Topical Review

Micromanufacturing of composite materials: a review

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Abstract
Composite materials exhibit advantages from the combination of multiple properties, which cannot be achieved by a monolithic material. At present, the use of composite materials in miniaturized scale is receiving much attention in the fields of medicine, electronics, aerospace, and microtooling. A common method for producing miniaturized composite parts is micromanufacturing. There has been, however, no comprehensive literature published that reviews, compares, and discusses the ongoing micromanufacturing methods for producing miniaturized composite components. This study identifies the major micromanufacturing methods used with composite materials, categorizes their subclasses, and highlights the latest developments, new trends, and effects of key factors on the productivity, quality, and cost of manufacturing composite materials. A comparative study is presented that shows the potential and versatility associated with producing composite materials along with possible future applications. This review will be helpful in promoting micromanufacturing technology for fabricating miniaturized products made of composite materials to meet the growing industrial demand.

Keywords: micromanufacturing, composite materials, microproducts, size effects, interfacial microstructure

1. Introduction

Recently, the use of miniaturized products has been strongly increasing throughout the globe [1]. There has been a continuously growing demand for compact, multifunctional, integrated miniature products. The demand is significant in the fields of electronics [2], microtooling [1], aerospace [3–5], medicine and biomedicine [5–7], information technology and telecommunications [8], automobiles, and microrobots [9, 10]. Consequently, products and devices are getting smaller, down to microscale, due to a near-future demand for nanoscale. This trend to miniaturization has, in fact, moved very quickly during the last two decades, driven primarily by electronics and silicon (Si)-based products. Therefore, Si-based micromanufacturing technologies, e.g. microelectromechanical systems (MEMS), photolithography, the lithographie, galvanoformung, abformung (LIGA) process, and electrochemical deposition [11, 12], have reached a mature level. Nevertheless, Si-based products have some intrinsic limitations with respect to geometry (limited to two dimensions (2D) and 2.5D), material (only Si), mechanical performance (limited motion, strength, and durability), and cost (not amenable to mass production) [11–13].

These issues have led researchers to find alternatives for producing three-dimensional (3D) microparts with the desired strength, better durability, complex geometry, better surface finish and cost-effectiveness, using metallic and ceramic
alloys and their composites [2, 13]. There has also been noticeable progress in micromanufacturing of different metal-, ceramic-, polymer-, and composite-based components. Their fabrication methods, operating principles, size effects due to miniaturization, batch production, and energy and material savings have been thoroughly researched [13–15]. Numerous books and articles are also available that point out various critical factors and features pertinent to micromanufacturing of these materials.

However, the possibilities of using bulk materials, such as metals, ceramics, polymers, and their alloys, are so saturated that it may be difficult to achieve the highest material properties, such as durability and reliability of the components, even when using the most advanced techniques [16]. Composite materials, on the other hand, exhibit endless possibilities for meeting many of the emerging industrial requirements, in terms of extreme mechanical, electrical, magnetic, optical, and thermal properties, that cannot be met by monolithic materials. The main advantages of composite materials are their high strength, toughness, stiffness, and resistance to creep resulting in less corrosion, wear, and fatigue compared to conventional materials [16, 17]. By choosing an appropriate combination, it is also possible to attain specific properties, such as a composite of copper–aluminum (Cu–Al) clad, which are lighter, stronger, more solderable, and more electrically conductive compared to individual alloys [18, 19]. Therefore, composite materials are indispensable in a variety of applications today from micro- to nanoscale.

Although micromanufacturing techniques for monolithic materials are plentiful, not all of them are equally applicable to the production of microcomponents of composite materials [20]. In addition, substantial research has been conducted on micromanufacturing of composite materials. However, this research is focused on an individual technique. Therefore, an article reviewing the existing micromanufacturing techniques of composite materials, highlighting the latest developments and future trends, will significantly benefit the scientific community and advance the micromanufacturing of composite materials. In the work presented here, state-of-the-art micromanufacturing techniques for producing microcomposite components incorporating superior properties are reviewed.

A fundamental description defining the concept of micromanufacturing and composite materials is provided first followed by an all-embracing but simple categorization. Since the field of composite materials is vast, the focus is primarily on metal- and ceramic-based composite materials, excluding organic and polymeric composites. Therefore, cutting-edge micromanufacturing methods of metal matrix composites (MMCs) and ceramic matrix composites (CMCs) are extensively reviewed, highlighting the latest developments and future trends/research scope. The key factors influencing productivity, cost, and quality of the micromanufacturing of composite materials, such as size effects and matrix-reinforcement interfacial characteristics, are also addressed and discussed. To demonstrate the potential for micromanufacturing of composite materials, a bimetallic composite of ceramic and steel was fabricated by a novel micromanufacturing method, namely hot compaction diffusion bonding (HCDB). The results obtained are presented and discussed. Finally, the progress on analytical modeling and simulation of the micromanufacturing of composite materials is presented. A comparative study is also presented that shows the potential for and versatility of producing composite materials along with possible future applications. This review will be helpful for promoting micromanufacturing technology for fabricating miniaturized composite components with attractive properties to meet the growing industrial demand.

2. Fundamentals of micromanufacturing and composite materials

2.1. Micromanufacturing

The concept and/or definition of micromanufacturing has been addressed by a number of researchers and industrial personnel, as reported in earlier studies [2, 11–15]. The simplest definition of micromanufacturing is a system for producing small-dimensional parts occupying less space and consuming less resources and energy by downsizing the complete production process. Since the equipment size is reduced, the mass of the system can be reduced dramatically. This results in reduced energy consumption, overhead cost, materials requirement, noise, and pollution and eventually facilitates a more environmentally friendly and viable production process. Due to a reduced manufacturing cycle and higher tool speed, micromanufacturing also leads to higher production rates. A study conducted in [21] demonstrated the influence of miniaturization and pointed out that a 1/10-scale reduction of the production facility may result in a 1/100-scale reduction of energy consumption when compared to that of a conventional production system/factory. The most noteworthy improvement of micromanufacturing is its ability to produce components having a feature size of less than 100 μm [22, 23], close to the size of a human hair. Figure 1 shows micromachined parts made of aluminum oxide ($\text{Al}_2\text{O}_3$)-reinforced 316L stainless steel composite materials that combine the hardness of ceramic and the strength of steel. A novel method, called the ‘soft molding technique,’ was used. The authors [20] claim that the hardness of 316L stainless steel was improved by 1.8 times, enabling the parts to be stronger, harder, and more wear resistant.

There are a number of techniques and processes that are used to manufacture miniaturized components. Based on the materials used, micromanufacturing can be broadly classified into two major categories: silicon and nonsilicon. In non-silicon-based micromanufacturing, the materials usually dealt with are metal, ceramic, polymeric, and composite. Consequently, a number of different manufacturing techniques are involved and are being practiced in the industry. A useful, simple, and all-embracing classification is presented in table 1, including typical applications and common materials used. There is also a common trend of combining multiple processes together, termed hybrid micromanufacturing [24]. The type of energy involved in these processes includes
2.2. Composite materials

With the rapid development of the modern manufacturing industry, composite materials are being extensively used as advanced multifunctional materials in various fields, such as electronics, aeronautics, medicine, automobiles, and machining tools, due to their unique properties that eliminate traditional limitations due to the physical and mechanical performance of monolithic materials [34, 35]. For example, tungsten carbide (WC) has good hardness and wear resistance but poor strength and toughness [36, 37], while high strength steel has excellent strength and toughness but low hardness and wear resistance [38–40]. A layered composite of WC and high strength steel can combine their advantages and be used in many engineering applications.

A composite material can be defined as a material fabricated from two or more integral materials with considerably different physical and chemical properties that, when combined, produce a material with characteristics different from the individual constituents. The individual constituents stay separate and distinct within the completed structure, differentiating composites from mixtures and solid solutions [41, 42]. Thus, every composite material, by definition, has essentially two components, a matrix, i.e. a continuous phase, which is armored by a reinforcement, i.e. a discontinuous phase. In cases where there are three or more constituents, the composite is termed to be a hybrid composite [43, 44]. Composites are available all around us in nature, e.g. wood, bone, tissue, etc. In industry, most of the composites are based on metals, ceramics, and polymers [17]. Composites can be classified in various ways. A useful and all-embracing classification can be made based on matrix and reinforcement, as shown in Table 2. The MMCs containing reinforcement, e.g. ceramic particles, whiskers, and fibers, are gaining much importance these days. The CMCs are considered to be the newest entrants in the field [45]. In this study, particular focus is given to micromanufacturing of metallic- and ceramic-based composite components.

2.3. Metal matrix composites

The need for new materials is constantly important to manufacturing industries. Better mechanical properties, reduced weight, and lower cost are the key factors for developing new materials [46]. Since current bulk materials eventually reach their limits, engineers are looking to composites to obtain extra strength, stiffness, and durability [47]. Metals and their alloys are largely manufactured and shaped in bulk form; however, they can also be intimately combined with another material in order to improve their performance. The resulting materials are MMCs [48]. Significant advancement in the development of MMCs has been achieved over the past few decades, with their incorporation into important industrial applications. These pioneering materials have opened up infinite possibilities for present material science and development [49]. The characteristics of MMCs can be designed into the material, custom-made, and dependent on the application [49]. When compared to polymer matrix composites, MMCs offer improved material properties. For example, compared to resin, metal matrices provide higher tensile and shear moduli, higher melting temperature, a lower thermal coefficient of expansion, better dimensional stability, better joinability, high ductility and toughness, and the ability to be fully dense [50, 51]. MMCs essentially consist of a metal or alloy as matrix material and a reinforcement of different kinds and shapes. Table 3 presents a detailed classification of MMCs with typical examples of materials used, their applications, and fabrication techniques.
Table 1. Micromanufacturing techniques [2–5, 13–33].

