and likelihood) of various common and emerging subtractively processed materials.

A discussion of the exposure pathways which may occur during machining (Section 3.1) is first presented, followed by the types of hazards which may occur in industrial environments (Section 3.2). Thereafter, an exploration of the existing data that directly measures (or infers) the occupational health implications associated with exposure to a range of different materials (Section 4) is described. This begins with a section dedicated to metals (Section 4.1), followed by one on ceramics (Section 4.2), fibrous composites (Section 4.3) and finally radioactive materials (Section 4.4). A range of recommendations are then proposed to remediate the risk profile associated with these materials (Section 5). In accordance with the STOP hierarchy of risk control, this begins with containment, extraction and ventilation (Section 5.1), followed by manual handling (Section 5.2), and finally clean-up-related implications (Section 5.3). Ultimately the document concludes with a summary of findings and an outline of future work (Section 6).

The literature review process employed a structured scoping approach (non-systematic). Searches were performed primarily using Google Scholar, PubMed and Web of Science and were supplemented with authoritative occupational health and safety standards/reporting. Sources were considered up to January 2025, with older studies retained where more recent evidence was sparse.

The search process was iterative, employing combinations of machining- and hazard-related terms using Boolean logic (e.g., "beryllium AND inhalation, "machining AND (hazards OR exposure OR inhalation)). Example key terms included the following: "hazards", "inhalation", "dermal contact", "radiation", "occupational health", "exposure", and "fallout", in addition to a number of terms pertaining to the specific topic under exploration (e.g., ceramics, lead, beryllium, alumina, fibres, silicon carbide).

Typical queries resulted in several hundred results, which were then screened to remove non-exposure-based research and non-English language publications (for the most part) and to focus upon the literature directly related to subtractive manufacturing (occupational health) or analogous exposure scenarios. Approximately 140–160 publications were examined in full, retaining 70–80 for citation (supplemented by key standards and regulatory documentation). Findings were thereafter processed and categorised thematically by material class.

3. Background

3.1. Contact During Machining

Within the industrial environment there are numerous ways in which the workforce, general public or broader natural environment can become exposed to hazardous substances. Whilst it is not always possible to avoid making contact with hazardous materials, it is crucial that exposure is properly managed as doing so allows the risk profile of said hazard to be controlled. Of course, varying material species are generally not hazardous in the same ways and to the same extent, and as such, the permissible contact modalities (e.g., through handling, or inhalation) and exposure limits within said modality, whilst appropriate for one type of material, may not be acceptable for another material species. Moreover, machining environments frequently involve multiple, simultaneous exposure pathways, and as such, the combination of these factors can make the prescription of adequate H&S guidelines extremely complex [11].

For these reasons, it is crucial that the industry understands the ways in which hazardous materials can make physical contact with the machine tool operator should said operator engage with those hazards knowingly or unknowingly. With this in mind, it is worthwhile to first consider the five primary ways in which machine tool operators/shop floor staff could come into contact with hazardous material during subtractive manufacturing. These are as follows:

- Physical handling of the workpiece material.
- Physical handling of swarf (i.e., chips and dust).
- Lubricant/Coolant exposure (microbial spoilage and suspended workpiece contaminants).
- Inhalation of particulates/dust/fumes.
- Exposure to radiation

Considering these contact modalities individually, physical handling of hazardous workpiece material considers contact during fixturing, removal from fixture, transit, inspection, testing, etc. Whilst this modality is almost certainly the most frequent source of exposure, its associated risk is often (though not always) lower than the other contact modalities. Primarily this is because the material is contained within a single solid mass during manual handling (as opposed to being contained as swarf). This generally precludes inhalation/ingestion and reduces the risk of ocular contact, typically reducing the risk profile to localised tissue injury (which for all but the most hazardous materials, i.e., radioactive metals, is generally minor, e.g., cuts and scratches, allergic contact dermatitis, etc.) and makes personal protective equipment (PPE) usage intuitive to adhere to (i.e., cut-proof gloves).

Despite the limited risk profile associated with the physical handling of workpiece material, swarf handling is comparatively much more challenging. Swarf has a higher surface area to volume ratio than billet workpiece material and is often of a significantly smaller form factor. For this reason, it can be easily blown into the air or suspended in fluid. Moreover, this finer morphology increases both the risk of dermal contact and (potentially) the capacity to penetrate through damaged skin, further elevating risk. For these reasons, when machining hazardous materials, it often worthwhile to strive for a fully accountable and contained machining cell, wherein all swarf is retained within the machine tool and prevented from entering the broader manufacturing environment.

Equally, in metals and some composite materials, machining swarf can be sharp, and as such, presents a cut risk to both the individual and the individual's PPE. This effect is particularly concerning in nuclear environments where contamination control is a priority, but even with this aside, open wounds should be a significant cause for concern as they provide a direct pathway for hazardous contaminants to enter the bloodstream. Ultimately, these complications necessitate rigorous control during the handling of high-risk machining swarf (i.e., metallic chips and composite dust/fragments).

In a sense, the challenges which are associated with lubricant/coolant handling are related to those of swarf generation, wherein fine particulates, dust and chips generated during the machining process can enter the fluid. This (now hazardous) spent coolant can splash into operators' eyes, make contact with their skin and, when vaporised, be inhaled. Likewise, it is also possible that hazardous material suspended or dissolved within lubricant/coolant fluid could be ingested in small volumes, which, though of low risk for the majority of materials (in the volumes which may reasonably be ingested during use), could present a significant health concern in some scenarios. These factors combine with the inherent risk profile associated with the use of spent lubricant/coolant [12] to present significant risk to machine tool operators.

Finally, and perhaps most prevalently, are the risks associated with the inhalation of airborne dust within the machining environment. These factors are particularly challenging because fine particulates are invariably produced during subtractive manufacturing processes and yet are often difficult to detect visually. Frequently this can lead to the neglect (wilful or otherwise) of respiratory hazards [13], allowing material to be inhaled, damaging respiratory tissue and ultimately facilitating the entrance of said hazardous substance into the bloodstream (via either the mucosa membrane of the upper airway or the alveolar-capillary barrier in the lungs).

Whilst this risk is markedly increased when machining hazardous materials, respiratory hazards have long since been associated with both machining and production work in general. In one 2020 article, Cummings and colleagues [14] conducted spirometry on a total of 388 workers across four manufacturing facilities, repeating testing after a 3.5 year follow up period. In their study, the authors reported that 11 of the 250 follow up participants exhibited a greater than 10% decline in forced expiratory volume over one second (FEV_1). Crucially, 10 of the 11 participants worked in a production (shopfloor) environment, stated by the authors to consist of the following: "a machine shop, welding rooms, paint booths and an assembly area where components were pieced together".

Ultimately, whilst the contact modalities which cause production workers to be harmed by hazardous materials are somewhat intuitive, the ways in which the public are exposed to hazardous materials (processed within the machining environment) is often less obvious. Typically speaking, contact occurs by improper disposal of machining-related waste products, wherein swarf and waste workpiece material is inappropriately landfilled, contaminated metalworking fluids are emptied into the waterways and fumes/airborne particulates are not properly managed

3.2. Types of Hazards

As an increasingly broad range of novel materials are machined, the types of hazards which machine tool operators (and the population in general) are exposed to, likewise, grow in tandem. These hazards can be categorised in a range of different ways. Although, it is perhaps most intuitive to consider the vector by which each hazard causes damage, therefore, this process is followed when categorising hazards in Table 1.

Table 1. Types of hazards present within the machining environment.

At Risk Party	General Type	Specific Type	Description/Examples
Human	Cellular Damage (Chemical/Biological)	Carcinogens	Carcinogens are substances/agents which cause cancer [15]. These are a significant risk factor within occupational health. Some examples include beryllium/beryllium compounds, asbestos, cobalt, chromium compounds and nickel.
		Toxicants/Chemically Toxic Substances	Toxicants are substances which cause harm through chemical action on biological tissue. They should not be confused with toxins, which are poisonous substances generated by the metabolic processes of living organisms [16]. Examples of toxicants include the following: beryllium, lead and chlorinated paraffins.
		Microbial Contaminants	Microbes are present in all scenarios, not least of which, within the machining process. Microbes in and of themselves are not inherently hazardous, although some species of microbes are harmful to life. Lubricants and coolants contain a high water content and lots of fats, providing a favourable environment for microbial growth. Additionally, biofilms often grow throughout the CNC machining centre and can be transferred to machined surfaces. Examples of specific microbial contaminants which might occur in metalworking fluids include mycotoxins (e.g., aflatoxin B1) and endotoxins [17].
		Irritants	Many materials and consumables used within machining processes are susceptible to microbial contamination and can induce discomfort/irritation; these include metalworking fluids and many species of swarf. In addition to these intuitive irritants, tramp oil may also irritate the skin and, as is often the case with lubricant oils, could lead to allergic contact dermatitis [18].
		Teratogens	These are substances which cause abnormalities during foetal development/cause congenital disability [19]. Example materials range from solvents, polymers (such as epoxy) and heavy metals such as lead and cadmium.
		Mutagens	Substances regarded as mutagenic are capable of inducing permanent changes to genetic material [20]. These are less common within the engineering environment; however, radioactive materials and heavy metals are mutagenic, as are polycyclic aromatic hydrocarbons (which may be generated during polymer machining) [21].
		Neurotoxicants	These are substances which alter the function of the nervous system [22]. Though not particularly commonplace during machining processes, heavy metals such as lead are regarded as neurotoxicants (see toxins for the distinction).

Table 1. *Cont.*

At Risk Party	General Type	Specific Type	Description/Examples
Human	Cellular Damage (Chemical/Biological)	Endocrine Disruptors	Materials and consumables which impact the human hormonal system are relatively commonplace within industrial environments; however, severe endocrine disruption is much less so. Of the endocrine disruptors which do occur in the machining environment, many are associated with the machining of polymers or heavy metals.
		Allergens	Fundamentally, allergens are substances which, though benign to many, produce an immune response in some portion of the population [23]. Many frequently machined materials can generate an allergic reaction when the individual is subject to consistent or prolonged exposure (e.g., chromium, nickel and cobalt). Dust and particulates can also generally be an allergen.
	Physical	Corrosives	Whilst there are limited examples of corrosive material which requires machining, many solvents and etchants used on machined components are corrosive and thus must be controlled to prevent damage to life, tooling/equipment and the environment.
		Radioactive Substances	Radioactive/irradiated material is a physical cause of cellular damage, cancer and acute radiation sickness (amongst other ailments). Anyone in contact with radioactive material must be mindful of their exposed dose of radiation in order to determine relative risk.
		Fire Hazards	The increased surface area of machined swarf relative to the bulk workpiece material heightens fire risk, particularly in metals such as titanium and its alloys. In addition to the combustion of typical engineering materials, there are also a range of novel materials, i.e., zirconia, which are pyrophoric and may necessitate special considerations.
		Ballistics (i.e., from explosions and rupture)	During machining, both workpiece materials and tooling can rupture causing the expulsion of projectile material. This material can cause injuries to individuals proximal to the machine tool. Injuries caused by machining shrapnel are increasingly concerning when hazardous (carcinogenic, toxic or radioactive) materials are used.
		Burns	The significant plastic deformation and friction associated with machining processes generate large amounts of heat. Often, this heat is expelled through the generation of chips which frequently leave the cutting tool at high velocity. These chips can cause burns. Hot chips are much more common in dry machining processes, such as those which make use of ceramic cutting tools. Additionally, in cryogenic-cutting-fluid-assisted processes, there is the additional risk of cold burns to the operator as a result of contact with the cryogen [12].
		Slips	Though not always a consequence of the machining processes, some contaminants generated during machining can enhance the risk of slippage. Generated swarf and dust, particularly carbon, which is often used as a solid lubricant [24], can create slippage risk. Any cutting fluid on the floor around the machine tool can cause slippage.
Environmental	Airborne Pollutants	Dust/Swarf	Many particulates which are generated during machining processes (i.e., swarf/dust) are light and small enough to be mobilised by the air. This can lead to inhalation by individuals proximal to the process.
		Cutting Fluid Mist	As cutting fluids evaporate or are otherwise sprayed into the air by the cutting process/delivery mechanism, they generally produce a fine particulate mist comprising either cutting fluid suspension or atomised constituents (hazardous and otherwise). When inhaled this can lead to a range of negative health implications in humans, including the following: bronchitis, alveolitis and cancer [25]. It also follows that this mist may be detrimental for other non-human animals and plant life, although this requires further exploration.

Table 1. *Cont.*

At Risk Party	General Type	Specific Type	Description/Examples
Environmental	Airborne Pollutants	Irradiated Particulates	Any particulates produced during the machining of irradiated material are themselves likely to be irradiated. This presents a particular risk as small material is capable of being suspended in air and fine particulates often spread across broad areas.
		Aerosols and Chemical Emissions	During the machining of some materials aerosols and chemical emissions can be generated that are harmful upon inhalation and potentially detrimental to the environment. These include metallic fumes (e.g., lead, beryllium), cutting-fluid mists and volatile organic compounds which are particularly prevalent during the machining of polymers or polymer-matrix composites.
		Greenhouse Gas	Many manufacturing processes generate greenhouse gases. Often, these pollutants contribute to climate change (which has the capacity to adversely affect life), and, in some cases, these gases can pose an asphyxiation risk. Carbon dioxide is the primary greenhouse gas associated with machining processes; wherein significant volumes are produced during the power generation necessary to operate the machine tool. In addition, other sources of carbon dioxide can be generated within the machining environment, such as that which is produced during CO_2-assisted metalworking fluid usage.
	Waterway Pollutants	Spent and Contaminated Cutting Fluid	Microbially spoiled coolant re-entering the waterways, e.g., via drainage. Coolant containing hazardous pollutants re-entering the waterways either by improper waste classification, improper disposal or errors at landfills.
		Dust/Swarf	Swarf and dust are often suspended in spent cutting fluid and, if the machine tool is not properly contained, may be present elsewhere in the machine shop, i.e., within mop water.
		Other Suspended Solids	In addition to swarf and dust, other suspended solids can be present within spent cutting fluids and machine shop water supplies. These can include fragments of tooling, fixturing and other materials present within the machining environment.
		Radioactive Particulates	Radioactive particulates may be present within both the spent cutting fluid (its accompanying filtration system) and any wastewater generated within the machining environment. These can re-enter the waterways by improper waste classification, improper disposal or errors at landfills.
	Landfill	Improper Waste Categorisation	Hazardous materials should not enter general waste disposal/recycling channels. Harmful or carcinogenic material could be placed into general disposal means, which would place both sorting agents and the general public at risk of contact.
		Hazardous Contamination of Non-Hazardous Material	Similarly, if a material has been exposed to hazardous contaminants, it should itself be regarded as such. In these scenarios it is important to seek guidance if it is not abundantly clear how the waste should be disposed of.
		Radioactive Material Disposal	Radioactive material falls into a disposal category unique to itself. Irradiated material cannot be disposed of through conventional (civilian) means and generally must be encased with a protective shielding to prevent the irradiation of proximal life. Radioactive waste should not be handled by humans, and as such, even if the irradiated material does not enter into the waterways/airways, in general it presents a significant danger to both handlers and adjacent plant/animal life. Historically, there have been a number of cases wherein radioactive material has been improperly disposed of; with the most prominent case study being the pollution of lake Karachay in central Russia [26].