| Major type | Subtypes | Geometry | Common materials | Typical parts | Typical application |
|------------|----------|----------|------------------|---------------|--------------------|
| Microforming—conventional | Microrolling (cross-wedge, ultrathin, flexible) | A few to 10 s of microns | Metals (Al, Cu, Ni, steel, Mg, Ti), alloys, and composites | Micromans, pins, tubular parts | Sheet metal, medical devices, implants |
| | Microforging | Hundreds of microns | Metals, metallic alloys, polymers | Microscrews, cans, gears, etc. | Microdevices, housing, and assembly |
| | Microextrusion (forward, backward, cross) | A few 100 nm to 10 s of microns | Metals, metallic alloys, polymers, composites | Microgears, pins, screws, gear shafts, cans, etc. | MEMS devices, watches, mechanical and electrical parts |
| | Microdeep drawing | Dia < 1 mm, 100 μm thickness | Various metals and composites | Microparts, housings, etc. | Electron guns, pressure sensors, UV sensors, etc. |
| | Microstamping (punching, blanking, bending) | Tens to several 100 μm | Metals, metallic alloys, (e.g. Al, Cu, Ni, steel), polymers | Lead frames, casing, microcups, gears, etc. | MEMS devices, electronics, medical, optical, and chemical |
| | Microembossing, coining | A few 100 nm to 10 s of microns | Polymers, glass, Al, Cu, brass, steel, etc. | Functionalized (2.5D) structures | Microoptical, fluidic devices, dies/molds, etc. |
| Microforming—advanced | Microhydroforming | Dia < 1 mm, 100 μm thickness | Various metals and composites | Microparts, tubes, complex shaped parts | Sheet metal, high-precision microparts |
| | Laser-assisted microforming | Several 100 s of microns | Various metals | Lead frames, 2-3D microparts | Microoptical, fluidic devices, dies, molds, etc. |
| | Microeletroforming | Dia < 1 mm, 100 μm thickness | Various metals | High aspect ratio microparts, etc. | Microoptical, fluidic devices |
| | Micromachining—conventional | Microdrilling | A few μm dia, 100 μm long | Metals, ceramics, polymers, composites | PCB board, microparts with holes, etc. | PCB industry, medical, electronic, aerospace, optical |
| | Micromilling [28] | Several 100 s of microns | Metals, polymers, alloys, composites | Complex 3D parts, pins, microgears, shafts, etc. | Microoptical, fluidic devices, dies, molds, etc. |
| | Microturning | A few 100 nm to 10 s of μs | Metals, metallic alloys, polymers, etc. | Complex 3D parts, microshafts, etc. | Microdevices, dies, molds, etc. |
| | Microgrinding | Several 100 s of microns | Metals, ceramics, polymers, composites | Microdrill, gears, shafts, hard-to-machine parts | Microtool industry, medical, electronics, aerospace |
| | EDM [27] | A few to 100 s of microns | Functional materials, conductive ceramics | Microgear, dies, mold fluidic devices, implants | Medical, electronics, micro tool industry, etc. |
| | Laser micromachining | 100 nm to 10 s of microns | Polymers, glass, Al, Cu, brass, steel | Functionalized (2.5D) structures | Microoptical, fluidic devices, dies/molds, etc. |
| | Jet machining (abrasive, water) | Several 100 s of microns | Glass, PMMA, PDMS, ABS, PTFE, polymers [33] | Complex 2-3D parts, microgears, shafts | Microfluidic devices, MEMS, electronics |
| | Ultrasonic | Submillimeter | Ceramic and brittle materials [32] | Complex, difficult-to-machine microparts | Microfluidic devices, MEMS, electronics |
| | Electron beam | Nanomachining | Various metals | Ultraprecision microparts | Microtool industry, medical |
| | Electrochemical | Submillimeter | Chemically reactive materials | Micromolds, dies, punches | Microdevices, microtooling, housings |
| | Microcasting | A few 100 μm to submillimeter | Tool steel, metal, ceramic powders | Micromolds, dies, punches, shafts, gears | Micromechanical, electronics, biotechnology |
| | Microinjection molding | Microns to submillimeter | Polymers, PDMS, ABS, PTFE | Various shaped 2D-3D microparts | Microoptics, microfluidics |


### 2.4. Ceramic matrix composites

Metal and metallic composites have been extensively used in industry; however, in certain applications, particularly involving high temperatures, they have reached a limit in their potential for further development. Ceramics, on the other hand, offer the advantage of operating at substantially high service temperatures. In addition, low density, high hardness, and chemical inertness extend potential ceramic performance limits beyond those achievable by metallic materials. Nevertheless, ceramic materials have intrinsic limitations of brittleness and poor strength reliability. In an effort to overcome these drawbacks, significant progress has been reported in the last two decades. The most important development appeared in the form of composites, i.e. the combination of multiple constituent phases with suitable microstructures in order to obtain the desired properties. Generally, ceramic composites are composed of two or more distinct ceramic phases combined on a microstructural scale to provide the properties that cannot be achieved by monolithic materials [63, 64].

In the arena of composite materials, CMCs are considered to be the latest entrants with a set of impressive properties and potential applications [45]. Due to advancements in the manufacturing process and technology, a wide variety of types of CMCs have come into use to meet the continuously growing industrial demand. These can be categorized into four major groups: (1) reinforced CMCs, (2) graded and layered composites, (3) refractory composites, and (4) nanostructured composites. Similarly, there are a number of different techniques for manufacturing CMCs, which are classified based on the materials used, kind of composites,
typical applications, and fabrication principle. Table 4 summarizes different matrices and fiber materials used in CMCs and different fabrication techniques with examples.

### 3. Microforming of composite materials

Microforming is one of the popular micromanufacturing methods, where the traditional metal-forming technology is scaled down to microscale. Microforming is usually defined as the forming of components or geometrical features with at least two dimensions in the submillimeter range. Microforming presents an emerging micromanufacturing technique due to a number of advantages over other micromanufacturing techniques. Process simplicity, better mechanical properties of the parts, high production rate, minimum material waste, and net shape characteristics are a few of the advantages [14, 70–73].

Figure 2 presents some microcomponents manufactured by microforming. A wide variety of material types are used for microforming, such as aluminum, copper, brass, nickel, titanium, magnesium, and steel. Recently, the use of composite materials has been receiving increased interest. Since material cost is a major concern in industrial production, replacing a part of the component with a cheaper material, while maintaining the desired functions of the part, may save

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**Table 4.** Matrix and fiber materials used in CMCs and their fabrication techniques [63–69].

| Types            | Subtypes          | Examples                                                                 |
|------------------|-------------------|--------------------------------------------------------------------------|
| **Matrix materials** |                   |                                                                          |
| Ceramics         | Single oxides     | Al₂O₃, ZrO₂, TiO₂, MgO, SiO₂, SiO₄                                     |
|                  | Mixed oxides      | Mullite (3Al₂O₃·3SiO₂), Spinel (MgO·Al₂O₃)                              |
|                  | Carbides          | SiC, B₄C, TiC                                                            |
|                  | Nitrides          | BN, Si₃N₄                                                               |
|                  | Intermetallics    | NiAl, Ni₃Al, TiAl, Ti₃Al, MoSi₂                                          |
|                  | Elemental         | Carbon (C), boron (B)                                                   |
| Glass-ceramics   | Li₂O- Al₂O₃-SiO₂ (LAS), MgO- Al₂O₃-SiO₂, SiO₂-Al₂O₃-MgO-K₂O-F               |
|                  | Glass             | Soda-lime, borosilicate, silica, fused quartz                            |
| Particulate      | SiC, TiC, Al₂O₃   |                                                                          |
| **Reinforcement materials** |               |                                                                          |
| Discontinuous fiber | Whiskers          | SiC, TiB₂, Al₂O₃                                                        |
| Continuous fiber  | Short fibers      | Glass, Al₂O₃, SiC.(Al₂O₃ + SiO₂), vapor-grown carbon fibers              |
|                  | Oxides            | Al₂O₃, (Al₂O₃ + SiO₂), ZrO₂, silica-based glasses                        |
|                  | Nonoxides         | B, C, SiC, Si₃N₄, BN                                                    |
| **Fabrication techniques** |            |                                                                          |
| Conventional techniques | Mixing matrix and fiber powders, cold press, and sintering               |
|                  | Hot pressing of CMC powder mixture                                      |
|                  | Pressure-assisted hot pressing                                          |
|                  | Reaction bonding                                                  |
|                  | Joining (layered composites): soldering, brazing, diffusion            |
|                  | Hybrid (combining two or more processes)                                |
| Advanced/novel techniques | Infiltration          | Liquid infiltration                                                        |
|                  | Directed oxidation                                                   |
|                  | *In situ* chemical reaction                                           |
|                  | Others: sol–gel, pyrolysis, self-propagating high-temperature synthesis (SHS), spark plasma sintering (SPS), pulse plasma sintering (PPS), HCDB |
significant cost. This, in fact, has generated increasing interest as a way to reduce the production cost. An example is shown in figure 2(b), where a brass part is replaced by cheaper steel. In addition, replacing part of the component with lightweight materials also results in reduced weight of the component. Thus, composite materials play a significant role in modern applications in terms of lower cost, lighter weight, and better mechanical properties. In this section, various cutting edge microforming technologies used to manufacture composite materials are presented as well as their future trends.

3.1. Microrolling of composite materials

Composite materials are popular because of their heavy industrial use, providing cheaper, lighter, and stronger alternatives to monolithic materials [76]. For example, the use of layered composite materials has recently received significant attention due to their lower cost and attractive mechanical, electrical, and magnetic properties. Laminated composite materials provide customizable properties for specific applications requiring high impact and fracture resistance [77, 78]. Such composite materials have a uniform distance between composite layers and are typically fabricated by physical vapor deposition (PVD) techniques, e.g. magnetron sputtering [79–81] and electron beam deposition [82–84]. Among mechanical means, rolling, hammering, and swaging are used to bond alternating sheets to fabricate a composite. However, rolling or roll bonding is reported to be one of the popular methods, due to good potential for commercialization due to its comparatively simple processing and low cost. Rolling can also be accompanied by a cold or hot system to customize the material functionalities. Usually, bottom-up PVD methods provide more refined and even microstructures while top-down mechanical techniques produce coarser, nonuniform microstructures. Nevertheless, uniformity of microstructures can be controlled to some extent during rolling by choosing materials with similar hardness and strain hardening rate, providing uniform layer deformation and reducing layer pinch-off.

Stover et al [85] fabricated a layered, microcomposite material of nickel (Ni) and Al using a repeated cold rolling method with initial billet thicknesses of 25 and 18 μm, respectively. They investigated the effects of thickness reduction and observed that at higher thickness reduction, less uniform layer deformation and more pinch-off occurs, compared to more gradual and smaller reduction at lower thickness reduction (figure 3). Eizadjou et al [86] implemented accumulative roll bonding (ARB) to fabricate an Al/Cu layered composite at room temperature and demonstrated the generation of nanostructured layered composite with superior properties. An increase in the number of passes may result in equiaxed grains with enhanced hardness [86]. As reported in [87], the flow stress ratio of two materials should be similar and chemically stable to achieve good metallurgical bonding between layers. Adding heat during microrolling can improve further grain refinement [88]. Another emerging approach is to add nanoparticles to improve the properties of composite materials. Yousefian et al [89] used titanium dioxide (TiO2) nanoparticles and observed significant improvement in tensile strength of aluminum MMC during microrolling. Thus, there are numerous techniques that could be implemented to enhance the properties of composite materials. However, the choice of materials used for microrolling is still limited, leading to a considerable scope of future research to attempt different combinations of materials with a number of potential future applications. In addition, as the trend is to obtain finer grain structure by improving material properties, severe plastic deformation (SPD) could be used to fabricate composite materials. Though there has been remarkable progress in SPD of bulk materials, their use in composite materials is limited [90–92]. The application of SPD in microrolling of composite materials may significantly improve the material properties and, therefore, deserves further research.

3.2. Microdeep drawing (MDD) of composite materials

MDD is a fundamental microforming process and regarded as one of the most applicable sheet metal forming processes. It is
widely used in many industries to produce microcomponents, such as microcylinder cups, rectangular cups, conical cups, spherical cups, hollows, and box-like parts [76, 93]. However, most of these microcomponents are made from bulk materials. Limited attention is paid to MDD of composite materials, though composite materials exhibit a number of attractive properties, as stated earlier. Laminated composite materials, for instance, can be used in manufacturing parts with different inner and outer conditions, such as corrosion, wear resistance, and thermal and electrical conductivities [94–96].

MDD of composite materials appears to be more complex than conventional forming methods. There are several associated parameters which cause problems. A number of defects may occur in the drawn parts, which must be accurately addressed and properly controlled to reduce the number of no-go parts as well as production costs. The parameters taken into account during MDD of composite materials include blank holding force (BHF), applied punch force, material properties of the blanks, thickness of the blanks, stacking sequence of the blanks, velocity of the punch, lubrication, and temperature conditions. In addition, the type of reinforcement used and its shape and size are also important. These factors are responsible for affecting the final products and can regulate the wrinkling effect, tearing effect, and fracture defects.

Many of these parameters are thoroughly discussed in conventional deep drawing as well as MDD of monolithic materials; however, they are not as developed in the case of composite materials. Jia et al [76] examined the effect of heating during MDD of 50 μm of an Al–Cu composite material (figure 4) and successfully fabricated a microcup without considerable fractures or wrinkles. Another important parameter is BHF, as reported in [94], which discusses MDD of an Al 1050 and stainless steel (SS) 304 laminate composite. Yin et al [18] examined the MDD of a cobalt (Co)-Al–Cu laminate composite and observed that an increase in holding time during heat treatment can improve the properties of the formed parts. Consequently, the interaction between the die and specimen plays a significant role in MDD of composite materials. The formability can also be greatly influenced by employing appropriate lubrication. Nanoparticle-based oil lubricant can improve drawability and reduce the forming load of composite materials, as observed in [93], which discusses MDD of an Al–Cu composite material. There has been
some progress in MDD of composite materials; however, the literature still does not describe the interfacial behavior of different laminates and/or matrix-reinforcement interactions during the course of MDD. The material flow characteristics of different layers (prevention of defects, e.g. wrinkling and fractures) during MDD needs to be acutely analyzed. Investigation of the stress and strain distribution of the drawn composite parts also requires further research to develop this promising field.

3.3. Other techniques for microforming composite materials

In addition to the aforementioned microforming techniques, microextrusion, microstamping, microbending, microembossing, micropunching, microblanking, and microcoining are also attracting attention in the forming of microproducts that have a variety of applications. However, not all of these techniques have been implemented in the manufacturing of composite-based microproducts. Examination of the potential for using the above techniques to fabricate microparts from composite materials is clearly lacking [97–104]. However, there have been some innovative microforming methods reported in recent years for the fabrication of composite parts. Patel et al [105] reported a novel microblast-driven microforming method and fabrication of a bismuth oxide (Bi$_2$O$_3$)-reinforced Al composite micropart. A mathematical model and critical forming processes have also been proposed. Bending and contact strengths of a carbon-reinforced silicon nitride-silicon carbide (Si$_3$N$_4$-SiC) composite were examined by Dusza et al [106] and its fracture mechanisms were illustrated. Cui et al [107] fabricated a microlaminated titanium boride-titanium aluminum (TiB-TiAl) composite sheet by employing a multistep heat treatment and pressing process. Zhang et al [108] conducted a simulation of a tin oxide/silver (SnO$_2$/Ag) particulate-reinforced MMC through microextrusion. The effects of the extrusion angle, the extrusion ratio, and the ram speed on the deformation and redistribution of particles during microextrusion were studied using the finite element (FE) method. When composite materials are microformed, the scenario may generally appear different than that of conventional techniques. The deformation behavior of reinforcement (particle distribution) used in the matrix plays a significant role in microforming. The size and type of reinforcement used and its interaction with the matrix material and tools may be a matter of substantial significance, which needs to be thoroughly investigated.

4. Micromachining of composite materials

Even though composite materials are processed near net shape, further machining operations are generally inevitable to ensure the accurate function for the application. Since the cutting/machining mechanism for composite materials is not well understood yet, experimental study to reveal the nature of the cutting behavior of composite materials requires significant experimental tests. To improve the proficiency of experimental works and extract more information, experimental methods have been designed to study the machinability of composite materials. A Taguchi-method-based experiment was studied during the machining of Al [109, 110] and hybrid MMCs [111]. Another approach is response surface methodology, as reported in [112] for cutting forces and in [113] for surface roughness. In addition, FE methods are also used to investigate the cutting mechanism of composite materials, as reported in [114], to examine the cutting mechanism of SiC/Al MMCs. In this section, various factors that influence effective micromachining of composite materials are discussed. In addition, some advanced non-traditional techniques that are used for micromachining of composite materials are also illustrated.

4.1. Factors affecting the machining of composite materials

The microstructure and grain distribution of composite materials play a significant role in the machining of composite materials. The grain size of commonly used engineering materials subject to micromachining falls in the range of 100 nm–100 μm [115, 116]. The radius of the tool edge (i.e. roundness) and feed rate value are frequently considered to be in the range of several hundreds of nanometers to several micrometers, which is also comparable to crystalline grain sizes. Therefore, the influence of grain size, grain distribution, and overall crystallographic nature of the composite materials plays a crucial role in micromachining, as detailed in [115, 117, 118]. It has been reported that a homogeneous
grain size distribution has a positive effect on better dimensional accuracy and high surface quality. The influences of metallurgical phases on cutting forces were studied by Vogler et al [119]. An FE model was proposed in [120–122] to evaluate the stress, strain, temperature, and damage distribution due to changes in grain size and grain distribution.

Another important parameter is the reinforcement used in a composite. Because of the presence of particulates/fibers, the material removal rate and chip formation mechanism appear differently in composite materials. Teng et al [114] carried out an FE simulation for the cutting mechanism of SiC/Al MMCs reinforced with micro- and nanosized particles using the FE method (ABAQUS). They reported that nanosized particles remained intact without fracture during the machining process and were more likely to produce continuous chips, in contrast to microsized particles that were easy to break and tended to form discontinuous chips (figure 5). Thus, a better machined surface quality with less defects can be obtained from nanosized, reinforced MMCs compared to their microsized counterparts. Based on the literature surveyed, the machining mechanism for composite materials is not yet fully understood, especially for micro- and nanoparticle-reinforced composites. Further investigation (theoretical and experimental) is required to reveal the fundamentals of micromachining of composite materials, in terms of stress and strain distribution, tool wear, failure mode, chip formation, and particle behavior.

Another important factor is the effect of strengthening. Machining is principally a process where materials are continuously or discontinuously fractured and then driven away under comprehensive fracture criteria [123]. The improved mechanical properties of composite materials, such as yield strength and toughness, considerably influence the material’s fracture characteristics. Several authors have attempted to estimate the reinforced yield strength by virtue of different strengthening mechanisms [124–126]. There are three key strengthening mechanisms: (1) Orowan, (2) increased dislocation density, and (3) load-bearing strengthening [124–128]. Zhang et al [124] proposed a model to predict the yield strength of nanoparticle-reinforced MMCs and revealed that the increased yield strength is governed by a number of factors, such as size and volume fraction of nanoparticles used, the difference in CTE values between the fiber and matrix, and the change in temperature after processing. A mathematical equation proposed to predict the increased yield strength is shown in equation (1):

\[ \sigma_{yc} = \sigma_{ym}(1 + f_{Orowan})(1 + f_{dislocation})(1 + f_{load-bearing}), \]

where \( \sigma_{ym} \) is the yield strength of the matrix material, and \( f_{Orowan}, f_{dislocation}, \) and \( f_{load-bearing} \) represent the aforementioned three strengthening mechanisms.

However, when dealing with practical conditions, the process of material removal appears much more intricate because of the complicated microstructural effects and cannot be explained by only yield strength. Therefore, further study is necessary to understand the fracture mechanism and chip formation during machining of composite materials [123–132].

Components made from laminate composites often need to be microfeatured through various machining operations, such as microperforation, microsawing, microrouting, and microgrinding. However, microperforation, or making a hole, is perhaps the most important and frequently used machining technique in laminated components [133]. Delamination may appear during machining of laminate composites which results in severe reductions in the load-carrying capacity of the component and, therefore, must be avoided. Delaminations not only decreases assembly tolerance and bearing strength but also has the potential for long-term performance deterioration under fatigue loads [134–136]. Delaminations may be initiated by three mechanisms, as shown in figure 6: peeling up of the top layer, punching out of the uncut layer near the exit, and the thermal stress mode [137, 138]. Peel-up
delamination occurs around the entry periphery of drilled holes (figure 6(a)). When the drill edge contacts the surface, a peeling force through the slope of the drill bit flutes results in separation of the plies from each other. Push-out delamination occurs at the exit periphery around the drilled holes (figure 6(b)). Thermal stress mode appears due to the heat that is generated during drilling because of the high-speed tool-specimen contact (figure 6(c)). It has been found that the delamination associated with push-out is more severe than with other mechanisms. Henceforth, most of the studies have paid more attention to push-out delamination [139–144].