The relative significance of the hazards which are listed in Table 1 also varies widely between machining contexts, providing important context for the subsequent sections. Clearly, whilst numerous hazards exist within industrial environments, it is also important to note that not all of the hazards discussed are equally present within the machining environment. In this regard, whilst hazards related to swarf and metalworking fluid use are extremely common, many of the other hazards listed would only be likely to occur in very niche machining contexts, and as such, do not necessarily warrant the same amount of diligence. As an example, whilst managing the hazards of radioactivity is the first priority for the small number of businesses who machine irradiated material, for the vast majority of machine shops it is wholly unnecessary to prepare for such eventualities.

Nonetheless, the industrial landscape is rapidly evolving. As such, whilst it may not be an efficient use of resources to prepare for every possible hazardous substance that could occur within the machining environment, emerging technological demand is rapidly changing the range of materials which manufacturers face. For this reason, ongoing assessment of specific hazard classes is essential to ensure preparedness for these emerging materials.

3.3. Standards and Regulatory Environment

A detailed description of legislation concerning these types of processes is beyond the scope of this review as it can vary by application, industry, country or region. Nevertheless, it is worthwhile to note that this regulatory variability often leaves end users with limited or fragmented guidance relative to other occupational safety domains. In this sense, although there is significant regulatory information concerning the design and manufacturing of machine tools, these requirements are distributed across multiple frameworks and can be difficult to interpret in practice. Adjacent to this, are the more general workplace health and safety related regulations, often agreed internationally, that work in conjunction with those machinery-specific documents.

Concerning machine tool operation specifically, a number of key international standards directly define baseline safety expectations for equipment design, guarding and containment. Examples of which include ISO 16090-1 (Machine tools safety—Machining centres, milling machines, transfer machines) [27], ISO 23125 (Machine tools—Safety—Turning machines) [28] and ISO 16089 (Machine tools—Safety—Stationary grinding machines) [29] which collectively describe a number of basic precautionary measures to eliminate hazards or reduce risks across, milling, turning and grinding machine tool usage. Whilst these resources provide an essential framework to de-risk machining processes, they fail to consider the additional complexities associated with emerging materials and machining strategies, making process- and material-specific assessments crucial.

In order to undertake such assessments, resources such as safety data sheets (SDS) are a critical resource for individuals handling hazardous materials. These documents outline safe handling and storage practices for a given material, in addition to providing procedural advice in the event of an emergency situation (i.e., spillage, human contact, etc.). These tools are not only a critical asset for educating at-risk parties and generating risk assessments but are also often necessitated by legal imperative. Nonetheless, SDS are, as a rule, generic documents, and as such, may not adequately account for the complexities of the manufacturing process which the material will be subjected to and the ways in which said process will impact the risk profile of the material. In this regard, such generic documentation is rarely able to consider how cutting mechanics (i.e., feed rates, cutting speed, uncut chip thickness, depths of cut, etc.), coolant strategy (e.g., flood coolant, high pressure through tool, minimum quantity lubrication, cryogenic machining, supercritical carbon dioxide, etc.) or chip morphology affect exposure risk. For these reasons, though critical for risk mitigation, SDS documents require supplementation and should not be relied upon unequivocally.

Similar can be said for the test standards and accompanying documentation developed by regional and international organisations (e.g., British Standards Institution (BSI), ASTM

International (ASTM), Deutsches Institut für Normung (DIN), Japanese Industrial Standards Committee (JISC), International Organization for Standardization ISO). Though often valuable, these standards typically relate to the method of sampling hazardous materials (for the purposes of workplace health and safety) rather than best practice for their safe processing. For this reason, these standards generally have disclaimers to prevent their misapplication; for example, ASTM documents often state "This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use." [30].

Ultimately, the timescales required for development and publication of test standards can be necessarily lengthy, requiring interlaboratory studies and international collaboration. This means that formal guidance can lag behind the requirements of users processing emerging hazardous materials or known materials using a new process, underscoring the need for proactive, engineering-led continuous assessment and review of safe machining practices.

4. Material Species Risk Profile

Whilst a proper understanding of material-specific risk is essential for achieving positive occupational health outcomes, direct human exposure data is not available for all of the materials discussed in the proceeding chapter. For this reason, although human data is prioritised wherever possible, toxicological studies involving animal models are referenced where mechanistic context in humans is lacking. These studies are interpreted qualitatively to illustrate if, and how, a given material causes harm, rather than to define quantitative exposure thresholds. The resulting insights are thereafter integrated with engineering considerations when evaluating machining-related risk.

4.1. Elemental Metals and Alloys

Although the manufacturing of metals has taken place for many thousands of years, the risk profile associated with their machining is rarely afforded the diligence it requires. As with any material species, there are hazards which are associated with the material class broadly, and hazards which are unique to a given type of metal or alloy, both of which are important to consider. One hazard which is common to a number of metals is the fire risk associated with their chips.

During machining, swarf often reaches an extremely high temperatures and is often exposed to increased oxygen content (per volume of material) as a result of its markedly increased surface area (relative to a billet of metal for example). In this regard, whilst many metals are combustible, they are not all equally susceptible to ignition. In fact, whilst a number of varieties of metals chips are extremely low ignition risk, others require significant precautions to be taken.

One of the metals which is at the greatest risk for combustion is magnesium and its alloys. In one recent article, Kuczmaszewski and colleagues [31] explored both the ignition temperature and time to ignition during the dry milling of magnesium alloys, noting that at a temperature of approximately 500 °C time to ignition ranged between 2 and 12 s, whilst at lower temperatures time was markedly prolonged. The authors went on to note that at the temperatures generated during machining trials chip formation was sufficiently rapid to limit combustion risk.

Despite this proclamation, the authors recommend the avoidance of cutting parameters which induce chip refining/intermediate chip fractions, as these refined chip geometries markedly increase the risk profile of magnesium machining processes. Practically speaking this would involve proper selection of parameters such as feed rate and depths of cut to assure desirable chip formation mechanics.

It is important to note that whilst emulsion coolant is commonplace for many materials, and may seem intuitive in a fire risk context, dry machining is generally regarded as best practice for magnesium. This is because water-based coolants (i.e., emulsions) often react with the metal and produce highly flammable hydrogen gas [32].

Despite this industry consensus, prior research has indicated that the volume of hydrogen produced when machining magnesium with water-based coolant is very low [33], and as such, the avoidance of coolants/lubricants may warrant future revision. In any case, it is worthwhile to remark that magnesium chips are markedly more valuable when machined without coolant, and as such, market-based factors may be a more significant driver for dry machining in this case.

Whilst the fire risk of magnesium and its alloys has been explored relatively extensively in both milling [34] and turning models [35], other combustible metals such as titanium alloys are less frequently considered. Although this is an intuitive consequence of the lower fire risk associated with titanium chips (relative to magnesium chips), the combustion of titanium swarf remains an important topic for evaluation.

The combustibility of titanium was explored by Takemoto and colleagues [36] who investigated the high-speed dry turning of Ti-6Al-4V. In their work the authors employed cutting speeds in the range of 200 m/min and 1000 m/min in addition to feed rates ranging from 0.005 mm/s and 0.05 mm/s, observing that chip temperature, and in turn, incidences of combustion increased as cutting speed increased and as feed rate decreased. They also noted that increased tool wear corresponded to a reduction in the critical cutting speed required for combustion.

Having noted these observations, it is perhaps unsurprising that the current best practice for the machining of titanium alloys makes use of abundant high-pressure coolant, and further, that dry machining is generally regarded as unsafe. In addition to abundant coolant use, assuring proper chip evacuation and regularly cleaning the machine bed remain good practices across many materials, even those with lower combustion risks.

Aside from fire risks, many metals present significant chemical/biological risks. Within nuclear power generation for example, the critical mass of a reactor (the minimum fissile material required to sustain a reaction) can be significantly reduced by enclosing the core within an envelope of material capable of reflecting the neutrons back inwards (into the core). Whilst these neutron reflectors can be made of materials such as graphite or tungsten, beryllium is often a preferred choice [37] due to its higher neutron scattering cross-section and reduced atomic mass (with the latter facilitating improved moderation and isotropic scattering).

In this regard, whilst beryllium and its compounds have marked benefits over more commonplace materials, they have been shown on numerous occasions to be carcinogenic to humans [38]. Most importantly, a strong correlation has been established in the literature between beryllium exposure and lung cancer [39], wherein inhalation of particulates/dust is a particular risk factor [40].

In 2003 Gordon and Bowser [41] conducted a systematic review on the genotoxicity and carcinogenicity of beryllium. Throughout their work, the authors noted that in both the epidemiological and animal studies, which were conducted prior to the review, beryllium exposure was linked to increased incidences of respiratory tract cancers. The authors highlighted that specific links between beryllium exposure and cancers of the trachea, bronchi, and lung have been observed across rat, hamster, and non-human primate models.

During one animal carcinogenicity study, a single exposure of beryllium metal aerosol for 8–48 min at 410–980 mg/m^3 generated lung tumours (most frequently adenocarcinomas) in 64% of exposed rats [42]. Similar observations were made during both a long term (180 days) beryllium sulphate exposure study [43] and an investigation into beryl ore exposure (in rat models) [44]. Despite this, the latter study also indicated that there was no increased incidence of cancer when both rats and hamsters were exposed to bertrandite ore. This contrast between the cancer-inducing properties of beryl ore compared to the relative benignity of bertrandite ore is likely a consequence of the much-reduced beryllium content which is present within bertrandite ore (relative to beryl ore) [45].

In addition to research exploring the carcinogenicity of beryllium, prior work has also been conducted to investigate the relationship between beryllium exposure and both beryllium sensitization (BeS) and CBD [46]. In that paper the authors observed that within a 'precision Beryllium machining plant' the prevalence of CBD/BeS was markedly higher amongst machine tool operators, wherein 11.5% of machinists were diagnosed with CBD/BeS relative to 2.9% elsewhere in the company.

Likewise, the authors noted that machinists were more likely to be exposed to smaller beryllium particles than other non-machining professions and that the beryllium exposure limits defined by US Occupational Safety and Health Administration at the time of the study were insufficient to protect workers from adverse beryllium-related health effects [47]. The latter observation was made because the majority of workers who developed CBD/BeS did so at an exposure below 2 $\mu g/m^3$. This observation serves to justify the marked tightening of the EU occupational exposure limit for beryllium to 0.2 $\mu g/m^3$ by 2026 [48], highlighting the discrepancy between historical and present-day regulatory thresholds.

It is also worthwhile to note that, despite significant evidence supporting the health hazards associated with beryllium exposure, there currently is no scientific consensus on the extent of the risk caused by beryllium nor, even more fundamentally, on the mechanisms by which beryllium causes harm. In this sense, a 2023 paper published on the topic [49] examined the four currently proposed mechanisms for beryllium toxicity and found that it was not possible at this stage to determine which, if any, of the models were most likely to be representative of the real mode of cellular damage generated by beryllium.

The authors state that in order to isolate the true mechanism of toxicity it would be necessary to determine the position of the beryllium cation within a protein complex. Whilst this is a challenging prospect, the near atomic resolution of techniques such as single-particle electron cryo-microscopy (cryo-EM) may make it possible to directly observe where and how the beryllium ion binds, particularly given an existing precedent within the literature [50].

Whilst beryllium toxicity is the topic of a significant amount of the scientific literature, many other chemically/biological hazardous metals are not discussed nearly as frequently. In some cases this is a consequence of the reduced risk profile of those materials, whilst in others recent consideration is not always warranted as current protocol is effective or the material may be in the process of being replaced by other material species.

One highly toxic material which is discussed frequently however is that of lead and its alloys, which is linked to decreased cognitive performance [51], cancer (tentative) [52], essential tremor (ET) [53], elevated blood pressure [54], decreased renal function [55] and fertility problems (amongst others) [56]. Recently the US Centers for Disease Control and Prevention (CDC) published a report on the full range of possible health effects which can be caused by lead exposure [57]. In their report the authors afford specific effort to exploring the impacts of lead toxicity within children, adults and pregnant women, the unique risks which should be managed in each case and their relationship to the mass of lead which the individual is exposed to.

The authors reference an earlier report from the American Academy of Pediatrics who state that, whilst the CDC uses a blood reference value of 3.5 $\mu g/dL$, "there is no identified threshold or safe level of lead in blood" [58]. In this regard, whilst 2.6% of preschool aged children in the United States, and 1 in 3 globally, had a blood lead concentration of 5 $\mu g/dL$

or greater (prior CDC reference cutoff, and current UK Health Security Agency cutoff), impairment of intellectual function and development is likely to precede these exposure values [59].