4.2. Nontraditional machining of composite materials

In many cases, micromachining of composite materials using conventional techniques or tool materials is difficult due to the presence of the abrasive reinforcing constituents, which may cause several problems, such as delamination, poor surface quality, and severe tool wear [145, 146]. Furthermore, conventional material removal methods often introduce surface flaws, cracks, and residual stresses in composite materials [146, 147]. In some cases, such as difficult-to-machine parts and ceramic-based brittle-like composites, conventional techniques fail to provide the desired machining performance. Many such limitations were overcome by the advent of nonconventional micromachining techniques. At present, there are a number of different nonconventional micromachining techniques being extensively used in many industrial applications, such as laser, electrical discharge machining (EDM), electrochemical machining (ECM), abrasive jet machining, and microgrinding. These processes are used to perform precision machining of composite materials where the material removal process is not affected by hardness, strength, or toughness of the specimen materials [148, 149].

Laser micromachining is an important modern technology for machining difficult-to-machine composite materials. Lie et al [151] produced holes of a few hundred micrometers in diameter in SiC/SiC composite using a picosecond laser. This was also done by Biswas et al [145] to microcut Al2O3-Al composite. Wang et al [150] combined laser heating with conventional machining for cutting silicon copernicum (SiCp)/2024 Al composite. Figures 7(a) and (b) present some typical examples of laser machining. Similarly, EDM is also used to machine parts made of composite materials. In this process, no mechanical force is applied; and it is independent of the specimen’s hardness. Li et al [152] produced microholes in zirconium diboride (ZrB2)-SiC-graphite composite using EDM. Paul et al [153] investigated microdrilling of newly developed SiC-20% boron nitride composite. Similarly several authors examined EDM micromachining of composite materials, such as SiCp–Al [149], SiC–titanium carbide nitride (Ti3CN) [154, 155], and SiC/Al [147]. Consequently, ECM was reported to be one of the most suitable processes for difficult-to-machine materials without a heat-affected zone. This process has been well exploited in various applications, offering a higher machining rate, better precision, and good control over the machined surface [156, 157]. Examples include machining a 400 μm hole in Al-Al2O3-boron carbide (B4C) hybrid MMCs [158], AA6061-titanium diboride (TiB2) [157], and Al-6% MMCs [159]. For machining glass and glass fiber-reinforced plastic (GFRP) composites, abrasive jet machining could be a suitable technique, as reported in [160]. Likewise, ultrasonic grinding is a preferred method for machining ceramic-based composites, as reported by Zhao et al [161], and grinding Al2O3-zirconia (ZrO2). Although the above results present various techniques for micromachining of composite materials, the fundamental mechanisms are not yet well understood [39, 40]. In addition, studies on the machinability of microreinforcement composite materials are plentiful; and there is inadequate literature on nanoreinforced composite materials. Therefore, further research is necessary to gain a comprehensive understanding of nanoreinforcement of composite materials.

5. Microcasting of composite materials

Microcasting, also known as microprecision casting [162], is one of the key micromanufacturing technologies, enabling the fabrication of miniature components. The technology has been successfully implemented to produce miniature parts in surgical instruments, dental devices, biotechnology instruments, and mechanical devices [163]. Microcasting is usually identified as an investment casting process, such as lost-wax and lost-mold techniques [164]. The advantages it offers include near net shape, complex parts, low materials loss, and quick production [165]. Other methods of microcasting include permanent mold and composite microcasting. In
permanent mold casting, the research is focused on finding suitable metal or graphite molds for casting miniature parts; while in composite casting, the focus is on connecting or assembling two different materials or structures [164].

The research focus on investment microcasting consists of finding appropriate casting parameters [162], an attainable aspect ratio [166], surface roughness [167], suitable pattern design [168], relationship among microcasting parameters, microstructures and mechanical properties [169–173], and analytical simulation [174]. However, investment casting produces a rough surface [167]. To overcome this drawback, permanent mold casting was introduced. However, this process is limited to low melting alloys, e.g. Al, magnesium (Mg), zinc (Zn), tin (Sn), and lead (Pb) [175, 176]. Baumeister et al [164] carried out permanent mold microcasting of Al-bronze using both metal (steel) and ceramic (graphite) molds and fabricated microgears of a few millimeters, as shown in figure 8. The method presented is still in the primary stage, due to its millimeter range; however, it can be implemented in practical production line conditions. Therefore, the application of permanent mold microcasting is of practical significance and deserves further research.

Another emerging micromanufacturing technique is composite casting for the production of complex-shaped microparts or microsystems consisting of different metals and ceramics. The major advantage of this method is the ability to fabricate multicomponent parts in one step without the use of any joining or assembling processes. The selected material combinations can fulfill intricate functionalities and improved mechanical properties. It is also possible to fabricate components with movable connections without an additional assembling step after casting. Ahmeti et al [177] examined metal-ceramic-composite casting of Al-bronze and ZrO2 ceramic. Two kinds of compounds were made: casting around the ceramic microparts with Al-bronze to fabricate a force-fitting compound, (similar to that in figure 9(a)) due to the different coefficients of thermal expansion (CTEs) of the materials used, and then allowing the shrinkage of Al-bronze from casting to room temperature. The casting into ceramic microcomponents, such as wheels, to form a compound with movable connections is shown in figure 9(b). However, one of the major challenges still remaining with composite casting is the ability to produce stable mechanical bonding between dissimilar materials. This drawback could be minimized by choosing appropriate combinations, by considering their physical properties, e.g. CTE, and wettability in order to form a force-fitting microsystem. Further works could be focused on improving the production system by extending the variety

Figure 7. Nonconventional micromachining of composite materials: (a) cross-sectional schematic diagram of the laser microcut workpiece [145] and (b) schematic view of laser-assisted micromachining (LAMM) [150]. (a) Reproduced with permission from [145]. (b) [150] (2018) With permission of Springer.

Figure 8. Permanent mold casting, (a) steel mold for gear wheel with milled cavity, (b) gear wheel cast with Al bronze in evacuated chamber (mold temperature of 280 °C), (c) graphite mold with milled structures (broad cross runner); and (d) Al bronze casting in permanent graphite mold. Three cracked graphite parts from the mold remained inside at mold temperature of 400 °C. [164] (2011) With permission of Springer.

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of materials for microcomposite casting and the characterisation of mechanical properties.

6. Microinjection molding of composite materials

Injection molding is a well-known technique for manufacturing near net-shaped products. The unique features of this process include mass production, cost effectiveness, ability to produce complex-shaped parts, and the use of various kinds of materials, including composite materials. To take advantage of these features, microinjection molding has been established as a promising route to the mass production of miniaturized components. However, although this process has been massively adopted for polymeric materials, its use for metal/ceramic-based microcomponents has been limited. Liu et al [178] reported a method called micropower injection molding (μPIM) and showed the possibility of implementing this method for producing metal or ceramic microcomponents. Merz et al [179] fabricated microgears and tensile test bars of a few hundred microns and made of ductile ZrO₂ and hardenable stainless steel, respectively.

Microinjection molding is the miniaturization of the traditional injection molding process; and it inherits the features of traditional ones in terms of low production cost, near net shape, geometric complexity, good tolerance, and reproducibility [180–182]. To date, the majority of microinjection molding processes have been based on the manufacturing of monolithic metal or ceramic materials. The exploration of this process for the fabrication of composite materials has just commenced. Kim et al [183] conducted a fundamental study on fabricating composite materials (figure 10(a)), as was done in [180] for WC-Co composites. Likewise WC-Cu and 316L and 17-4PH composite materials were used by Kim et al in [184,185] (figure 10(b)), respectively. Some hybrid techniques have also been reported, as mentioned in [186], using a laser micromachining technique to manufacture microcomponents of stainless steel and ZrO₂ composite materials.

Although studies have already revealed the viability of manufacturing microcomponents made of composite materials using microinjection molding, the research and development in this field is still at its embryonic stage and many shortcomings need to be investigated. In addition, compared to traditional methods, microinjection molding has intrinsic
challenges because of the submicron or nanopowders used as raw materials; and the accuracy is in the micronscale [187]. However, the advancements in automation and control technology, together with improved tooling accuracy, may minimize the deviation of the final products and the difficulties arising from production in the future.

7. Microjoining of composite materials

Joining (at macro-, micro-, or even nanoscale) has become an important part of today’s manufacturing and assembly process, providing components with multifunctional abilities. Successful microjoining appeared to be one of the very essential techniques for manufacturing composite parts at ever-smaller scales. It has been used extensively in many fields, such as microelectronic packaging and interconnection, medical implants, batteries, sensors and transducers, and optoelectronics [188]. There is a continuously growing need to join nanoscale building blocks, for example, nanowires and nanotubes, with micro- and mesoscale devices [189, 190]. Due to ever-advancing miniaturization, microjoining is constantly facing new challenges. The prime target for joining methods is to provide a permanent connection between parts and/or building blocks through an effective chemical or mechanical bonding. An interlayer might also be incorporated when the individual parts are not compatible in atomic structure, e.g. a ceramic/metal joining. A number of different techniques are reported to join components in microscale. This include microelectronic wire bonding [191, 192], solid-state diffusion bonding [193, 194], bonding using nanoparticles [195–197], diffusion soldering and brazing [198, 199], laser microwelding [200–202], electron beam microwelding [203, 204], resistance microwelding [205, 206], adhesive bonding [207], ceramic/ceramic bonding [208–211], ceramic/metal bonding [40, 212], and so on. Figures 11(a) and (b) show typical examples of microjoining of similar and dissimilar materials, respectively. A good understanding of microjoining, in many cases, requires multidisciplinary knowledge from various fields, i.e. materials science (metallurgy), solid and fluid mechanics, physics, chemistry, and electrical engineering and electronics. Simplicity in design, easy control, and higher bonding quality will be some of the aspirations of future research work in the field of microjoining.

8. Other micromanufacturing techniques of composite materials

A summary of different micromanufacturing techniques of composite materials is presented in table 5. In addition to these micromanufacturing techniques, laser-based hybrid techniques, additive micromanufacturing, advanced sintering processes (e.g. hot isostatic pressing, spark and pulse plasma sintering), and soft lithography are also attracting substantial attention for use in fabricating microproducts made of composite materials. Recently, staged achievements have been made in laser-based micromanufacturing, including laser additive manufacturing [215, 216], selective laser melting [217, 218], laser microstructuring combined with micro-lithography [219], laser raster scanning [220], and laser surface engineering [221]. Obuh et al. [219] proposed a low-cost micromanufacturing method based on laser microstructuring and noncleanroom microlithography techniques and fabricated MEMS switches and varactors. MEMS movable structures were fabricated out of 14 μm thick aluminum foils that were suspended via 5 μm thick SU-8 dielectric anchors (figure 12(a)). Gu et al. [215] fabricated a WC-reinforced iron (Fe)-based MMC using laser additive manufacturing. Hassannin et al. [222] fabricated a multilayer, functionally graded microceramic microgear component made of Al2O3 and ZrO2 using soft lithography, without any significant crack at the joining area.

Another important advancement in micromanufacturing of composite materials is additive manufacturing. Currently, there are a number of research studies that are focused on these techniques. Li et al. [223] fabricated Cu and Cu-Ni-alloy-reinforced Fe-based metallic glass composite microcomponents using 3D additive manufacturing. Similar techniques were...
adopted in [224] to fabricate microparts made of Ti alloy composites with TiB discontinuous reinforcement using selective laser melting, in [225] to manufacture Al matrix composite microparts, and in [226] to fabricate microparts made of TiB$_2$-reinforced 316 L SS. A detailed review of 3D micro-additive manufacturing techniques can be found in [227].

Franchin et al [228] introduced a method called direct ink writing to manufacture CMC microcomponents. Alias et al [229] used low-temperature, co-fired ceramic technology to fabricate a laminate composite material of glass and ceramic. These recent developments indicate that there is a common trend of developing new methods and techniques combining multiple manufacturing processes. These modern hybrid techniques show the possibility of manufacturing microparts made of various types of composite materials, including fiber/particle-reinforced, laminate, and functionally graded materials; and thus, they deserve further research.

9. Key factors in micromanufacturing of composite materials

Due to the extensive demand for microcomponents in modern applications, their manufacturing techniques have received ample attention by numerous scholars. Scaling down various parameters of a conventional manufacturing process from macroscale to microscale is a well-known strategy. However, although the advancement of micromanufacturing technology can benefit from a comparatively mature scientific background, there are certain issues that cannot be mechanically copied from traditional manufacturing, and these also distinguish between them. Consequently, when dealing with the manufacturing of composite materials, there are additional factors, such as fiber/matrix interaction, that appeared during the scaling down to microscale. In this section, some of the key issues related to the micromanufacturing of composite materials are addressed.

9.1. Size effects

Size effects can be generally defined as the deviations from the expected results which occur when the geometrical dimension of a process or specimen is changed or typically reduced [230]. There are three main categories of size effects based on density, shape, and microstructure [230], as presented in figure 13. Accordingly, in microforming, there is another type of size effect called the tribological size effect [14]. These size effects generate a number of different problems, including mechanical, tribological, and scatter of material behaviors, which have been extensively studied by many authors [73, 231]. Subsequently, in order to deal with size effects, various strategies have been reported, such as microstructural refinement [103] and applying heat during micromanufacturing [232]. Size effects in composite materials appear to be even more serious; particularly the size and amount of reinforcement used in the composite which are important factors, as detailed in Wisnom et al [233]. It was reported that there is a tendency for the strength to decrease with increasing specimen volume. It was also found that the size effect reduces with increasing scale. However, scaling laws
in composite materials are not straightforward, rather they are substantially intricate due to the heterogeneous nature of their microstructures involving variations in fiber diameter and length, fiber/matrix interface, ply layer, free edge effects, and stress gradients. Size effects in composite materials also depend on the length and diameter of fibers, their volume fraction, and the manufacturing technique used [234, 235]. Presently, a major worldwide research effort is underway regarding the possibility of producing very high-strength composites in laminate form. A signiﬁcant size effect in such composites might well provide a complementary avenue for improved strength properties by obtaining finer ﬁlaments.

9.2. Interfacial behavior

The characteristics of a composite material can be attributed to three main factors: (1) the reinforcing element or ﬁber, (2) the matrix material, and (3) the ﬁber/matrix interface. The ﬁber/matrix interface in composite materials is of great importance as the internal surface area occupied by the interfaces is considerably high. For example, for a composite material containing a moderate ﬁber fraction, it can be as high as 3000 cm² cm⁻³ [51]. The factors that inﬂuence the interface area in a composite include surface roughness of the reinforcements (most ﬁbers or reinforcements show some degree of roughness [236]), crystallographic nature of the interface, and interactions at the interface. Figure 14 shows a typical example of an interface of a composite material. The bonding that takes place at the interface can be of the mechanical, physical, or chemical type. It should be noted that maximizing the bond strength is not always the objective. If the interface is too strong, i.e. stronger than the reinforcement, it will cause embrittlement; and the interface will have the lowest strain to failure. Therefore, an interface with an optimum interfacial bond strength is preferred with an enhanced toughness but without much sacrifice on the strength parameters. Optimum interfacial bond strength can be obtained in two ways: treatment of the ﬁber or reinforcement surface or modiﬁcation of the matrix composition. Therefore, during micromanufacturing, close attention should be given to make sure the optimum interface strength is maintained in order to obtain the desired quality of the composite materials.

10. Experimental demonstration

In order to demonstrate the potential of micromanufacturing of composite materials, a bimetallic composite of cemented WC and high strength steel was fabricated. A novel micromanufacturing approach was implemented, namely HCDB. In this process, the simultaneous effects of heating and pressurizing were combined. Heat was generated by electrical resistance through Joule effects by flowing an electrical current across the electrically conductive samples. The experiment was conducted in a Gleeble® 3500 thermomechanical simulator. The Gleeble 3500 is a powerful machine capable of executing a number of experimental operations with highly precise control in a high vacuum environment. In this process, the current passed through the powder compact in single or multiple pulses resulting in very short processing times causing a rapid binding between individual powder particles. Thus, coalescence of powder particles happened very quickly. In addition, obtaining the full density of the powder resulted in progressive pressure. Consequently, carbide particles interacted with steel at their interface at elevated temperatures and pressure, resulting in elemental interdiffusion between them. This eventually led the WC-10Co to bond with the AISI 4340 steel, and a bimetallic composite of ceramic and steel was achieved. The effects of various experimental parameters, such as sintering time, compression pressure, and sintering temperature, were analyzed to optimize the operating conditions. Figure 15 shows the cross-sectional micrograph of the bimetal composite obtained at a temperature of 1250 °C, with a compression pressure of 160 MPa and sintering time of 20 min.

As can be seen in Figure 15, good bonding between the ceramic and steel materials was achieved. The mechanical properties of the bimetal composite were determined by the evaluation of microhardness across the specimen and measurement of the bonding shear strength. It was revealed that powder-solid bonding, based on the HCDB technique, promotes mutual interdiffusion of alloying elements thus contributing to the fabrication of a cermet-metal bimetallic composite with fair bonding. However, the interdiffusion of elements was not signiﬁcant at lower experimental conditions (i.e. sintering time, compression pressure, and temperature). By increasing these parameters, bonding can be enhanced. The maximum bonding strength achieved was 223 MPa, with 98% density of the sintered carbide (relative to the theoretical density) and a microhardness of 2272.3 HV at 1250 °C. The WC-10Co/4340 steel bimetal composite developed has substantial potential to be used in applications where high hardness and high strength are simultaneously necessary.
11. Simulation and modeling of composite materials

Metal and CMCs are replacing other bulk materials in applications where the higher costs are offset by enhanced performance. Due to the lack of a clear understanding of the reinforcement/matrix behaviors, it is necessary to apply a trial and error method to successfully fabricate the composite, which is often very expensive. Therefore, to take the benefit of the potential of MMCs and CMCs and to reduce the risks of unwanted component failure, modeling and simulation tools, such as finite element analysis (FEA), come in handy for nondestructively estimating material performance at operating conditions and temperatures. Finite element analysis can be used to evaluate mechanical properties, such as interlaminar shear properties, cumulative damage failure, and crack propagation [237]. In this section, we present some of the recent developments for examining and validating the design, mechanical properties, and failure modes of composite materials using FEA during micromanufacturing.

11.1. Simulation of micromanufacturing for composite materials

In composite materials, residual stresses (RSs) can be generated by thermal mismatch between the reinforcement and matrix materials or between alternating sheets during the manufacturing process. It may severely impact the strengthening of microcomposite components. Therefore, unlike conventional methods, micromechanics-based simulation methods are preferred for developing a comprehensive analysis of the effects caused by thermal RSs during the manufacturing of microcomposites. It is reported that thermal RSs can considerably decrease the yield strength and ultimate tensile strength of composite materials. Therefore, consideration of thermal stresses is essential for a realistic prediction of the overall elastoplastic characteristics of composite materials during micromanufacturing [238].

Haghoo et al [239] conducted a simulation on carbon nanotube (CNT)-reinforced Al composites. The variables considered included fiber volume fraction (FVF), aspect ratio and directional behavior of CNTs, degree of CNT agglomeration within the matrix on the elastic modulus, thermal expansion behavior, and the overall elastoplastic response of CNT-reinforced Al composite materials. Aghdam et al [240] simulated the influences of manufacturing parameters and FVF on residual stresses in SiC/Ti composites. The effects of the coating, interaction layer, and stress relaxation were also considered. As can be seen in figure 16, a 3D representative volume element (RVE) consisting of a quarter of fiber, coating, interaction layer, and corresponding matrix material was used to evaluate RSs within the MMC. Stress contours for the axial stress distributions in the fiber and matrix of a
The SiC/Ti-alloy composite system are plotted in figures 18(c) and (d). Dimensions of the constituent of the RVE were obtained by calculating the fiber volume fraction using the following equations:

\[ \pi R_2^2 = 4a f \]

(2)

\[ R_2 = R_1 \sqrt{(1 - \nu_f)} \]

(3)

where \( \nu_f \) and \( \nu_c \) are the fiber and coating volume fractions, respectively, \( R_1 \) and \( R_2 \) are the outer and inner radius of the coating, and \( a \) denotes the width of the RVE, as shown in figure 18.