Lead exposure during pregnancy is associated with reduction in birth weight, postnatal growth, head circumference and height, in addition to delayed pubertal development [60]. Many of the negative health implications of lead exposure are associated with the inhibition of "iron, zinc and calcium, minerals essential to proper brain and nerve development" [57]. Unfortunately, individuals can become exposed to lead via a range of means, most commonly via ingestion and inhalation, but likewise from both endogenous and dermal routes (i.e., absorption through cuts and abrasions from external contact, or embedded objects).

Within the machining environment, inhalation and dermal absorption are commonplace. The former exposure methodology is typically a consequence of the mobilisation of fine lead dust generated during the machining process, whilst the latter mode of exposure is often caused by handling of the workpiece material (pre- and post-machining process) and dermal exposure to dust or contaminated metalworking fluid. Aside from inhalation and dermal absorption, the risk of ingestion post-machining process also warrants consideration. The aforementioned dust can be transferred to the skin and can thereafter reach the mouth (by contact with hands for example) and be ingested, ultimately necessitating rigorous handling and clean-up protocol to be in place throughout the machining process.

Whilst beryllium and lead are likely the most chemically/biologically hazardous metals which are frequently machined, a number of other metals are also potentially hazardous to machine tool operators. These include the following:

- Chromium compounds and alloys.
- Cobalt and cobalt-based alloys.
- Cobalt chromium alloys.
- Nickel and nickel-based alloys.

Of these four metals, chromium, though often used as an alloy addition, in its solid form is the least frequently machined, finding very few use cases. Nonetheless, contact with chromium is implicated with a number of chemical/biological hazards. Most pertinently, a small fraction of the population is allergic to chromium and, when making dermal contact, can develop allergic contact dermatitis [61]. Whilst this can be easily mitigated by proper manual handling control, the inhalation of chromium (albeit, generally chromium III or VI which are unlikely to be present within the machining environment) often causes inflammatory changes to the respiratory tract and has the capacity to illicit mutagenic and/or carcinogenic effects in humans.

Likewise, both nickel and cobalt can similarly generate adverse autoimmune responses in a number of individuals. Again, this primarily manifests as forms of allergic contact dermatitis. In one recent publication from Schuttelaar and colleagues [62], the prevalence of sensitization to a number of metals was studied. Across the five European countries (The Netherlands, Germany, Italy, Portugal and Sweden) included in the study, the age-standardised sensitivity prevalence to nickel, cobalt and chromium were 14.5%, 2.1% and 0.8%, respectively. Interestingly, nickel allergies were found to be markedly more common in women, particularly those which have past or current piercing use.

Aside from dermatitis, Public Health England (which as of 2021 was supplanted by the UK Health and Security Agency (UKHSA)) identifies a number of other negative health implications associated with Nickel exposure [63]. Acute ingestion is said to be associated with nausea, vomiting, diarrhoea and headaches whilst chronic inhalation can lead to "rhinitis, sinusitis, anosmia and in extreme cases perforation of the nasal septum". In addition to these health implications, the International Agency for Research on Cancer

(IARC) states that Nickel compounds are carcinogenic to humans (Group 1, i.e., known to cause cancer) whilst metallic nickel is possibly carcinogenic to humans (Group 2B) [64]. This observation (that nickel compounds present greater carcinogenicity risk) is consistent with the findings of Public Health England who noted that an enhanced risk was associated with nickel carbonyl relative to metallic nickel.

The carcinogenicity of cobalt has similarly been explored by the IARC, who classified both cobalt metal and soluble cobalt (II) salts as probably carcinogenic to humans [65]. This determination was reached as a consequence of evidence of cancer in animal models in addition to strong mechanistic evidence in human primary cells. In addition to carcinogenicity, the inhalation of cobalt metal dusts has been linked to "interstitial fibrosis, interstitial pneumonitis, myocardial and thyroid disorders and sensitization of the respiratory tract." [66]. Moreover, polycythaemia and erythroid hyperplasia of the bone marrow have previously been identified during animal cobalt trials [67].

Finally, cobalt chromium (CoCr) may be subject to unique chemical/biological risks, but in any case, is implicated with some of the specific risks which are associated with exposure to both cobalt and chromium in isolation. Over recent years, both the occupational risk profile associated with the production of CoCr components and the medical risks associated with exposure to CoCr within a clinical setting (i.e., the recipients of osseointegrative joint replacement) has been increasingly explored. Unfortunately, however, whilst occupational research has focused upon the manufacture of CoCr medical implants, there is limited research which pertains to the specific risk faced by machine tool operators and the machining industry at large.

One paper on this topic was written by Leghissa and colleagues [68] who monitored both the cobalt and chromium content within the urine of 31 individuals employed in dental prosthesis production. In their study, the authors sought to characterise which processes within the manufacturing environment, i.e., analysis and duplication of plaster cast model in hydrocolloid and/or silica, wax modelling, coating in refractory material, dowel application, alloy melting, casting and finishing (machining), lead to the greatest exposure. In this regard, finishing, which is undertaken by hand via the use of "rotating cutters at variable speeds from 4000 to 20,000 RPM" was found to be the manufacturing process which led to the greatest exposure.

When compared to casting (which featured the next greatest exposure), the finishing environment (non-ventilated) contained 150% more cobalt and equivalent chromium content (0.05 mg) per cubic metre of air. Throughout the study urinary cobalt levels ranged from 0.8 to 6.6 μg/L throughout the day whilst average levels ranged from 1.13 to 1.91 μg/L. Notably these average cobalt levels are markedly higher than the previously observed general population averages of 0.57 ± 0.1 μg/L [69]. Contrastingly, only the post-shift average chromium levels which were observed on one of the two tested days exceeded the population average levels (0.69 μg/L as opposed to the reference value of 0.61 ± 0.11 μg/L), and even in this case statistical significance cannot be inferred.

As such, whilst chromium/cobalt levels were not systemically raised in all workers operating in a mechanical finishing capacity, in many individuals' urine cobalt was heightened by the presence of airborne dust/swarf. Unfortunately, this work does not highlight which health and safety protocol was in place at the production centre beyond the fact that the finishing process was conducted "by hand". In this regard, it is not possible to determine if personal protective equipment (PPE) was not provided, if PPE was provided but not used, or if the PPE was inadequate, and as such, it is impossible to make production-based suggestions in this area.

Despite these observations, the presence of elevated chromium/cobalt levels in the air infers either an inadequacy in or absence of the localised extraction of said dust and swarf.

As such, given that exposure to these materials is implicated with a range of negative health outcomes, dust/swarf containment and inhalation avoidance should be regarded as a priority for the subtractive manufacturing sector.

Aside from occupational risk, there is currently significant debate as to the extent and frequency of toxicity related complications in CoCr implants. One recent study from Samaragandi and colleagues [70] explored the case of a 64-year-old woman who presented with symptoms of CoCr toxicity after having undergone a CoCr on polyethylene revision of a fractured ceramic hip joint prosthesis. Whilst the patient initially reported positively as to the efficacy of the hip replacement surgery, approximately a year post-surgery the patient developed sudden deafness in the left ear, followed by fluctuating deafness in the right ear. Shortly thereafter the patient began to present with a reduction in visual acuity, hypothyroidism, neuropathy and ultimately an inability to walk; symptoms which, though incorrectly diagnosed a number of times, were ultimately found to be a consequence of CoCr toxicity.

Importantly, the patient's symptoms were attributed to abrasion of the CoCr hip joint caused by residual hard third-body abrasives remaining from the previous hip replacement surgery. These abrasives ultimately wore down both the polyethylene bearing surface and the CoCr prosthesis, leading to CoCr poisoning. In this regard, whilst contact should be managed, this volume of exposure is not likely to be commonplace during typical surgical intervention and, in any case, is almost certainly not representative of typical machining exposure.

4.2. Ceramics

Although ceramic materials are a species in and of themselves, many ceramics are metal compounds, and as such, are generally subject to many of the same risks of the metallic materials of which they are composed. One pertinent example in this regard is that of beryllium oxide (beryllia), which is implicated with many of the same risks of beryllium metal (Section 4.1). It is carcinogenic, can cause CBD, irritates both the eyes and respiratory tract (potentially causing pneumonitis) and is dermally hazardous.

One important difference, however, between beryllia and beryllium metal is the fact that dust generation during machining is invariable when machining beryllia due to the fact that ceramics are brittle and do not form the sort of chips which are commonplace for metals. In this sense, whilst dust and fine particulates are generated during the manufacture of metals, they are created in significantly greater volume when machining ceramics.

An additional concern is that engineering ceramics, owing to their inherently high hardness, tends to generate large volumes of abrasive third body debris during the machining process. This material can then readily become airborne during machining, presenting significant operational challenges to the machine tool and producing a tangible inhalation risk for the machine tool operator. These dangers are particularly exacerbated when cutting chemically/biologically hazardous materials.

Aside from beryllia, which is highly hazardous to inhale, even commonplace ceramics present a marked inhalation risk. Many naturally occurring ceramic materials and some functional ceramics contain silica which can be liberated during cutting processes. In those scenarios, respirable crystalline silica (RCS) may be inhaled which can lead to negative health implications such as silicosis. In one recent paper discussing this subject matter, Pascual del Pobil y Ferré and colleagues [4] studied the incidence rate of silicosis across 485,917 attendees of the University General Hospital of Alicante and the University Hospital of San Juan.

In their research, the authors found a total of 19 cases with a mean age of 51.58 ± 15.74 years. Importantly, 68.4% of patients were employed in the handling of artificial quartz aggregates (AQA) as either an assembler, cutter or sander of kitchen and bath countertops with crystalline silica contents of 70–90%. Of the remaining six cases of silicosis, one occurred in a woman who worked in a dental laboratory setting finishing dental prosthesis, whilst the occupation of the remaining five cases were not described within the study.

Importantly, the vast majority of silicosis incidences occurred in those that were involved with the subtractive processing of crystalline silica-based ceramics, wherein each of the workers exposed to AQA noted inadequate ventilation within the workplace. These findings imply significant risk across the subtractive processing of high silica content materials.

While silicosis is unique to materials containing crystalline-free silica, inhalation-related hazards are common during ceramic machining, where inflammation and irritation of the respiratory tract can occur following exposure to a range of different airborne particulates. In this sense, although there is a growing body of literature which explores the health hazards associated with zirconia (ZrO_2) nanoparticles [71], materials such as zirconia are nonetheless generally considered safer to machine than their metallic counterparts (due to their increased thermal stability and thus, absence of ignition risk relative to pyrophoric metallic fines [72]).

Of the other ceramic materials which are frequently machined, whilst they are not devoid of risk, they are, generally speaking, markedly less hazardous than materials such as beryllia and natural ceramics containing silica. Nonetheless, precaution should still be taken to avoid the inhalation of airborne ceramic particulates regardless of their specific chemistry (in proportion to their risk). The occupational health risks associated with exposure to alumina, for example, have been relatively well documented in both animal and epidemiological studies.

One recent paper explored the potential health impact of alumina nanoparticle exposure (Al_2O_3 NP) using Swiss albino mice as a model system [73]. During the study the authors noted significant aluminium retention in the brain, liver, spleen, kidneys and testes, in addition to histopathological lesions in the brain and liver, enzymatic inhibition, neurodegeneration and DNA damage, generally following a dose–response relationship.

Whilst these findings suggest that high concentrations of Al_2O_3 NP may lead to systemic and neurological pathologies, it is important to note that the exposure route pursued in the study was high-dose oral administration rather than inhalation. When this factor is considered alongside the use of an animal model, it remains to be seen if the observed pathologies would manifest in humans under representative machining exposure conditions.

Aside from this experimental animal-based research, Voisin and colleagues undertook a retrospective study of five workers occupationally exposed to aluminium oxide (either in an aluminium smelting or alumina processing context) [8]. In their research the authors analysed samples of bronchoalveolar lavage (BAL) fluid and lung parenchyma using transmission electron microscopy (TEM). In doing so, it was noted that a high concentration of alumina fibres was present (in excess of 10,000,000 per gram of dry lung tissue) in two of the five tissue samples, whilst fibre content was present in the BAL fluid of three patients. Importantly, evidence of the biopersistence of these fibres is suggested by the fact that biological samples were collected more than four years after four of the five patients had finished working in the aluminium/alumina processing industry.

Whilst this study does not inherently imply that there is a pathological risk associated with the presence of retained ceramic fibres in lung tissue, it does nonetheless imply that those fibres are retained. In this regard, until further research displaying the health risk associated with ceramic fibre content is available, additional precaution should be taken when machining or processing components comprising fibrous content, not least of which ceramic-matrix composites (CMCs), which are discussed in the proceeding section.

4.3. Composites

Composite materials are particularly interesting from a hazard mitigation perspective due to their material heterogeneity. In this regard, when considering the risk profile associated with machining a composite material, it is necessary to consider the hazards associated with each of the phases which exist within the component.

Typically speaking, composites feature a distinct matrix and reinforcement phase; although, this is not always true. In any case, regardless of the role played by each phase within the composite material, their individual hazards have to be considered in addition to those which may be created by the combination of those materials.

As an example, whilst ceramic materials are not generally a significant risk of pyrophoricity and are not typically flammable, metal-matrix composites (MMCs) often feature both ceramic and metallic phases, and as such, can experience both metallurgical- and ceramic-related hazards. In this regard, whilst boron carbide, for example, is not pyrophoric in and of itself, a composite material comprising zirconium and boron carbide would be at risk of pyrophoricity during machining. Likewise, this material would also feature the additional risks posed by the fine atomized ceramic powder which may extend above and beyond the inhalation (and ocular) risk associated with just the metallic matrix.

One hazard type which occurs in a range of different composite materials is the unique risk associated with the machining of fibrous materials. Whilst finely machined fibres present a range of risks (i.e., irritation of the skin, ocular problems, etc.) to machine tool operators (amongst others), their inhalation risk is likely the most profound. In many regards, this particular hazard has gained significant traction as a consequence of the now well-documented occupational risks associated with the handling of asbestos (i.e., within civil engineering, construction, etc.). In this sense, although not completely alike, many composites are, like asbestos, fibrous, and as such fears (many of which are well founded) exist around the risk profile associated with the inhalation of such engineering fibres.