Jia et al [76] developed an FE simulation model to examine the deformation behavior of a two-layer Al–Cu composite (\( \sim \)50 μm thickness) during MDD by employing a continuum shell element in ABAQUS software (figure 17). The Voronoi tessellation model was introduced to represent the grains of the laminate composite material for addressing the size effects of the blank during micromanufacturing. Each Voronoi tessellation was assigned with different mechanical properties based on experimental data, thereby conserving the grain heterogeneity. Therefore, accurate results can be obtained [241, 242]. Application of nanolubricants during MDD of an Al–Cu composite was investigated in [93], and significant improvement in the formability of the drawn parts was reported. Adding nanolubricant also reduces the drawing force, providing more uniform thickness distribution, and improves the surface quality of the microcomponent drawn. According to the literature reviewed, the existing simulation works are mostly based on microforming techniques, particularly microrolling and MDD. There are also a few research studies on various composite materials, including MMCs and CMCs, to evaluate fiber/matrix interactional behaviors during their manufacturing processes. However, a limited number of studies were observed to simulate other micromanufacturing techniques, such as micromachining and microcasting of composite materials. This leads to a substantial scope of further research, with numerous possibilities for obtaining exciting results to solve many of the practical problems.

11.2. Modeling of an innovative micromanufacturing method for composite microdrill

A composite of WC and high strength steel could be developed to manufacture a composite microdrill (CMD) with outstanding overall performance. The outer WC with nanocrystalline grains can offer high hardness, wear-resistance, and rupture strength, while the inner steel material could provide high strength and fracture toughness. A direct powder/solid, consolidation-extrusion forming technology could be implemented to fabricate a CMD. The schematic diagram of the proposed microextrusion system is presented in figure 18. Die 1 will be used for powder solidification and extrusion forming, while dies 2 and 3 will be used to fabricate
the CMD. Dies 2 and 3 will be removable and could be disassembled conveniently when the extrusion process is complete. The values \( l_s \), \( l_f \), and \( D \) represent the shank length, flue length, and diameter of the CMD produced, respectively. Microdrills several hundreds of micrometers in diameter will be produced. Die 3 will be rotatable and is designed as split construction with cutting grooves because of the undercut on the part during the extrusion process. Die 3 will be designed based on the flue structure of the CMD produced.

In addition, FE modeling could be employed to simulate the behavior of WC powder and the bonding phenomena with high strength steel. Constitutive relationships that describe the behaviors of both materials during solidification could be included in the FE model. Because the material properties of the steel and WC are very different, nonuniform deformation will occur during the composite extrusion processes. Consequently, in microextrusion, the size of the deformation zone is comparable to the size of constituent grains; and, therefore, grain orientation has an impact on strain distribution. Each single grain has to deform not only in accordance with the shape of the tool but also its favorable orientation. The random orientation and size of each single grain leads to inhomogeneous material behavior, so that scatter increases with decreasing specimen size. Therefore, a careful consideration of these parameters is necessary for successful simulation as well as experimental investigation to fabricate such a microproduct, due to future evolutionary prospects.

**12. Conclusions and recommendations**

In this study, we presented the potential for micro-manufacturing composite materials. Although there are many research studies on individual micromanufacturing techniques, as well as composite materials, there is no comprehensive literature that reviews the state-of-the-art micromanufacturing techniques of composite materials. Since monolithic materials have already reached their limit, composite materials represent an emerging future in which composites will have many industrial applications, particularly where superior material properties are required. Fabricating composite materials in microscale is a challenging task. Unlike conventional materials, composite materials require precise consideration of a number of factors when they are micromanufactured. In this study, the existing micromanufacturing techniques used for fabricating composite materials were identified. Their latest development, new trends, and the effects of key factors were addressed and discussed. A comparative study was presented showing the potential and versatility for producing composite materials along with their possible future applications. The drawbacks of the existing techniques and the research gaps were determined, and guidelines for meeting future demand were provided. In addition, there is a growing need for more analytical modeling/simulation works in most of the fields covered in this study, as most of the available results to date have tended to be experimental in nature. The key recommendations that can be drawn from this study are summarized as follows:

- Unlike macromanufacturing, the choice of composite materials is limited in micromanufacturing. This requires substantial additional research to attempt different combinations of matrix and fiber constituents for producing microcomponents of composite materials.
- Though there are numerous methods used for micro-manufacturing of bulk materials, many of them have yet to be implemented for manufacturing of composite materials. Since there are two or more distinct phases involved in a composite material, their appropriate distribution and uniform flow must be controlled for successful fabrication.
- There has been noticeable progress in the microforming of composite materials. The techniques involved include microrolling, microextrusion, MDD, and nonconventional approaches. Compared to bottom-up methods (e.g. PVD), these techniques provide coarser and nonuniform microstructures. Nevertheless, uniformity can be improved by selecting appropriate combinations of materials with similar hardness and strain hardening rates during microforming. Adding nanoparticles has also been shown to be another promising tactic to improve the microstructure. Similarly, applying heat could improve further grain refinement.
- Another advancement reported is the microforming of laminate composite materials using various techniques, such as microrolling and MDD. However, these techniques still lack descriptions of the interfacial behavior of the different laminas used. The material flow characteristics of different layers, prevention of defects (e.g. fracture and wrinkling during MDD), and investigation of stress and strain distribution of the composite parts formed require further research.
- Obtaining finer (nanocrystalline) grain structure is reported to be a common trend for improving material properties, such as high strength/hardness, improved ductility/toughness, enhanced diffusivity, and better thermal, electrical, and magnetic properties. The use of SPD in fabricating composite materials is still new, leading to a need for further substantial research.
• Although composite materials are processed in near net shape, further machining operations are often inevitable. However, machining mechanisms for composite materials are not yet well understood, requiring considerable experimental studies to reveal the nature of the machining behavior of composite materials. Various aspects, such as the effects of microstructure, strengthening mechanism, minimum chip thickness, and effects of lamination, require further investigation to fully understand the characteristics of the micromachining of composite materials.

• In many cases, micromachining of composite materials using conventional techniques or tools is difficult due to the presence of reinforcing constituents. This could be overcome by employing nonconventional techniques, e.g. laser, EDM, ECM, abrasive jet machining, and micro-ultraprecision grinding. In addition, FE methods could also be used to simulate and analyze the cutting behavior of composite materials.

• Investment casting is reported to be a popular method for producing composite material microparts. However, the intrinsic limitation of poor surface quality of this technique compels us to find alternative techniques. Permanent mold casting is a prominent method in macroscale techniques; however, it could be implemented in microscale techniques. Another emerging micromanufacturing technique is composite casting for producing complex-shaped microparts or microsystems consisting of different metals and ceramics. Hence, the major challenge is to produce stable mechanical bonding between dissimilar materials. This drawback could be minimized by choosing appropriate combinations. Further work could be focused on improving the production system, expanding the variety of materials used for microcomposite casting, and the characterization of mechanical properties.

• Although studies have already revealed the viability of microinjection molding for manufacturing composite material microcomponents, research and development in this field is still in its embryonic stage; and many shortcomings still need to be addressed. Advancements in automation and control technology, together with improved tooling accuracy, may positively minimize the deviation of the final products and the difficulties arising from production systems using this technique.

• Microjoining is an emerging manufacturing technique that provides components with multifunctional abilities. A good understanding of microjoining, in many cases, requires multidisciplinary knowledge from various fields, i.e. materials science (metallurgy), solid and fluid mechanics, physics, chemistry, and electrical engineering and electronics. Simplicity in design, easy control, and higher bonding quality will be one of the objectives of future research in the field of microjoining of composite materials.

• In addition to conventional techniques, there are a number of nonconventional advanced micromanufacturing techniques. They include laser-based techniques, additive micromanufacturing, advanced sintering processes (e.g. hot isostatic pressing and spark and pulse plasma sintering), and soft lithography. These techniques are attracting considerable attention in fabricating microproducts made of composite materials. Consequently, there is a trend of combining multiple methods together that is referred to as hybrid techniques, which has significant practical applications and deserves further research.

• Size effects have been a major concern for producing miniature products regardless of the type of materials used. When dealing with composite materials, additional factors, such as size, shape, and volume of reinforcement in the matrix and fiber/matrix interaction, that appear to be important to accurately address scaling down to microscale need to be considered. In addition, an optimum bonding strength between reinforcement and matrix materials is also required. Therefore, obtaining an optimum bonding strength and analyzing the size effects may provide an avenue for future research to improve the quality of composite material microparts.

• In conclusion, as monolithic materials cannot meet many of the extreme requirements, composite materials have the potential to solve problems. However, their usage in microscale is still limited, providing unlimited opportunities for future research. The aim of this paper was, therefore, to be a helpful tool for promoting the micromanufacturing technology of composite materials.

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References

[1] Hasan M, Zhao J and Jiang Z 2017 A review of modern advancements in micro drilling techniques J. Manuf. Process. 29 343–75
[2] Alting L et al 2003 Micro engineering CIRP Ann. 52 635–57
[3] Lee S et al 2002 Design and fabrication of a micro fuel cell array with ‘flip-flop’ interconnection J. Power Sources 112 410–8
[4] Men D-S, Kim J and Kim C-J 2003 A distributed gas breather for micro direct methanol fuel cell (/spl mu/DMFC) IEEE 16th Annual Int. Conf. on Micro Electro Mechanical Systems, 2003. MEMS-03 (Kyoto) (IEEE)
[5] Khanna R 2003 MEMS fabrication perspectives from the MIT microengine project Surf. Coat. Technol. 163 273–80
[6] Trukenmüller R et al 2002 Low-cost thermofoming of micro fluidic analysis chips J. Micromech. Microeng. 12 375
[7] Chován T and Gutmann A 2002 Microfabricated devices in biotechnology and biochemical processing Trends Biotechnol. 20 116–22
[8] Mounier E 2002 MEMS the alternative semiconductor business Proc. 3rd Euspen Int. Conf. Eindhoven (Netherlands)
[9] Hayashi I and Iwatsuki N 1998 Micro moving robotics *Proc. 1998 Int. Symp. Micromechatronics and Human Science* MHS’98 (Piscataway, NJ: IEEE)

[10] Dudenhoeffer D D et al 2001 Development and implementation of large-scale micro-robotic forces using formation behaviors *Proc. SPIE* 4364 159–69

[11] Rai-Choudhury P 1997 Handbook of Microlithography, Micromachining, and Microfabrication: Microlithography (Bellingham, WA: SPIE) (https://doi.org/10.1117/3.2265070)

[12] Fukuda T and Menz W 1998 *Micro Mechanical Systems: Principles and Technology* vol 6 (Amsterdam: Elsevier)

[13] Koç M and Özel T 2011 Micro-Manufacturing: Design and Manufacturing of Micro-Products (New York: Wiley)

[14] Jiang Z, Zhao J and Xie H 2017 Microforming Technology: Theory, Simulation and Practice (Wollongong: Elsevier)

[15] Razali A R and Qin Y 2013 A review on micro-manufacturing, micro-forming and their key issues *Proc. Eng.* 53 665–72

[16] Klárová M 2015 *Composite Materials—Study Support* (Ostrava: Technical University of Ostrava)

[17] Hull D and Clyne T W 1996 An Introduction to Composite Materials (Cambridge: Cambridge University Press)

[18] Yin H et al 2018 Micro forming of metallic composites *Proc. Manuf.* 15 1429–36

[19] Chen S-Y et al 2016 Solidification process and microstructure of transition layer of Cu–Al composite cast prepared by method of pouring molten aluminum *Trans. Nonfer. Met. Soc. China* 26 2247–56

[20] Imbabi M and Jiang J 2009 Fabrication of free standing 316-L stainless steel–Al2O3 composite micro machine parts by soft moulding *Acta Mater.* 57 4751–7

[21] Okazaki Y, Mishima N and Ashida K 2002 Microfactory and micro-machine tools 1st Korea-Japan Conf. on Positioning Technology (Korea)

[22] Qin Y et al 2008 Development of a new machine system for the forming of micro-sheet-products *Int. J. Mater. Forming* 1 475–8

[23] Chern G-L and Chuang Y 2006 Study on vibration-EDM and mass punching of micro-holes *J. Mater. Process. Technol.* 180 151–60

[24] Qin Y 2010 Overview on micromanufacturing *Micromanufacturing Engineering and Technology* (Oxford: Elsevier) pp 1–23

[25] Qin Y 2010 *Micromanufacturing Engineering and Technology* (Boston, MA: William Andrew)

[26] Masuzawa T 2000 State of the art of micromanichining *CIRP Ann.-Manuf. Technol.* 49 473–88

[27] Qin Y et al 2010 Micro-manufacturing: research, technology outcomes and development issues *Int. J. Adv. Manuf. Technol.* 47 821–37

[28] Srinivasa Y and Shumugam M 2013 Mechanistic model for prediction of cutting forces in micro end-milling and experimental comparison *Int. J. Mach. Tools Manuf.* 67 18–27

[29] Zhu D and Zeng Y B 2008 Micro electroforming of high-aspect-ratio metallic microstructures by using a movable mask *CIRP Ann.* 57 227–30

[30] Ran J and Fu M 2014 A hybrid model for prediction of ductile fracture in micro-scaled plastic deformation of multiphase alloys *Int. J. Plast.* 61 1–16

[31] Byron S and Lee Y 2007 Calculation of strain gradient in flow formulation using strain surface function and its applications in micro rolling *J. Mater. Process. Technol.* 192 218–24

[32] Jain V et al 2014 Micromachining: a review—II *Proc. Inst. Mech. Eng.* 228 995–1014

[33] Ghobeyti A et al 2007 Surface evolution models for abrasive jet micromachining of holes in glass and polymethylmethacrylate (PMMA) *J. Micromech. Microeng.* 17 2175

[34] Xu J et al 2016 Microstructure and hot deformation behaviour of high-carbon steel/lower-carbon steel bimetal prepared by centrifugal composite casting *Int. J. Adv. Manuf. Technol.* 86 817–27

[35] Ojo-kupoluyi O J et al 2017 Role of carbon addition on the microstructure and mechanical properties of cemented tungsten carbide and steel bilayer *Int. J. Adv. Manuf. Technol.* 92 3363–71

[36] Lou D et al 2003 Interactions between tungsten carbide (WC) particulates and metal matrix in WC-reinforced composites *Mater. Sci. Eng.* 340 155–62

[37] Zafar S and Sharma A K 2014 Development and characterisations of WC–12Co microwave clad *Mater. Charact.* 96 241–8

[38] Thomazic A, Pascal C and Chai W 2010 Fabrication of (cemented carbides/steel) bilayered materials by powder metallurgy *Mater. Sci. Forum* 631 239–44

[39] Pascal C et al 2007 Elaboration of (steel/cemented carbide) multilayer by powder metallurgy *Mater. Sci. Forum* 534 273–80

[40] Hasan M et al 2018 Analysis of sintering and bonding of ultrafine WC powder and stainless steel by hot compaction diffusion bonding *Fusion Eng. Des.* 133 39–50

[41] Contributors W 2018 Composite material. Wikipedia, The Free Encyclopedia. p. 871960821

[42] Prasanan P 2018 Introduction to Composites (https://scribd.com/document/224247777/Composite)

[43] Barbero E J 2017 Introduction to Composite Materials Design (Boca Raton, FL: CRC Press)

[44] Mishra S et al 2003 Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites *Comp. Sci. Technol.* 63 1377–85

[45] Chawla K K 2013 *Ceramic Matrix Composites* (Socorro: Springer)

[46] Kumar M, Gupta R K and Pandey A 2018 A review on fabrication and characterstics of metal matrix composites fabricated by stir casting *IOP Conf. Ser.: Mater. Sci. Eng.* 377 012125

[47] Everett R 2012 *Metal Matrix Composites: Processing and Interfaces* (New York: Academic)

[48] Mortensen A and Llorca J 2010 Metal matrix composites *Annu. Rev. Mater. Res.* 40 243–70

[49] Kainer K 2006 *Basics of Metal Matrix Composites* (Geesthacht: Wiley) pp 1–54

[50] Chou T W, Kelly A and Okura A 1985 Fibre-reinforced metal-matrix composites *Composites* 16 187–206

[51] Chawla K K 2012 *Composite Materials: Science and Engineering* (New York: Springer)

[52] Kainer K 2006 *Metal Matrix Composites: Custom-Made Materials for Automotive and Aerospace Engineering* (Geesthacht: Wiley) (https://doi.org/10.1002/3527608117)

[53] Feest E 1988 Exploitation of the metal matrix composites concept *Met. Mater.* 4 273

[54] Clyne T and Withers P 1995 *An Introduction to Metal Matrix Composites* (Cambridge: Cambridge University Press)

[55] Mortensen A and Llorca J 2010 Metal matrix composites *Annu. Rev. Mater. Res.* 40 243–70

[56] Nourbakhsh S, Liang F and Margolin H 1990 Interaction of cBN particulate and stainless steel by hot compaction *Int. J. Adv. Manuf. Technol.* 5 1–5

[57] Tuler F R et al 1988 *Deformation Mechanism Mapping of SiC/Al Metal Matrix Composite Materials* (Materials Park, OH: ASM International) pp 321–5

[58] Rawal S P 2001 Metal-matrix composites for space applications *JOM* 53 14–7
Li X-B, Zu G-Y and Ping W 2015 Microstructural development and its effects on mechanical properties of Al/Cu laminated composite Trans. Nonferrous Met. Soc. China 25 36–45

Kainer K U 2006 Metal Matrix Composites: Custom-Made Materials for Automotive and Aerospace Engineering (New York: Wiley)

Garg S K 2018 Optimization of wire electrical discharge machining parameters for machining of Al/Zr02 (P) metal matrix composite Doctoral Dissertation

Warren R 1991 Ceramic-Ceramic Matrixes (Dordrecht: Springer)

Naslain R R 1996 Ceramic matrix composites High-Temperature Structural Materials ed R W Cahn et al (Dordrecht: Springer) pp 67–78

Krenkel W 2008 Ceramic Matrix Composites: Fiber Reinforced Ceramics and Their Applications (New York: Wiley)

Hyde A R 1990 Ceramic matrix composites Mater. Des. 11 30–6

Low I-M 2006 Ceramic-Matrix Composites: Microstructure, Properties and Applications (Cambridge: Woodhead)

Naslain R R 2005 Fiber-reinforced ceramic matrix composites: state of the art, challenge and perspective Kompozity (Composites) 5 3–19

Low I M 2018 Advances in Ceramic Matrix Composites: Introduction 2nd edn (Amsterdam: Elsevier) pp 1–7

Fu M and Chan W 2013 A review on the state-of-the-art microforming technologies Int. J. Adv. Manuf. Technol. 67 2411–37

Fujihara K et al 2007 Influence of micro-structures on bending properties of braided laminated composites Compos. Sci. Technol. 67 2191–8

Chen M, Hsieh H and Wu W 2006 The evolution of microstructures and mechanical properties during accumulative roll bonding of Al/Mg composite J. Alloys Compd. 416 169–72

Fu M W and Chan W L 2014 Micro-Scaled Products Development Via Microforming (Springer Series in Advanced Manufacturing) vol 10 (London: Springer) pp 978–9

Leventon W 2015 Drawing Attention: Interest Grows in Deep-Drawn Forming of Microparts, in MICROmanufacturing (Plymouth: Tech-Etch)

Atif A and Fereshteh-Saniee F 2013 Deep drawing process of steel/brass laminated sheets Composites B 47 75–81

Jia F et al 2017 Experimental and numerical study on micro deep drawing with aluminium-copper composite material Proc. Eng. 207 105–6

Toroghinejad M R et al 2013 Investigation of nanostructured aluminum/copper composite produced by accumulative roll bonding and folding process Mater. Des. 51 274–9

Chaudhari G P and Acoff V 2009 Cold roll bonding of multilayered bi-metal laminate composites Compos. Sci. Technol. 69 1667–75

Knepper R et al 2009 Effect of varying bilayer spacing distribution on reaction heat and velocity in reactive Al/Ni multilayers J. Appl. Phys. 105 083504

Besnoin E et al 2002 Effect of reactant and product melting on self-propagating reactions in multilayer foils J. Appl. Phys. 92 5474–81

Rogachev A et al 2004 Gasless combustion of Ti–Al bimetal multilayer nanofoils Combust. Explosion Shock Waves 40 166–71

Floro J 1986 Propagation of explosive crystallization in thin Rh–Si multilayer films J. Vac. Sci. Technol. A 4 631–6

Ma E et al 1990 Self-propagating explosive reactions in Al/Ni multilayer thin films Appl. Phys. Lett. 57 1262–4