Despite this, whilst the risks to lung health caused by asbestos inhalation were formally established over one hundred years ago [74], much of the research exploring the inhalation of other composite materials remains much more in its infancy. Whilst work has been conducted to characterise the extent of the health risks posed by exposure to existing fibres [75], research into the hazards of modern engineering/structural fibre exposure is much more limited.

This is primarily due to the fact that high-performance fibrous composite materials, of the sort which are now commonplace in many performance-driven sectors (i.e., CFRP, CMCs, etc.), have not been in use at any significant volume for much of history. For this reason, it is generally not possible to observe the long-term occupational health implications of their machining (at least in large cohort studies). Nonetheless, one paper attempting to understand the health hazards of carbon-fibre-reinforced polymers (CFRPs) exposed rats to aerosols of carbon fibre at target concentrations of 50 or 100 mg/m^3 for periods of one to five days [76].

In the aforementioned paper the authors noted that the five-day exposure period generated a transient inflammatory response in the lungs of the exposed rats which followed a dose–response relationship with fibre content. Despite this, whilst lactate dehydrogenase (LDH), an enzymatic marker for tissue damage, was present in the BAL fluid of the rats shortly after carbon fibre inhalation, effects returned to baseline within 10 days of initial exposure. Ultimately, this led the authors to conclude that the pulmonary toxicity of carbon fibres is not equivalent to that of crystalline silica or asbestos and as such should not present fibrosis risk if appropriate occupational control is applied. This finding was later reinforced in the work of Zhang and colleagues [77].

Of course, this prior work has focused upon animal models, and as such, until long term safety can be proven in humans, occupations which are directly involved with engineering fibres should be conducted with an abundance of caution. In this regard, given the fact that, at least in principle, all forms of elongated dust particle/fibrous material have the potential to cause tumours if long, thin and durable enough in vivo [78], this caution should also extend to ceramic-matrix composites (CMCs). Unfortunately, however, due to the relative infancy of CMCs, there is limited research on the specific occupational risks associated with their manufacture/machining. Nonetheless, a small amount of research does exist on the occupational risks associated with ceramic fibres.

Between 1991 and 1993 Pott and colleagues [79,80] exposed rats to intraperitoneal injection of both SiC whiskers and granular SiC at doses of between 0.05 and 25 mg and 250 and 1000 mg, respectively. In doing so the authors noted that whilst exposure to the granular SiC only yielded a 0.8% and 0% increase in tumour rates (at 250 mg and 1000 mg, respectively), SiC whiskers lead to a 12.5–97% increase in tumour prevalence relative to the baseline.

This increased cancer risk followed a dose—response relationship with the mass of exposed material, which was not likewise observed during granular SiC trials. Interestingly, the whisker sample was found to contain approximately 107,000,000 fibres/mg in excess of 5 μm in length with an aspect ratio in excess of 5/1 (which exceed the defined limits for World Health Organisation (WHO) biopersistent fibre), whilst the granular material was later found to contain only 58,000 WHO qualifying fibres/mg [78].

This increased carcinogenicity risk is particularly concerning given the previously discussed research of Voisin et al. [8] who showed that, at least in the case of alumina, fibre content was maintained in the lungs for a number of years post-exposure. Nonetheless, at least in the case of alumina fibres, a prior rat inhalation study from Pigott and colleagues [81] found that, even after continued exposure of 86 weeks to refractory alumina fibre, pulmonary tumours were not observed. This finding was in stark contrast with the positive control of rats exposed to chrysotile asbestos which reliably generated both benign and malignant tumours, ultimately implying that the fibres used in the study were non-carcinogenic.

Of course, this paper is only a single case study, and as such should not be taken as proof of alumina fibre safety, particularly given the work of Pott and colleagues which showed that the size of the exposed fibres played a significant role in the carcinogenicity, or lack thereof, of the material. Moreover, more recent work has found a correlation between the intrapleural injection of alumina and mesothelioma for some aluminosilicate fibres, though one is markedly weaker than the link between mesothelioma and asbestos [82].

With these caveats in mind it is worthwhile to remark upon the findings of the prior chapter which note that, in general, significant inhalation risk remains associated with a wide range of ceramic materials. As such, even though there is currently limited evidence pertaining to CMC materials, safety protocol should be put in place during the machining/processing of all ceramics, fibrous or otherwise.

As a final note, aside from the risks associated with fibrous materials, it is also worthwhile to consider that polymer matrices, in addition to the solvents which are used in their manufacturing, may be hazardous [83], particularly during inhalation (either in dust [84], or during combustion [85]). Clearly this presents a significant challenge within the machining environment as subtractive processing generates dust and the high temperatures generated during machining could potentially lead to the combustion of the (often thermosetting) polymer matrix. Ultimately, these factors are likely to lead to the downstream mobilisation of harmful combustion products.

4.4. Radioactive Materials

Given the significant administrative, technical and legal controls existing around nuclear materials, the capacity within industry to work directly with irradiated and nuclear materials is generally only accessible to a small number of highly regulated contractors. In this sense, the machining of irradiated material remains an extremely niche capacity which is often conducted in laboratory-based or military settings.

As a result of this reality, it is unlikely that the machining of radioactive material will become a capacity which is commonplace within industry; however, the associated risk profile should be considered nonetheless and precaution should be taken both during the handling and machining of said material. As such, it is worthwhile to consider the range of negative health implications which can be caused by radiation to appreciate the gravity of the risk which needs to be managed, these include the following [86]:

- Nausea and vomiting.
- Hair loss.
- Acute radiation syndrome.
- Radiation burns.
- Cellular damage (ferroptosis, pyroptosis, immunogenic cell death etc. [87]).
- Cancer.
- Death (by radiation sickness or cancer—in the former, death is often caused by disease which cannot be properly mediated due to loss of white blood cells).

Whilst occupational machining studies are limited, significant research has been conducted exploring these health effects, much of which was undertaken in the aftermath of the second world war bombings of Hiroshima and Nagasaki, in addition to the prevalent nuclear disasters which have occurred throughout the 20th century. Douple and colleagues [88] for example, analysed the available data on radiation-related pathologies on the populations of Hiroshima and Nagasaki.

In their work, the authors collated the currently available data on adverse, cancer- and non-cancer-related health implications post-exposure. The authors, thereafter, explored the excess absolute risk rate (the ratio of the risk of disease occurrence in an exposed population compared to an unexposed baseline) associated with said disease in order to understand the proportion of the diseases incidence which can be attributed to nuclear bomb exposure.

Douple et al. note that 438 cases of leukaemia were observed amongst the (initially 120,000 and now over 200,000 person) cohort of individuals who took part in a broad-scale unified study programme. Of those 438 cases, 196 (44.7%) were attributed to the radiation exposure of the two nuclear bombs, wherein, at all defined (estimated) dosage bands, increasing exposure contributed to increased numbers of excess deaths. This dose–response relationship was also replicated in the proportion of solid cancer cases within the cohort which were attributable to nuclear bomb exposure, wherein, of a total of 15,702 cases of solid cancer, 1698 (10.8%) were estimated to be a consequence of the excess radiation exposure.

Aside from the carcinogenicity of the atomic bomb, a number of non-cancer-related health implications were observed across the cohort; these included the following: lens opacities (cataracts), thyroid disease, heart disease/strokes, chronic liver disease, uterine myoma, hypertension, psychological trauma, aberrations to immune response, cognitive decline and birth related defects in utero (although no correlation has been found between parental radiation exposure and pregnancy abnormalities within unexposed foetuses).

Of course, whilst these effects occurred in the greatest concentration during the atomic bomb events in Hiroshima and Nagasaki, case studies exploring the negative effects of radioactive material exposure extend beyond combat scenarios. Other pertinent examples include those exposed to nuclear-power-generation-related accidents, weapon-testing-related fallout, and other contacts with nuclear materials, i.e., radiographic contact, knowingly and otherwise (such as the Goiânia accident [89]).

Given the extensive risk profile associated with contact with irradiated material, the machining environment must be properly managed such that any human contact is avoided and, equally, that the risk of criticality accidents are prevented. Of course, this can and must be managed prior to the onset of any machining works [75], wherein appropriate means must be taken to control the mass of fissile material present within the facility at any one time.

These risks should be controlled with reference to the fact that neutron reflection, i.e., from other materials, or even machining coolants/lubricants, can cause a sub-critical mass of fissile material to reach criticality. With this in mind, a significant margin of safety should be afforded to storage mass limits. However, even if the risk of criticality can be removed in its entirety, radioactive material still presents a number of significant challenges within the machining environment. In this sense, whilst the direct occupational risk associated with the machining of radioactive substances is not well understood, broadly speaking, the risk profile can be analogised relative to other non-subtractive manufacturing nuclear experiences.

Most pertinently, the risks of nuclear fallout, though commonly studied in wartime contexts, is a hazard which can be equally present during the machining of irradiated material. This is because, just as an explosion generates fine atomised material (in addition to vapours of iodide and other volatile radionuclides [90]), so does the machining of said irradiated component. In this regard, the inhalation/ingestion-related pathologies observed in individuals downwind of nuclear tests and accidents are likely to be reminiscent of those which could be faced by machine tool operators if exposure is not properly controlled.

As such, whilst there is no significant occupational health data monitoring the wellbeing of individuals who are involved in the machining of nuclear material, it can be safely assumed that any adverse health effects experienced in other nuclear exposures could potentially be experienced within the industrial environment (if proper precautions are not afforded to the process).

Aside from the biological implications associated with radioactive material, there are also a number of non-radiation specific challenges associated with the machining of some radioactive materials, most pertinently, pyrophoricity. In this regard, whilst it is typically the case that uranium dioxide is used as fuel in nuclear power generation, within the manufacture of nuclear weapons metallic radioactive material (enriched uranium or plutonium-gallium) is generally employed.

In the former case, because uranium dioxide is a ceramic, it is generally manufactured by powder-processing techniques and typically does not require machining. Metallic uranium (or plutonium–gallium) on the other hand, often requires machining in order to generate the requisite component geometry for the application. Unfortunately, however, whilst the machining of all radioactive materials is a significant cause for concern, radioactive metals such as enriched uranium and plutonium are particularly hazardous, owing both to their combustion risk and the risk of criticality which they pose.

One article which explores the pyrophoricity of uranium was written by Plys and colleagues [91] who examined the underlying phenomena which causes the pyrophoricity of uranium in addition to prior combustion events which have been observed. In the case of the former, at a simplistic level, the pyrophoricity of many nuclear materials is already relatively well understood.

Fundamentally, when exposed to air the metal rapidly oxidises; this oxidation is exothermic and as such if the heat generated by the process is sufficient for the metal to ignite (which is influenced by both the specific surface area of the material and the ignition environment), i.e., heat production exceeds the heat loss to the atmosphere until ignition temperature is reached, a fire can be generated. Often, this fire is self-sustained and is difficult to manage as a consequence of the many other pre-discussed risks associated with radioactive material. The risk profile is often further exacerbated as water contact can cause the release of hydrogen gas (at least in the case of uranium), potentially causing explosions.

Recent data on the pyrophoricity of uranium has noted that small masses of material, particularly swarf from machining processes, presents a significant combustion risk [92]. Whilst this is intuitive, given the previously discussed ignition mechanics of uranium (which is replicated in a number of other radioactive metals), it nonetheless creates a significant challenge within the machining environment.

Currently, the best practice for the extinguishing of uranium fires involves the use of dry powder agents; however, this may not always be practicable and as such any handling of pyrophoric radioactive material warrants the use of a unique fire protocol. Both uranium and plutonium fires have been recorded as early as 1954 in a US atomic energy commission (AEC report) [93], and, although they differ in some keyways (i.e., their reaction products with water), a similar protocol (e.g., dry powder) is necessary for both materials.

Finally, it is also worthwhile to note that not all ionising materials, are the radioactive metals or ceramics which we often associated with radiation-related hazards. In fact, many materials which are not radioactive in their as-manufactured state can be irradiated by the application in which they are used or must be machined within a radioactive environment.

In the former case, it may be necessary to machine irradiate materials in a research environment to conduct destructive testing on the component and measure the impacts of said operational environment (radiation-related and otherwise) on the part, or to generally assess the quality and in-service life of said component. Likewise, machining may have to be conducted within a radioactive environment if a part requiring rework cannot be readily or safely removed from its environment (e.g., during decommissioning efforts, etc.). This could be as simple as re-drilling and tapping a hole within a component situated within a reactor.

Clearly, if a material has been irradiated, and presents an ionisation risk during occupational contact (i.e., it has undergone neutron activation) it is important that contact (dermal, ocular, inhalation and ingestion) is appropriately managed. In this sense, whilst many of the safety protocols associated with the machining of typical radioactive metals/ceramics may likewise need to be implemented, the material may have unique (non-radioactivity-related) hazards or may exacerbate the ionisation-related risk profile of the material. An example of the latter would be a material which, during machining, forms a fine inhalable dust or a fibrous composite material, for which inhalation risk would be markedly increased.

Likewise, when components have to be machined within a radioactive environment, it is important to consider how said environment affects the practicalities of the machining process being conducted. For example, it may not be possible to apply a water-based coolant to the cutting zone if there is a risk of hydrogen gas emission from proximal uranium components or if the coolant could act as a neutron reflector and cause criticality risk.

Similarly, procedures may have to be put in place to facilitate the evacuation and management of any chip material within radioactive environments. This fine, high specific surface area material presents a significant ignition risk and can also act as an abrasive third body, restricting the motion of internal components within a reactor (for example) or leading to increased wear and ultimate component failure. These factors can increase the need for rework and replacement within the system and ultimately lead to further operational challenges.

4.5. Summary of Material-Specific Risks

In order to consolidate the findings presented in Sections 4.1–4.4, the key occupational hazards of each materials class are summarised in Table 2. This overview serves as a concise reference point, highlighting the principal exposure routes and risk modalities considered within the narrative discussion. Additionally, it serves to highlight in which areas risks are well-established (e.g., beryllium carcinogenicity) and in which areas knowledge gaps remain (e.g., ceramic fibre biopersistence). The table is intended as a quick reference guide for practitioners and a structural summary for readers.

Table 2. Material risk summary.

Material Class	Main Hazards Identified	Key Notes
Metals and Alloys	Pyrophoricity and swarf combustion challenges (e.g., Mg, Ti, Al, etc.) due to high surface area flammable chips. Carcinogenicity (e.g., Be, Ni, Co, Cr) and dermatitis risk to operators. Propensity to induce allergic sensitisation (e.g., Ni/Co/Cr) and chronic disease (e.g., CBD). Cardiovascular, renal and reproductive pathologies (e.g., Pb).	Emulsion cutting fluids to be avoided with Mg (H_2 generation), dry machining preferred. Chip evacuation and handling critical for Ti, Mg, Al, etc. Be: marked inhalation, contact and ingestion risk, requires strict OEL compliance (0.2 $\mu g/m^3$) [36]. No safe exposure threshold for Pb in blood.
Ceramics	Inhalation and ocular hazards due to the fine airborne particulates. Irritation of respiratory tract, silicosis (in ceramics containing crystalline silica, e.g., quartz countertops), etc. Potential ceramic nanoparticle bioaccumulation (brain, liver, kidneys, testes), oxidative stress, neurodegeneration, damage (animal models). Potential carcinogenicity and chronic disease risk (e.g., beryllia).	Dust and particulate generation not easily avoided due to brittle fracture mechanics. Containment and extraction necessary. Beryllia requires the same (or potentially, greater) precautions as metallic beryllium.
Composites	Ceramic fibre biopersistence in lung tissue, unclear pathology in aluminium oxide, potential carcinogenicity in SiC whiskers. Inhalation and ocular hazards resulting from hazardous matrix combustion products and fibre particulate matter inhalation. Transient pulmonary inflammation from CFRP dust (reduced risk relative to asbestos).	Heterogeneous risk profile due to the differential makeup of the matrix and reinforcement. MMCs combine the risks of metals (e.g., pyrophoricity) and ceramics. Ceramic fibre inhalation (e.g., SiC whiskers) found to be carcinogenic in animal models. Should be regarded as high-risk until long-term data is established.
Radioactive Materials	All contact, inhalation and ingestion present a significant risk to life. Effects of ionising radiation includes nausea, vomiting, burns, acute radiation syndrome, cellular damage, death. Long term exposure pathologies include, cataracts, thyroid disease, cardiovascular disease, teratogenicity, cognitive decline, etc. Pyrophoricity risks are present, which are not easily mitigated. Criticality accident risk due to critical mass issues (e.g., via swarf accumulation) or neutron reflection (e.g., from cutting fluids, the machine tool, etc.).	Machining of irradiated/nuclear materials is generally niche and restricted to military/laboratory contexts. Direct subtractive manufacturing research is very limited. Advanced fire suppression protocol is necessary, cutting fluids may be non-viable. Containment and remote handling are critical in order to machine these materials. Proper storage of machined components and swarf is essential.

5. Recommendations

Clearly there are a multitude of hazardous materials which can be present within the machining environment. Whilst established H&S guidelines address a number of commonly machined substances, there remain significant gaps where rigorous assessment is lacking. In this regard, the purpose of this review is not to propose new standards to fill those gaps, but rather to highlight a number of key materials and considerations and to begin to suggest remedial measures which should inform future best practice guidance. As such, the following subsections outline practical strategies in areas such as containment, swarf management, PPE and exposure monitoring, which together represent critical avenues for the risk reduction.

5.1. Containment, Extraction and Respirators

Generally speaking, machine tools which are used to machine hazardous materials must prevent said hazardous substances from escaping the machining centre and inadvertently re-entering the workshop environment. Most fundamentally, this is focused upon the extent to which the machine tool containment can prevent users from inhaling any hazardous fumes or particulate matter. Typically, the primary barrier against operator exposure is the use of an enclosed machine tool; however, recent work from Levilly and colleagues notes that current enclosures are largely incapable of managing particulates suspended in gaseous coolant/lubricant constituents [94]. In this regard, whilst programming related input and proper health and safety practice is highly valuable, the implementation of robust extraction technologies remains critical.

Often extraction is conducted via the use of local exhaust ventilation (LEV) systems. Typically speaking, LEV systems have historically not been commonplace within the machining environment, and as such, occupational lung disease has, as is demonstrated throughout the previously discussed literature, proven to be commonplace. In recent times, however, the UK Health and Safety Executive (HSE) guidance has stated that LEV systems should be in place in any CNC machining contexts wherein cutting fluid mist is generated [95]. The report outlines that an appropriate LEV system should achieve the following:

- Enclose as much of the machine tool as possible (i.e., by enclosing the machine tool with retrofitted panels as necessary).
- Be either a standalone unit or a centralised system linking two or more machines.
- Discharge extracted air to a safe place outside the building, away from doors, windows and air inlets (in practice this will be subject to local regulation, licencing and controls).
- Ensure a suitable high-efficiency air cleaning device is in place if the air is recirculated back into the workshop.
- Provide an easy way of checking that it is working correctly (e.g., an airflow indicator).

Of course, these principles are of further importance when machining hazardous materials owing to the fact that the risk profile associated with their contact/inhalation is markedly higher. Moreover, in certain hazardous materials, i.e., radioactive substances, protocols will require revision. As an example, the criteria defined by HSE, which states that air should be discharged "to a safe place outside the building", will not apply to irradiated gases and particulate matter. In those cases, the LEV system would be required to discharge the material directly into containment and must not be released into the atmosphere.

Likewise, when machining hazardous substances, it is crucial that the filtration system is sufficient for the application. In order to determine this, it is important to consider the particulate size and volume likely to be generated across the broad range of subtractive processes which may be employed during the machining of a given hazardous material.

Having done so, it is crucial that sufficient testing is conducted on the LEV system with a proxy medium representative of the hazardous material against which it is to be protected.

Generally speaking, it is worthwhile to discuss directly with LEV suppliers the types of material which are to be machined, as filters are typically selected to address specific types of contaminants. Nonetheless, LEV systems are generally categorised according to the volume and size of particulate matter which they are capable of containing, and as such, increasing levels of filtration (HEPA and otherwise), often necessitates an increased number of stages and are increasingly necessitated as the severity and likelihood of the risk being realised increases. One recent paper has shown longitudinal displacement ventilation to be the most efficient extraction strategy; however, this should clearly be assessed on a case-by-case basis [96]. In any case, having decided upon an appropriate filtration strategy, it is worthwhile to consider how long the LEV system has to be in operation prior to opening the machine tool door and exposing any of its contents to the operator.

In this regard, it is crucial that when the door is opened no inhalable matter (particulates or fumes) remains within the machining centre, and as such, that the machine tool operator can safely work within the centre. Ideally this time period would be assessed on a case-by-case basis via the use of particulate/harmful medium monitoring equipment placed at various junctions in and outside the machine tool and through a rigorous experimental design, although this is not always feasible. In lower risk scenarios much of the benefits of this experimentation can be gained by conducting smoke clearance time tests, involving filling the machine with a non-hazardous smoke and recording the time taken for the LEV system to clear said smoke. Needless to say, whilst useful, this is not sufficient for all applications and should be assessed by an H&S professional.

Having established that sufficient time has been afforded to the LEV system for clearance, it is also important to assure that filters are maintained and replaced appropriately. This involves first affording consideration to how long the filters should be used prior to disposal, followed by how they should be disposed of and by whom. In the former case, HSE states that LEV filtration systems should be thoroughly examined and tested at least every 14 months [97]; however, when machining hazardous materials it is worthwhile to conduct regular airflow tests and to frequently inspect any filters for damage.

Considering the practicalities of disposal, generally speaking, assessments should be conducted by a trained technician wearing the requisite PPE sufficient to protect said individual from any of the hazards associated with the materials that have previously been machined on that machining centre. Used filters should of course be disposed of through the appropriate means for hazardous waste (although Hepa filters used in non-hazardous contexts can generally be landfilled via conventional means).

Regardless, if the machine tool itself is not appropriately sealed, the LEV system in isolation will not be sufficient to prevent particulate material from escaping the machine tool. In most cases, the use of gaskets and seals on any door or openings within the CNC machining centre are sufficient to prevent particulates from escaping the machine tool. Often, these seals comprise polymers such as rubber and serve to generate an airtight seal when the door is closed. It is worthwhile to note that some CNC machine spindles make use of positive pressure systems [98] to prevent the ingress of contaminants into the machine tool, and as such, it is possible that a similar air curtain, or pneumatic-based strategy could be utilised to prevent hazardous particulates from escaping the machine tool; however, this does not seem to be commonplace currently.

Ultimately, if the escape of hazardous particulate matter and fumes cannot be prevented, it may be necessary to explore suitable PPE strategies. Generally, masks or respirators are used to mitigate inhalation-based risks. The former are typically sufficient to prevent the inhalation of coarse particulate matter, whilst the latter is often necessary with fine particles or hazardous fumes. As is generally the case, different variations of masks and respirators are recommended for different applications within the machining environment depending on both type and concentration of the hazard, in addition to the duration of exposure, working environment, comfort and fit. These include the following:

- N95, FFP2 and FFP3 masks.
- Half-face respirators.
- Full-face respirators (filter, powered air and supplied air).
- Chemical cartridge respirator.
- Self-Contained Breathing Apparatus (SCBA).

Of course, whilst preventing particulate inhalation is often a priority, it is not the only containment-related task necessary when machining hazardous materials. In cases of pyrophoricity for example, it is useful to consider how a CNC machining centre can reduce the ignition risk during machining and be prepared for said ignition should it occur. One way in which ignition risk can be reduced is via the use of an inert atmosphere during the machining process.

Typically, this involves the pumping of inert gas such as Argon into the machining centre, wherein the displacement of oxygen reduces the volume of fuel present within the cutting environment and subsequently reduces the capacity to sustain combustion. Whilst this type of technology is very prevalent within additive manufacturing and casting, there currently are no traditional machine tools which support Argon usage. Nonetheless, it may be possible to adapt an Argon-equipped hybrid additive subtractive machine tool [99] to supply Argon during machining (rather than solely during additive manufacturing).

Despite prospective applications, the use of inert gas during machining presents a number of challenges. For one, an Argon machine tool must be hermetically sealed in order to prevent leakage, it poses an additional asphyxiation risk to the machine tool operator and also it has been shown to be associated with reductions in tool life during turning applications (although performance was compared against emulsion coolant, rather than dry conditions) [100].

For these reasons, if an inert atmosphere is not necessary from a part-quality perspective and is only required to prevent fire risk, it may be worthwhile to consider the opportunity cost against the use of fire extinguishing and containment technology. Of course, if the cost of the material is extremely high, or damage to the machine tool cannot be managed during ignition events, this would not be feasible. Although, in other scenarios it may be markedly more resource efficient to make use of a sprinkler/flood/deluge system and internal fireproofing of the machine tool.

Whilst this more reactive approach may be desirable for some materials it is not suited to all pyrophoric materials. When machining uranium, for example, fluid-based deluge is not desirable, as ignition can be maintained underwater and thus the task of extinguishing the fire is very challenging. Moreover, when machining highly radioactive materials, the inability to handle components/swarf directly increases the difficulty associated with remediating any fires and increases the likelihood of both escalation and negative health effects on the part of the fire service response. In these contexts, it is critical to both minimise the likelihood of ignition and to put in place robust methodology in the event of a fire.

When machining radioactive material, it is also worthwhile to consider the necessity, or lack thereof, of radiation shielding between the operator and any workpiece material contained within the machining centre. Of course, one of the most effective means of removing proximal radiation risk is to increase the separation between the machine tool and the operator (although this may not always be possible).

In this regard, whilst remote operation should be the strife of manufacturing engineers and HSE professionals alike, in scenarios where close contact is necessary, a radiation attenuating shield or curtain should be considered. Typically, shielding is made of lead owing to its high density (and thus, capacity for attenuation), however given the occupational toxicity of lead, it may be worthwhile to explore other materials such as Tungsten, Bismuth and concrete or, alternatively, remote machining strategies.

Aside from radiation risks, it may also be necessary to erect shielding for other machining-related hazards. One pertinent example being spark/UV related shielding. Feasibly, this could be incorporated in the machine tool window; however, it may be easier, particularly from a warranty retention perspective, to make use of an external structure. This type of shielding would be of particular use in high MRR roughing operations, such as the ceramic milling of nickel-based superalloys or ferrous materials, due to the significant volume and intensity of sparks produced. As such, whilst UV protection is perhaps not intuitive, it is likely extremely useful due to the adverse effects which prolonged exposure can have on both ocular (i.e., photokeratitis or cataracts) and dermal health (e.g., skin cancer).

5.2. Material Handling

Many of the hazardous materials discussed throughout Section 4 should not be directly handled. This presents a significant challenge within the machining environment, particularly to machine tool operators who need to load, fixture and unload components, but also to individuals involved in the receipt, transit and inspection of goods pre- and post-machining process (e.g., metrologists, etc.). Of course, the extent to which the machine shop workers need to be shielded from dermal exposure to a given material varies significantly from material to material. At one extreme, this may involve periodic occupational health checks with machine tool operators (amongst others) to assess if they are noticing any contact related irritation, whilst at the other extreme, this could involve a total removal of human–material contact.

In scenarios where contact is not permissible, there are a number of means by which it can be avoided. In the first case, attempts to eliminate, substitute or control the process should be explored; however, where this is no feasible way to avoid contact mitigation should focus upon the use of personal protective equipment (PPE). In this regard, whilst gloves should not be worn when operating rotating machinery (due to entanglement risk), setup, removal and post-process handling of machined components/workpieces can be made significantly safer via glove use. In this sense, although suitable glove composition is highly process-specific, common types include the following:

- Nitrile.
- Neoprene.
- Butyl rubber.
- Natural rubber.
- PVC.
- Viton® (synthetic rubber polymer) [101].
- Silver Shield®/4H®/Norfoil® (multi-layer laminate, typically; ethylene vinyl alcohol and polyethylene) [102].
- Lead (radiation attenuating).
- Barium-coated natural rubber.
- Other radiation attenuation gloves, i.e., Secure Touch® XR1 [103].

It may also be necessary to wear further PPE in order to prevent dermal contact elsewhere on the body during handling. This can involve the use of lab coats, aprons or full protective suits with varying degrees of protection. Typically speaking, aprons are most commonly used within the nuclear environment and are generally made of lead (in order to attenuate radiation). Protective suits which are used when handling hazardous materials are, generally, intentionally impermeable with the outlook of providing a physical barrier from contaminants. In highly radioactive contexts, fully encapsulated suits or thyroid shields (lead or equivalent collars used to attenuate the irradiation of the thyroid) may also be necessary. In the former case, the suits are typically fully sealed at all seams/closures and make use of integrated breathing apparatuses which supply clean air to the wearer.

It can also be important to use PPE when handling non chemically/biologically hazardous material if the component produces a significant cut risk to the operator. Typically speaking this is more necessary after the machining process than prior to the machining process, as supplied material is generally deburred prior to transit, although it can be best practice to afford an abundance of caution to material handling. In one recent study, "metal items, such as nails, metal stock, and burrs accounted for 38.4% of the injuries" which occurred occupationally in a cohort of 1166 north American patients with hand/finger injuries [104]. For these reasons, it may be wise to wear cut-proof gloves whenever handling engineering materials; although, this is of course not always practicable and could, in certain applications, increase the risk profile.

With this in mind, it is clear that PPE alone is not sufficient to prevent contact with hazardous materials and, in particular within nuclear environments, all PPE solutions are broadly incapable of providing complete protection from ionising radiation. Nonetheless, PPE is an essential tool in managing the risk profile associated with hazardous-material handling and should be used in conjunction with safe exposure limits when short-term human contact is of an acceptable risk profile and is deemed unavoidable for the application. Nonetheless, there are of course scenarios where the handling of a given material is of too great a risk for operators (i.e., direct contact with fissile metal). In such scenarios it is generally necessary to make use of manual handling solutions.

In these contexts, it is important to consider the capacity of the automated handling strategy to conduct the range of tasks that are needed from it. In this regard, lifting apparatuses capable of fixturing components within a machine tool would likely be markedly more complex and expensive than those only required to move material from location to location. With this being said, even manual handling strategies which solely can lift and traverse material from location to location face challenges due to the inability to load and unload the material by hand (as is generally employed in conventional crane strategies). As such, the majority of "off the shelf" handling strategies require some form of manual loading of the component, and if this is not possible due to contact hazards, bespoke strategies are generally necessitated [105].

Whilst these manual handling (lifting) strategies are generally necessitated in hazardous contexts, they often add significant complexity and additional risk to the manufacturing process. Handling machinery can often feature un-restricted moving parts and, when improperly utilised, can create risks associated with hauled material falling from a tall height and colliding with individuals or machinery within the workshop environment. In addition, this machinery must be maintained throughout its life, and as such, once the machine/crane is contaminated with a hazardous material, any maintenance or service engineering related staff are placed at risk of said hazard. For this reason, cranes used in extremely hazardous environments, such as those involved in the direct handling of nuclear material, are often sacrificial and are manufactured such that they are not anticipated to require any human intervention throughout their usable life. This, of course, adds significant costs to the process.

Even omitting the challenges of maintaining bespoke handling equipment, the initial capital outlay associated with their purchase is generally significant. One reason for this is the machinery must be manufactured to extremely demanding standards such that if anyone needs to interface with the equipment, they will not have to interact (beyond safe exposure limits) with the hazard. Again, taking a nuclear example (primarily because they have the most pronounced risk profile), any sharp material or components protruding from the crane generally must be avoided in order to reduce the risk of radiation exposure and contamination. This ultimately necessitates the broadscale deburring of all contactable parts and the filling of structural members with foam (or other snag prevention alternatives), ultimately incurring additional costs.

Having established that manual handling machinery is necessary, it is also important to consider how the machine/crane will be delivered to and installed on-site. Of course, complex installation practices which require significant human input are not desirable in hazardous environments, and as such, these risks must be contrasted with the risks of human handling (with PPE) to assess if manual-handling-related machinery is necessitated. Similar transit-related risks pertain to the material themselves, wherein many hazardous materials cannot be stored through conventional means and may necessitate storage in an argon atmosphere, for example, or under temperature or light exposure control. These are all factors which must be incorporated into a handling method statement well in advance of the receipt of goods.

5.3. Clean-Up and Swarf Handling

Although preparing an industrial environment for hazardous material machining is of primary importance, material related hazards do not end at the completion of a given block of trials or manufacturing cycle. Rather, it is crucial to consider how these hazards will be removed from the machining centre after the material in question has been processed. In this regard, the extent of post-process clean-up which is necessitated will very much be dependent upon the extent of the risk posed by the materials machined, in addition to the re-use cases which are likely to be made for the machine tool in question.

To this point, not all machining centres can be re-commissioned once exposed to a given hazardous material, and even of those which can, not all can be re-commissioned through means that are financially or operationally sensible. For these reasons, if a machining centre has processed a particularly hazardous material, and that material is a large portion of the machine shops throughput/workload, it may be prudent to maintain one or more machining centres specifically for that particular hazardous material. In doing so, any cleaning and recommissioning costs are removed and clarity is established in the use of the machining centre, meaning there would be no doubt within the workforce as to if said machine tool has been contaminated with hazardous substances. This is of clear value to the industry as clarity around the risk profile of a given process is likely to markedly reduce the likelihood of exposure events.

It should, however, also be noted that maintaining one machine tool for the machining of all broadly hazardous substances may not be sufficient, particularly because there are inherent risks associated with the mixing of materials. There are two primary reasons for this, foremost, there is a strong possibility that one material species may become contaminated by the hazardous material species previously used on that machine tool (creating material handling/inhalation risks otherwise unanticipated for the intended workpiece material). Of course, this could be addressed by providing the workforce with knowledge of the historical use of the machine tool; however, transmission of this information may be a challenge, and ignorance to prior hazards would create significant health risk.

In addition to contamination concerns, it is also true that contact between differing material species can lead to chemical reactions taking place within the machining centre, which, in turn, may create additional unique hazards to both the machine tool and operator. In terms of machine tool risk, many materials when in contact can produce a galvanic cell and lead to the corrosion of the machining centre (aluminium and copper, for example, have markedly different electrochemical potential and thus pose a significant risk in that regard). One example being that machining centres which have manufactured Zinc components previously (for example) likely should not be used to machine materials necessitating the use of chlorinated cutting fluids due to potential toxic fume generation ($ZnCl_2$) [106].

Despite this, it is likewise true that many small manufacturing businesses do not have the scale or finances necessary to relegate an entire machine tool to the processing of one specific material. Equally, many businesses will be asked to machine a hazardous substance as a one-off or small batch job. In these scenarios, it is clearly not possible to relegate usage of said machining centre to one very narrow and specific context. As such, it is worthwhile to consider some of the steps necessary to recommission a machining centre, these include the following:

- Risk assessment of the potential hazard profile.
- Thoroughly clean the inside (and outside of the machining centre).
- Drain and appropriately dispose of any spent coolant.
- Thoroughly clean out the coolant sump and any chip collection areas.
- Dispose of any contaminated material/PPE.
- Inspect, repair and test all machine systems.
- Undertake any lubrication and maintenance procedures.
- Test the functionality of the machine tool.
- Certify the machine tool and define any updates to the use case of the machining centre (caused by any residual hazards for example).

Of course, it is not always possible to remove hazards from the machine tool and re-commission it for general use. The most pertinent example of this is when radioactive material has been machined. In these scenarios, the irradiated tool will remain so until any residual radiation decays. Needless to say, the time frame for this decay could last a short period of time but will more likely persist for a number of years. If these radiation-related effects were relegated to a small section of the machine tool, it could be recommissioned via the replacement of contacting parts; however, swarf moves throughout machinery via the conveyor system, and coolant (which carries radioactive material) is frequently recirculated throughout the machine tool and sump. For these reasons, it is generally not possible or worthwhile to reuse machinery used in the processing of radioactive material.

Regardless as to if the machine tool is to be recommissioned or not, it is also worthwhile to consider how any hazardous swarf will be handled, disposed of and (in some contexts) tracked throughout the machining centre. Clearly, machine tools have limited space with which to contain swarf and as such disposal is necessitated. This disposal presents a number of challenges dependent upon the types of hazards which the workpiece materials possess. In pyrophoric contexts, swarf cannot be allowed to agglomerate on the bed of the machine tool because it presents increased ignition risk, whilst in chemically/biologically hazardous materials the act of physically removing the swarf from the machining centre presents significant risk.

Radioactive metal swarf is, generally speaking, extremely high-risk to handle due to its ionising effects; likewise, it is often pyrophoric, so regular clearance of the machine bed is necessary. This would almost certainly require some manual handling intervention. However, using an approach which is devoid of human intervention may make it difficult to recover the entirety of the material from the machining centre, which may be necessary for highly regulated substances such as Uranium or Plutonium metal.

Assuming that the swarf can be recovered from the machine tool, both sustainability imperatives and an evolving regulatory environment make storage and recycling highly pertinent environmental, safety and traceability issues. Hazardous materials often must be sealed to prevent toxic fumes from escaping and to limit access by unaware parties within the industrial environment. Additionally, pyrophoric materials may have to be stored in an inert atmosphere, and potentially in smaller discrete quantities to reduce ignition risk. Generally speaking, swarf should thereafter be placed in a clean, dry and secure location to prevent air and moisture ingress and should be kept in a labelled, segregated container. In the case of uranium specifically (as well as other materials such as zirconium), swarf containment should be properly ventilated to manage any gaseous release of hydrogen. Of course, containment strategies must also comply with regulatory standards, and staff involved in handling should be sufficiently trained.

As a final note, aside from the clean-up of the machining centre itself, it is also necessary to assure that the individuals involved with the machining process are properly cleaned/sanitised post-process, and that any PPE which they have worn is appropriately stored or disposed of. In relatively low-risk contexts, this may involve only a hand washing procedure, whilst in more hazardous environments it may be necessary to shower post-machining process. Often, showering/personal cleanliness related procedures will be preceded by the bagging and cleaning/disposal of any PPE worn during the process, wherein the re-usability of the PPE is generally subject to the type of hazard posed, type of PPE worn, and the extent of exposure during the manufacturing process.

6. Conclusions and Future Work

The work undertaken in this review serves to highlight and characterise the numerous hazardous materials which are commonplace within the engineering environment. In doing so, this study provides the manufacturing sector with insight into the risks associated with the machining of both materials that are currently commonplace and those which are increasingly finding emerging use cases. It is thus the intention of the author that the work undertaken not only serves as resource exploring hazardous materials and their respective risk modalities, but also as an initial exploration into the remedial action which can be taken to assure that the machining environment (within which these materials are processed) is as low-risk as possible.

Beyond cataloguing risks (and remedial actions), the review highlights a number of cross-cutting insights. Pertinently, whilst hazards may be intrinsic to the material itself, they can be amplified or minimised significantly by the modification of the machining process. In pyrophoric metals for example, chip evacuation and morphology is intrinsically tied to the combustion risk of the swarf. As such, practical factors such as coolant strategy, feed rate and tool morphology (which determine both chip evacuation, size and shape) directly affect how hazardous a material is. This observation also extends to materials which present an inhalation risk, and because cutting parameters determine particulate size, they also determine the biopersistence, carcinogenicity and, broadly, the relative risk that these particulates pose to health.

It is also important to note that whilst this review outlines a significant portion of the scientific literature (particularly around the occupational hazards of many of the aforementioned engineering materials) it is not possible to fully capture all of the considerations which need to be made within the machining environment. For this reason, the following subject matter has not been thoroughly considered within this report but should be explored at a later date:

- The occupational health risks of other, non-fibrous composite materials.
- The impact of hazards on the machine tool, e.g., how does particulate ingress effect the wear of moving parts within the machining centre (e.g., third body abrasion).
- What makes a given machine tool suitable for the machining of hazardous material, and given this, how should the machine tool specification be generated.

- How can the machining environment be made more ergonomically comfortable to the machine tool operators.
- The sustainability implications associated with the machining of hazardous materials.

Despite its necessarily bounded scope, this study effectively highlights a number of areas where research is well evidenced (e.g., beryllium carcinogenicity, lead neurotoxicity, etc.) and likewise those which require further work (e.g., the long term effects of ceramic engineering fibre inhalation, direct radioactive machining insight, etc.). Whilst future research likely should move beyond descriptive studies (and towards integrated risk frameworks), this review nonetheless highlights the need for further targeted experimental research and broad longitudinal monitoring, highlighting the criticality of future work to both mitigate emerging health risks and close knowledge gaps.

Ultimately, it is important to recognise that no single review can encompass the entire corpus of risk data posed by hazardous materials, and as such consensus is difficult to establish. Whilst this work effectively outlines key considerations across a broad range of material classes, it is no substitute for detailed, material-specific analysis and assessment. It is thus crucial that any decisions on safety-related practices, when handling both well-established and emerging materials, arise as a consequence of thorough literature review, consultation with H&S professionals and regulatory approval.

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References

1. Park, R.M. Risk Assessment for Metalworking Fluids and Respiratory Outcomes. *Saf. Health Work* **2019**, *10*, 428–436. [CrossRef]
2. Bouchardy, C.; Schüler, G.; Minder, C.; Hotz, P.; Bousquet, A.; Levi, F.; Fisch, T.; Torhorst, J.; Raymond, L. Cancer risk by occupation and socioeconomic group among men—A study by the Association of Swiss Cancer Registries. *Scand. J. Work Environ. Health* **2002**, *28* (Suppl. S1), 1–88.
3. Colt, J.; Friesen, M.; Stewart, P.; Donguk, P.; Johnson, A.; Schwenn, M.; Karagas, M.; Armenti, K.; Waddell, R.; Verrill, C.; et al. A Case-Control Study of Occupational Exposure to Metalworking Fluids and Bladder Cancer Risk among Men. *Occup. Environ. Med.* **2014**, *71*, 667–674. [CrossRef]
4. Del Pobil y Ferré, M.A.P.; Sevila, R.G.; Rodenas, M.G.; Medel, E.B.; Reos, E.F.; Gil Carbonell, J. Silicosis: A former occupational disease with new occupational exposure scenarios. *Rev. Clín. Española* **2019**, *219*, 26–29. [CrossRef]
5. Madl, A.K.; Unice, K.; Brown, J.L.; Kolanz, M.E.; Kent, M.S. Exposure-Response Analysis for Beryllium Sensitization and Chronic Beryllium Disease Among Workers in a Beryllium Metal Machining Plant. *J. Occup. Environ. Hyg.* **2007**, *4*, 448–466. [CrossRef] [PubMed]
6. Kreiss, K.; Mroz, M.M.; Newman, L.S.; Martyny, J.; Zhen, B. Machining risk of beryllium disease and sensitization with median exposures below 2 $\mu g/m^3$. *Am. J. Ind. Med.* **1996**, *30*, 16–25. [CrossRef]
7. Bonavigo, L.; De Salve, M.; Zucchetti, M.; Annunziata, D. Radioactivity release and dust production during the cutting of the primary circuit of a nuclear power plant: The case of E. Fermi NPP. *ProProg. Nucl. Energy* **2010**, *52*, 359–366. [CrossRef]
8. Voisin, C.; Fisekci, F.; Buclez, B.; Didier, A.; Couste, B.; Bastien, F.; Brochard, P.; Pairon, J. Mineralogical analysis of the respiratory tract in aluminium oxide-exposed workers. *Eur. Respir. J.* **1996**, *9*, 1874–1879. [CrossRef]

9. Lindholm, M.; Reiman, A.; Tappura, S. The evolution of new and emerging occupational health and safety risks: A qualitative review. *Work* **2024**, *79*, 503–521. [CrossRef]
10. González, E.R.; Cockburn, W.; Irastorza, X. *ESENER-1 Overview Report: European Survey of Enterprises on New and Emerging Risks*; European Agency for Safety and Health at Work: Luxembourg, 2010.
11. CBarbey, C.; Bonvallot, N.; Clerc, F. Health Outcomes Related to Multiple Exposures in Occupational Settings: A Review. *Saf. Health Work* **2024**, *15*, 382–395. [CrossRef]
12. Proud, L.; Tapoglou, N.; Slatter, T. A Review of CO_2 Coolants for Sustainable Machining. *Metals* **2022**, *12*, 283. [CrossRef]
13. Safe Work Australia. Not All Hazards in the Workplace are Visible. 2021. Available online: https://www.safeworkaustralia.gov.au/safety-topic/hazards/occupational-lung-diseases/overview (accessed on 5 August 2024).
14. Cummings, K.J.; Stanton, M.L.; Kreiss, K.; Boylstein, R.J.; Park, J.-H.; Cox-Ganser, J.M.; Virji, M.A.; Edwards, N.T.; Segal, L.N.; Blaser, M.J.; et al. Work-related adverse respiratory health outcomes at a machine manufacturing facility with a cluster of bronchiolitis, alveolar ductitis and emphysema (BADE). *Occup. Environ. Med.* **2020**, *77*, 386–392. [CrossRef] [PubMed]
15. National Cancer Institute. Carcinogen. 2025. Available online: https://www.cancer.gov/publications/dictionaries/cancer-terms/def/carcinogen (accessed on 21 January 2025).
16. Merriam Webster Inc. Toxin. 2025. Available online: https://www.merriam-webster.com/dictionary/toxin (accessed on 21 January 2025).
17. Saha, R.; Donofrio, R.S. The microbiology of metalworking fluids. *Appl. Microbiol. Biotechnol.* **2012**, *94*, 1119–1130. [CrossRef]
18. Meza, F.; Chen, L.; Hudson, N. Investigation of respiratory and dermal symptoms associated with metal working fluids at an aircraft engine manufacturing facility. *Am. J. Ind. Med.* **2013**, *56*, 1394–1401. [CrossRef] [PubMed]
19. Genetic Alliance. *Understanding Genetics: A District of Columbia Guide for Patients and Health Professionals*; Genetic Alliance: Washington, DC, USA, 2010. Available online: https://www.ncbi.nlm.nih.gov/books/NBK132140/ (accessed on 21 January 2025).
20. National Human Genome Research Institute. Mutagen. 2025. Available online: https://www.genome.gov/genetics-glossary/Mutagen (accessed on 21 January 2025).
21. Pashin, Y.V.; Bakhitova, L.M. Mutagenic and carcinogenic properties of polycyclic aromatic hydrocarbons. *Environ. Health Perspect.* **1979**, *30*, 185–189. [CrossRef] [PubMed]
22. Agrawal, O.D.; Kulkarni, Y.A. Dietary neurotoxins: An overview. In *Diet and Nutrition in Neurological Disorders*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 351–364. [CrossRef]
23. American Academy of Allergy Asthma & Immunology. Allergen Defined. 2024. Available online: https://www.aaaai.org/tools-for-the-public/allergy,-asthma-immunology-glossary/allergen-defined (accessed on 21 January 2025).
24. Krishna, P.V.; Srikant, R.R.; Rao, D.N. Solid lubricants in machining. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2011**, *225*, 213–227. [CrossRef]
25. Kumar, P.; Jafri, S.A.H.; Bharti, P.K.; Siddiqui, A. Study of Hazards Related To Cutting Fluids and Their Remedies. *Int. J. Eng. Res. Technol.* **2014**, *3*, 1225–1229.
26. Merkushkin, A.O. Karachay Lake is the Storage of the Radioactive Wastes Under Open Sky. In Proceedings of the International Youth Nuclear Congress, Bratislava, Slovakia, 9–14 April 2000; Nuclear Proceedings and Multimedia Presentation. 2001. Available online: https://www.osti.gov/etdeweb/biblio/20236675 (accessed on 5 August 2024).
27. *ISO 16090-1:2022*; Machine Tools Safety—Machining Centres, Milling Machines, Transfer Machines. International Organization for Standardization: Geneva, Switzerland, 2022.
28. *ISO 23125:2015*; Machine Tools—Safety—Turning Machines. International Organization for Standardization: Geneva, Switzerland, 2015.
29. *ISO 16089:2025*; Machine Tools—Safety—Stationary Grinding Machines. International Organization for Standardization: Geneva, Switzerland, 2025.
30. ASTM International. *Guide for Air Sampling Strategies for Worker and Workplace Protection*; ASTM International: West Conshohocken, PA, USA, 2021. [CrossRef]
31. Kuczmaszewski, J.; Zagórski, I.; Dziubinska, A. Investigation of ignition temperature, time to ignition and chip morphology after the high-speed dry milling of magnesium alloys. *Aircr. Eng. Aerosp. Technol.* **2016**, *88*, 389–396. [CrossRef]
32. Spicer, A.; Kosi, J.; Billups, C.; Pajek, J. *Machining Magnesium with Water Base Coolants*; SAE International: Warrandale, PA, USA, 1991. [CrossRef]
33. Tomac, N.; Tønnessen, K.; Rasch, F.O. Safe Machining of Magnesium. In *Advanced Manufacturing Systems and Technology*; Springer: Vienna, Austria, 1996; pp. 177–184. [CrossRef]
34. Zhao, N.; Hou, J.; Zhu, S. Chip ignition in research on high-speed face milling AM50A magnesium alloy. In *Proceedings of the 2011 Second International Conference on Mechanic Automation and Control Engineering, Inner Mongolia, China, 15–17 July 2011*; IEEE: New York, NY, USA, 2011; pp. 1102–1105. [CrossRef]
35. Carou, D.; Rubio, E.M.; Davim, J. Analysis of ignition risk in intermittent turning of UNS M11917 magnesium alloy at low cutting speeds based on the chip morphology. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2015**, *229*, 365–371. [CrossRef]

36. Takemoto, S.; Sato, M.; Matsuno, T.; Yamamoto, K. Chip Combustion in High-speed Dry Cutting of Titanium Alloy. In Proceedings of the International Conference on Leading Edge Manufacturing in 21st Century: LEM21, Tokyo, Japan, 13–17 November 2017; Volume 9, p. 116. [CrossRef]
37. Beeston, J. Beryllium metal as a neutron moderator and reflector material. *Nucl. Eng. Des.* **1971**, *14*, 445–474. [CrossRef]
38. National Toxicology Program. *Report on Carcinogens, Fifteenth Edition Beryllium and Beryllium Compounds*; Department of Health and Human Services: Durham, NC, USA, 2021. Available online: https://www.ncbi.nlm.nih.gov/books/NBK590916/ (accessed on 21 January 2025).
39. Sanderson, W.T.; Ward, E.M.; Steenland, K.; Petersen, M.R. Lung cancer case—Control study of beryllium workers. *Am. J. Ind. Med.* **2001**, *39*, 133–144. [CrossRef] [PubMed]
40. US Department of Health and Human Services. *Toxicological Profile for Beryllium*; US Department of Health and Human Services: Atlanta, GA, USA, 2023.
41. Gordon, T.; Bowser, D. Beryllium: Genotoxicity and carcinogenicity. *Mutat. Res. Mol. Mech. Mutagen.* **2003**, *533*, 99–105. [CrossRef]
42. Nickell-Brady, C.; Hahn, F.F.; Finch, G.L.; Belinsky, S.A. Analysis of K-*ras p53* and *c-raf* -1 mutations in beryllium-induced rat lung tumors. *Carcinogenesis* **1994**, *15*, 257–262. [CrossRef]
43. Schepers, G.W.; Durkan, T.M.; Delahant, A.B.; Creedon, F.T. The biological action of inhaled beryllium sulfate; a preliminary chronic toxicity study on rats. *AMA Arch. Ind. Health* **1957**, *15*, 32–58.
44. Wagner, W.; Groth, D.; Holtz, J.; Madden, G.; Stokinger, H. Comparative chronic inhalation toxicity of beryllium ores, bertrandite and beryl, with production of pulmonary tumors by beryl. *Toxicol. Appl. Pharmacol.* **1969**, *15*, 10–29. [CrossRef] [PubMed]
45. Werder, G.W.; Foley, N.K.; Jaskula, B.W.; Ayuso, R.A. *U.S. Department of the Interior U.S. Geological Survey Fact Sheet 2016–3081 October 2016 Beryllium—A Critical Mineral Commodity—Resources, Production, and Supply Chain*; USGS: Reston, VA, USA, 2016. Available online: https://pubs.usgs.gov/fs/2016/3081/fs20163081.pdf (accessed on 5 August 2024).
46. Kelleher, P.C.; Martyny, J.W.; Mroz, M.M.; Maier, L.A.; Ruttenber, A.J.; Young, D.A.; Newman, L.S. Beryllium Particulate Exposure and Disease Relations in a Beryllium Machining Plant. *J. Occup. Environ. Med.* **2001**, *43*, 238–249. Available online: https://journals.lww.com/joem/fulltext/2001/03000/beryllium_particulate_exposure_and_disease.12.aspx (accessed on 21 January 2025). [CrossRef] [PubMed]
47. OSHA. BERYLLIUM & COMPOUNDS (as Be). Occupational Safety and Health Administration. Available online: https://www.osha.gov/chemicaldata/531 (accessed on 5 August 2024).
48. European Parilament and the Council of the European Union. *Directive (EU) 2019/983 on the Protection of Workers from the Risks Related to Exposure to Carcinogens or Mutagens at Work*; Official Journal of the European Union: Brussels, Belgium, 2019.
49. Elguero, J.; Alkorta, I. The dubious origin of beryllium toxicity. *Struct. Chem.* **2023**, *34*, 391–398. [CrossRef]
50. Choi, S.H.; Lee, S.S.; Lee, H.Y.; Kim, S.; Kim, J.W.; Jin, M.S. Cryo-EM structure of cadmium-bound human ABCB6. *Commun. Biol.* **2024**, *7*, 672. [CrossRef]
51. Fenga, C.; Gangemi, S.; Alibrandi, A.; Costa, C.; Micali, E. Relationship between lead exposure and mild cognitive impairment. *J. Prev. Med. Hyg.* **2016**, *57*, E205–E210.
52. Liao, L.M.; Friesen, M.C.; Xiang, Y.-B.; Cai, H.; Koh, D.-H.; Ji, B.-T.; Yang, G.; Li, H.-L.; Locke, S.J.; Rothman, N.; et al. Occupational Lead Exposure and Associations with Selected Cancers: The Shanghai Men's and Women's Health Study Cohorts. *Environ. Health Perspect.* **2016**, *124*, 97–103. [CrossRef]
53. Louis, E.D.; Jurewicz, E.C.; Applegate, L.; Factor-Litvak, P.; Parides, M.; Andrews, L.; Slavkovich, V.; Graziano, J.H.; Carroll, S.; Todd, A. Association between essential tremor and blood lead concentration. *Environ. Health Perspect.* **2003**, *111*, 1707–1711. [CrossRef]
54. Gambelunghe, A.; Sallsten, G.; Borné, Y.; Forsgard, N.; Hedblad, B.; Nilsson, P.; Fagerberg, B.; Engström, G.; Barregard, L. Low-level exposure to lead, blood pressure, and hypertension in a population-based cohort. *Environ. Res.* **2016**, *149*, 157–163. [CrossRef]
55. Harari, F.; Sallsten, G.; Christensson, A.; Petkovic, M.; Hedblad, B.; Forsgard, N.; Melander, O.; Nilsson, P.M.; Borné, Y.; Engström, G.; et al. Blood Lead Levels and Decreased Kidney Function in a Population-Based Cohort. *Am. J. Kidney Dis.* **2018**, *72*, 381–389. [CrossRef]
56. Kumar, S. Occupational and environmental exposure to lead and reproductive health impairment: An overview. *Indian J. Occup. Environ. Med.* **2018**, *22*, 128. [CrossRef]
57. Agency for Toxic Substances and Disease Registry. *What are Possible Health Effects from Lead Exposure?* Agency for Toxic Substances and Disease Registry: Atlanta, GA, USA, 2023. Available online: https://archive.cdc.gov/www_atsdr_cdc_gov/csem/leadtoxicity/physiological_effects.html (accessed on 15 July 2024).
58. Council on Environmental Health; Lanphear, B.P.; Lowry, J.A.; Ahdoot, S.; Baum, C.R.; Bernstein, A.S.; Bole, A.; Brumberg, H.L.; Campbell, C.C.; Lanphear, B.P.; et al. Prevention of Childhood Lead Toxicity. *Pediatrics* **2016**, *138*, e20161493. [CrossRef]

59. UK Health Security Agency. *Lead Exposure in Children Surveillance System (LEICSS) Annual Report, 2023*; UK Health Security Agency: London, UK, 2023. Available online: https://www.gov.uk/government/publications/lead-exposure-in-children-surveillance-reports-from-2021/lead-exposure-in-children-surveillance-system-leicss-annual-report-2023 (accessed on 15 July 2024).
60. Liu, Y.; Téllez-Rojo, M.M.; Sánchez, B.N.; Zhang, Z.; Afeiche, M.C.; Mercado-García, A.; Hu, H.; Meeker, J.D.; Peterson, K.E. Early lead exposure and pubertal development in a Mexico City population. *Environ. Int.* **2019**, *125*, 445–451. [CrossRef] [PubMed]
61. Bregnbak, D.; Johansen, J.D.; Jellesen, M.S.; Zachariae, C.; Menné, T.; Thyssen, J.P. Chromium allergy and dermatitis: Prevalence and main findings. *Contact Dermat.* **2015**, *73*, 261–280. [CrossRef] [PubMed]
62. Schuttelaar, M.L.A.; Ofenloch, R.F.; Bruze, M.; Cazzaniga, S.; Elsner, P.; Gonçalo, M.; Naldi, L.; Svensson, Å.; Diepgen, T.L. Prevalence of contact allergy to metals in the European general population with a focus on nickel and piercings: The EDEN Fragrance Study. *Contact Dermat.* **2018**, *79*, 1–9. [CrossRef]
63. Public Health England. *Nickel Toxicology Overview*; Public Health England: London, UK, 2009. Available online: https://assets.publishing.service.gov.uk/media/5a7e0302ed915d74e622386f/Nickel_Toxicological_Overview_phe_v1.pdf (accessed on 16 July 2024).
64. International Agency for Research on Cancer. *Iarc Monographs on the Evaluation of Carcinogenic Risks to Humans*; International Agency for Research on Cancer: Lyon, France, 1990; Available online: https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/Chromium-Nickel-And-Welding-1990 (accessed on 16 July 2024).
65. International Agency for Research on Cancer. *Cobalt, Antimony Compounds, and Weapons-Grade Tungsten Alloy*; International Agency for Research on Cancer: Lyon, France, 2023; Available online: https://publications.iarc.fr/618 (accessed on 16 July 2024).
66. Occupational Safety and Health Administratio. Health Hazards >> Cobalt Dust. U.S. Department of Labor. Available online: https://www.osha.gov/etools/sawmills/plant-wide-hazards/health-hazards/cobalt-dust (accessed on 16 July 2024).
67. Waltner, K. Kobalt und Blut. *Klin. Wochenschr.* **1929**, *8*, 313. [CrossRef]
68. Leghissa, P.; Ferrari, M.T.; Piazzolla, S.; Caironi, M.; Parigi, P.C.; Lebbolo, E. Cobalt exposure evaluation in dental prostheses production. *Sci. Total. Environ.* **1994**, *150*, 253–257. [CrossRef] [PubMed]
69. Minoia, C.; Sabbioni, E.; Apostoli, P.; Pietra, R.; Pozzoli, L.; Gallorini, M.; Nicolaou, G.; Alessio, L.; Capodaglio, E. Trace element reference values in tissues from inhabitants of the European community I. A study of 46 elements in urine, blood and serum of Italian subjects. *Sci. Total. Environ.* **1990**, *95*, 89–105. [CrossRef]
70. Samargandi, R.; Le Nail, L.-R.; Hetaimish, B.; Saad, M. Cobalt-chromium toxicity following revision of total hip replacement. *Saudi Med. J.* **2024**, *45*, 194–198. [CrossRef]
71. Hichem, N.; Hadjer, Z.; Fateh, S.; Feriel, L.; Wang, Z. The Potential Exposure and Hazards of Zirconia Nanoparticles: A Review. *Ecotoxicol. Environ. Contam.* **2022**, *17*, 1–21. [CrossRef]
72. Cooper, T.D. *Review of Zirconium-Zircaloy Pyrophoricity*; Rockwell Hanford Operations: Richland, WA, USA, 1984. [CrossRef]
73. De, A.; Ghosh, S.; Chakrabarti, M.; Ghosh, I.; Banerjee, R.; Mukherjee, A. Effect of low-dose exposure of aluminium oxide nanoparticles in Swiss albino mice: Histopathological changes and oxidative damage. *Toxicol. Ind. Health* **2020**, *36*, 567–579. [CrossRef] [PubMed]
74. CI of Factories. *Annual Report of the Chief Inspector of Factories and Workshops for 1898*; HMSO: London, UK, 1898.
75. Vu, V.T.; Lai, D.Y. Approaches to characterizing human health risks of exposure to fibers. *Environ. Health Perspect.* **1997**, *105*, 1329–1336. [CrossRef]
76. DWarheit, D.B.; Hansen, J.F.; Carakostas, M.C.; Hartsky, M.A. Acute Inhalation Toxicity Studies in Rats with a Respirable-Sized Experimental Carbon Fibre: Pulmonary Biochemical and Cellular Effects. *Ann. Work Expo. Health* **1994**, *38*, 769–776. [CrossRef]
77. Zhang, Z.; Wang, X.; Lin, L.; Xing, S.; Wu, Y.; Li, Y.; Wu, L.; Gang, B. The Effects of Carbon Fibre and Carbon Fibre Composite Dusts on Bronchoalveolar Lavage Component of Rats. *J. Occup. Health* **2001**, *43*, 75–79. [CrossRef]
78. Rödelsperger, K.; Brückel, B. The Carcinogenicity of WHO Fibers of Silicon Carbide: SiC Whiskers Compared to Cleavage Fragments of Granular SiC. *Inhal. Toxicol.* **2006**, *18*, 623–631. [CrossRef]
79. Pott, F.; Roller, M.; Rippe, R.M.; Germann, P.-G.; Bellmann, B. Tumours by the Intraperitoneal and Intrapleural Routes and their Significance for the Classification of Mineral Fibres. In *Mechanisms in Fibre Carcinogenesis*; Brown, R.C., Hoskins, J.A., Johnson, N.F., Eds.; Springer: Boston, MA, USA, 1991; pp. 547–565. [CrossRef]
80. Pott, F.; Roller, M.; Althoff, G.; Kamino, K.; Bellman, B.; Ulm, K. Estimation of the carcinogenicity of inhaled fibres. *VDI Berichte* **1993**, *1075*, 17–77. (In German)
81. GPiggott, H.; Gaskell, B.A.; Ishmael, J. Effects of long term inhalation of alumina fibres in rats. *Br. J. Exp. Pathol.* **1981**, *62*, 323–331.
82. Pigott, G.H.; Ishmael, J. The effects of intrapleural injections of alumina and aluminosilicate (ceramic) fibres. *Int. J. Exp. Pathol.* **1992**, *73*, 137–146. [PubMed]
83. Hannu, T.; Frilander, H.; Kauppi, P.; Kuuliala, O.; Alanko, K. IgE-Mediated Occupational Asthma from Epoxy Resin. *Int. Arch. Allergy Immunol.* **2009**, *148*, 41–44. [CrossRef]

84. Luchtel, D.; Martin, T.; Boatman, E. Response of the rat lung to respirable fractions of composite fiber-epoxy dusts. *Environ. Res.* **1989**, *48*, 57–69. [CrossRef]
85. Whitehead, G.S.; Grasman, K.A.; Kimmel, E.C. Lung function and airway inflammation in rats following exposure to combustion products of carbon–graphite/epoxy composite material: Comparison to a rodent model of acute lung injury. *Toxicology* **2003**, *183*, 175–197. [CrossRef]
86. World Health Organization. *Radiation and Health*; WHO: Geneva, Switzerland, 2023; Available online: https://www.who.int/news-room/questions-and-answers/item/radiation-and-health (accessed on 23 July 2024).
87. Jiao, Y.; Cao, F.; Liu, H. Radiation-induced Cell Death and Its Mechanisms. *Health Phys.* **2022**, *123*, 376–386. [CrossRef]
88. Douple, E.B.; Mabuchi, K.; Cullings, H.M.; Preston, D.L.; Kodama, K.; Shimizu, Y.; Fujiwara, S.; Shore, R.E. Long-term Radiation-Related Health Effects in a Unique Human Population: Lessons Learned from the Atomic Bomb Survivors of Hiroshima and Nagasaki. *Disaster Med. Public Health Prep.* **2011**, *5*, S122–S133. [CrossRef]
89. Vinhas, L.A. Overview of the Radiological Accident in Goiânia. In *Security of Radioactive Sources*; IAEA, Ed.; International Atomic Energy Agency: Vienna, Austria, 2003; pp. 347–355. Available online: https://inis.iaea.org/records/3yjp0-csf19 (accessed on 15 September 2025).
90. Simon, S.L.; Bouville, A.; Beck, H.L.; Anspaugh, L.R.; Thiessen, K.M.; Hoffman, F.O.; Shinkarev, S. Dose Estimation for Exposure to Radioactive Fallout from Nuclear Detonations. *Health Phys.* **2022**, *122*, 1–20. [CrossRef] [PubMed]
91. MPlys, G.; Epstein, M.; Malinovic, B. *Uranium Pyrophoricity Phenomena and Prediction*; FAU99-4; Fauske & Associates, Inc.: Burr Ridge, IL, USA, 1999.
92. Plys, M.G. *Uranium Pyrophoricity Phenomena and Prediction (FAI/00-39)*; FAI: Richland, WA, USA, 2000. [CrossRef]
93. Battelle Pacific Northwest Labs. *AEC Uranium Fire Experience*; Battelle Pacific Northwest Labs: Richland, WA, USA, 1954. [CrossRef]
94. Levilly, R.; Sauvain, J.-J.; Andre, F.; Demange, V.; Bourgkard, E.; Wild, P.; Hopf, N.B. Characterization of occupational inhalation exposures to particulate and gaseous straight and water-based metalworking fluids. *Sci. Rep.* **2024**, *14*, 18814. [CrossRef]
95. HSE. MW1 COSHH Essentials for Machining with Metalworking Fluids. 2021. Available online: www.hse.gov.uk/metalworking/water.htm (accessed on 21 January 2025).
96. Yao, H.; Qiu, S.; Lv, Y.; Wei, S.; Li, A.; Long, Z.; Wu, W.; Shen, X. Indoor Particulate Matter Transfer in CNC Machining Workshop and The Influence of Ventilation Strategies—A Case Study. *Sustainability* **2023**, *15*, 6227. [CrossRef]
97. HSE. LEV—Frequently Asked Questions. HSE.Gov. Available online: https://www.hse.gov.uk/lev/faqs.htm (accessed on 31 July 2024).
98. HAAS. OM-1/OM-2 Positive Ventilation Kit—Spindle Head—Installation. Haascnc.Com. Available online: https://www.haascnc.com/service/troubleshooting-and-how-to/how-to/om-1--om-2-positive-ventilation-kit-spindle-head-installation-ad0167.html (accessed on 5 August 2024).
99. DMG MORI. LASERTEC 65 DED Hybrid. Dmgmori.Com. Available online: https://en.dmgmori.com/products/machines/additive-manufacturing/powder-nozzle/lasertec-65-ded-hybrid (accessed on 5 August 2024).
100. Ezugwu, E.O.; Da Silva, R.B.; Bonney, J.; Machado, Á.R. The Effect of Argon-Enriched Environment in High-Speed Machining of Titanium Alloy. *Tribol. Trans.* **2005**, *48*, 18–23. [CrossRef]
101. Viton. Viton™ Fluoroelastomer: The Imagination Component. Chemours. Available online: https://www.viton.com/en/ (accessed on 29 January 2025).
102. Honeywell. Silver Shield®—SSB. Honeywell. Available online: https://automation.honeywell.com (accessed on 29 January 2025).
103. Barrier Technologies. *Secure Touch Radiation Protection Gloves*; Barrier Technologies: Davie, FL, USA, 2018; Available online: https://barriertechnologies.com/wp-content/uploads/2018/04/Barrier-Technologies-Radiation-Protection-Gloves.pdf (accessed on 29 January 2025).
104. Sorock, G.S.; Lombardi, D.A.; Hauser, R.B.; Eisen, E.A.; Herrick, R.F.; Mittleman, M.A. Acute Traumatic Occupational Hand Injuries Type, Location, and Severity. *J. Occup. Environ. Med.* **2002**, *44*, 345–351. [CrossRef] [PubMed]
105. SCX Specialist Handling Solutions. Moving Humans Away from Harm. KSG. Available online: https://scx.co.uk/capability/moving-humans-away-from-harm/ (accessed on 25 July 2024).
106. Agency for Toxic Substances and Disease Registry. *Toxicology Profile for Zinc*; Agency for Toxic Substances and Disease Registry: Atlanta, GA, USA, 2005. Available online: https://www.ncbi.nlm.nih.gov/books/NBK600535/ (accessed on 5 August 2024).