Dyer T, Munir Z and Ruth V 1994 The combustion synthesis of multilayer NiAl systems Scr. Metall. Mater. 30

Stover A et al 2013 An analysis of the microstructure and properties of cold-rolled NiAl laminate foils J. Mater. Sci. 48 5917–29

Erazdijou M et al 2008 Investigation of structure and mechanical properties of multi-layered Al/Cu composite produced by accumulative roll bonding (ARB) process Compos. Sci. Technol. 68 2003–9

Gomez X and Echeberria J 2003 Microstructure and mechanical properties of carbon steel A210–superalloy Sanicro 28 bimetallic tubes Mater. Sci. Eng. 348 180–91

Masahashi N et al 2006 Fabrication of iron aluminum alloy/steel laminate by clad rolling Metall. Mater. Trans. A 37 1665–73

Yousefian R, Eminoddin E and Baharnezhad S 2018 Manufacturing of the aluminum metal-matrix composite reinforced with micro-and nanoparticles of TiO2 through accumulative roll bonding process (ARB) Rev. Adv. Mater. Sci. 51 1–11

Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 Bulk nanostructured materials from severe plastic deformation Proc. Mater. Sci. 45 103–89

Azushima A et al 2008 Severe plastic deformation (SPD) processes for metals CIRP Ann. 57 716–35

Tsujii N et al 2003 ARB (accumulative roll-bonding) and other new techniques to produce bulk ultrafine grained materials Adv. Eng. Mater. 5 338–44

Jia F et al 2018 Investigation on the formability of Al-Cu composite material in micro deep drawing process with different lubrication conditions 21st Int. Symp. on Advances in Abrasive Technology (Toronto: Ryerson University)

Afshin E and Kadhkodayan M 2015 An experimental investigation into the warm deep-drawing process on laminated sheets under various grain sizes Mater. Des. 87 25–35

Mistri J N, Kothari K D and Sharma G K 2014 Experimental and Simulation study of Deep drawing process-a review Int. J. Adv. Eng. Res. Dev. (IJAERD) 1 22–33

Karajibani E, Fazli A and Hashemi R 2015 Numerical and experimental study of formability in deep drawing of two-layer metallic sheets Int. J. Adv. Manuf. Technol. 80 113–21

Egger E and Engel U 2004 Process characterization and material flow in microforming at elevated temperatures J. Manuf. Process. 6 1–6

Hirata K 2007 Fabrication of micro-billet by sheet extrusion J. Mater. Process. Technol. 191 283–7

Shi W et al 2018 Refining whisker size of 2024Al/Al13B4O33w composite through extrusion and its effects on the material’s micro-structures and mechanical properties Mater. Charact. 138 98–106

Krishnan N, Cao J and Dohda K 2007 Study of the size effect on friction conditions in microextrusion: I. Microextrusion experiments and analysis J. Manuf. Sci. Eng. 129 669–76

Eichenhüller B, Engel U and Geißdörfer S 2008 Process parameter interaction in microforming Int. J. Mat. Forming 1 451–4

Chan W L, Fu M W and Yang B 2011 Study of size effect in micro-extrusion process of pure copper Mater. Des. 32 3772–82

Rosochowski A et al 2007 Micro-extrusion of ultra-fine grained aluminum Int. J. Adv. Manuf. Technol. 33 137–46

Wang J, Olah A and Baer E 2016 Continuous micro-/nano- fiber composites of polylamid 6/polyethylene oxide with tunable mechanical properties using a novel co-extrusion technique Polymer 82 166–71

Patel V K et al 2018 Performance characterization of Bi2O3/Al nanoenergetics blasted micro-forming system Def. Technol. 15 98–105
[106] Dusza J et al 2008 Bending and contact strength of a Si3N4 + SiC micro/nano composite in Mater. Sci. Forum 567 177–80
[107] Cui X et al 2019 Fabrication, microstructure characterization and fracture behavior of a unique micro-laminated TIB-TiAl composite J. Alloys Compd. 775 1057–67
[108] Zhang X P and Castagne S 2010 FEM investigation of particle behavior in particulate reinforced metal-matrix composites during micro-extrusion Key Eng. Mater. 417 417–21
[109] Dabade U A and Joshi S S 2009 Analysis of chip formation mechanism in machining of Al/SiCp metal matrix composites J. Mater. Process. Technol. 209 4704–10
[110] Kwak J S and Kim Y S 2008 Mechanical properties and grinding performance on aluminum-based metal matrix composites J. Mater. Process. Technol. 201 596–600
[111] Basavarajappa S, Chandramohan G and Davim J P 2008 Some studies on drilling of hybrid metal matrix composites based on Taguchi techniques J. Mater. Process. Technol. 196 332–8
[112] Gaitonde V N, Karnik S R and Davim J P 2008 Some studies in metal matrix composites machining using response surface methodology J. Reinf. Plast. Compos. 28 2445–57
[113] Palanikumar K, Shannugam K and Davim J P 2009 Analysis and optimisation of cutting parameters for surface roughness in machining Al/SiC particulate composites by PCD tool Int. J. Mater. Prod. Technol. 37 117–28
[114] Teng X et al 2018 Comparison of cutting mechanism when machining micro and nano-particles reinforced SiC/Al metal matrix composites Compos. Struct. 203 636–47
[115] Liu X et al 2005 The mechanics of machining at the microscale: assessment of the current state of the science J. Manuf. Sci. Eng. 126 666–78
[116] Xu Z et al 2014 Geometry and grain size effects on the forming limit of sheet metals in micro-scaled plastic deformation Mater. Sci. Eng. A 611 345–53
[117] Uhlmann E, Pfitz S and Schauer K 2005 Micro milling of sintered tungsten–copper composite materials J. Mater. Process. Technol. 167 402–7
[118] Chae J, Park S S and Freiheit T 2006 Investigation of micro-cutting operations Int. J. Mach. Tools Manuf. 46 313–32
[119] Vogler M P, DeVor R E and Kapoor S G 2003 Microstructure-level force prediction model for micro-milling of multi-phase materials J. Manuf. Sci. Eng. 125 202–9
[120] Chuzhoy L et al 2002 Microstructure-level modeling of ductile iron machining J. Manuf. Sci. Eng. 124 162–9
[121] Chuzhoy L et al 2003 Machining simulation of ductile iron and its constituents: I. Estimation of material model parameters and their validation J. Manuf. Sci. Eng. 125 181–91
[122] Pramanik A, Zhang L C and Arsecularatne J A 2007 An FEM investigation into the behavior of metal matrix composites: tool–particular interaction during orthogonal cutting Int. J. Mach. Tools Manuf. 47 1497–506
[123] Liu J, Li J and Xu C 2014 Interaction of the cutting tools and the ceramic-reinforced metal matrix composites during micro-machining: a review CIRP J. Manuf. Sci. Technol. 7 55–70
[124] Zhang Z and Chen D L 2006 Consideration of Orowan strengthening effect in particulate-reinforced metal matrix nanocomposites: a model for predicting their yield strength Scr. Mater. 54 1321–6
[125] Zhang Z and Chen D L 2008 Contribution of Orowan strengthening effect in particulate-reinforced metal matrix nanocomposites Mater. Sci. Eng. A 483–484 148–52
[126] Zhang Z and Chen D L 2007 Prediction of fracture strength in Al2O3/SiCp ceramic matrix nanocomposites Sci. Technol. Adv. Mater. 8 5–10
[127] Lloyd D J 1994 Particle reinforced aluminium and magnesium matrix composites Int. Mater. Rev. 39 1–23
[128] Nakayama K, Arai M and Kanda T 1988 Machining characteristics of hard materials CIRP Ann.-Manuf. Technol. 37 89–92
[129] Fang N and Wu Q 2004 A new methodology for modeling material constitutive behavior using an orthogonal machining test Trans. North American Manufacturing Research Institute of SME
[130] Joshi S S, Ramakrishnan N and Ramakrishnan P 2001 Micro-structural analysis of chip formation during orthogonal machining of Al/SiCp composites J. Eng. Mater. Technol. 123 315–21
[131] Shaw M and Vyas A 1993 Chip formation in the machining of hardened steel CIRP Ann.-Manuf. Technol. 42 29–33
[132] Joshi S 1997 Some studies on machining of squeeze cast and extruded Al/SiCp composites PhD Thesis Indian Institute of Technology (Bombay) 400 076 India
[133] Liu D, Tang Y and Cong W L 2012 A review of mechanical drilling for composite laminates Compos. Struct. 94 1265–79
[134] Mishra R et al 2010 Neural network approach for estimating the residual tensile strength after drilling in uni-directional glass fiber reinforced plastic laminates Mater. Des. 31 2790–5
[135] Gaitonde V et al 2008 Analysis of parametric influence on delamination in high-speed drilling of carbon fiber reinforced plastic composites J. Mater. Process. Technol. 203 431–8
[136] Jain S and Yang D C 1994 Delamination-free drilling of metal matrix composites J. Eng. Ind. 116 475–81
[137] Wong T, Wu S and Croy G 1982 An analysis of delamination in drilling composite materials 14th National SAMPE Technical Conf.
[138] Abrate S and Walton D 1992 Machining of composite materials: I. Traditional methods Compos. Manuf. 3 75–83
[139] Hocheng H and Tsao C 2006 Effects of special drill bits on drilling-induced delamination of composite materials Int. J. Mach. Tools Manuf. 46 1403–16
[140] Tsao C and Hocheng H 2007 Effect of tool wear on delamination in drilling composite materials Int. J. Mech. Sci. 49 983–8
[141] Davim J P, Rubio J C and Abrao A 2007 A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates Compos. Sci. Technol. 67 1399–45
[142] Durlo L M P et al 2010 Drilling tool geometry evaluation for reinforced composite laminates Compos. Struct. 92 1545–50
[143] Shyha I et al 2010 Effect of laminate configuration and feed rate on cutting performance when drilling holes in carbon fibre reinforced plastic composites J. Mater. Process. Technol. 210 1023–34
[144] Khasha R U et al 2010 Machinability analysis in drilling woven GFR/epoxy composites: I. Effect of machining parameters Composites A 41 391–400
[145] Biswas R, Kuar A and Mitra S 2008 Influence of machining parameters on surface roughness in Nd:YAG laser micro-cutting of alumina-aluminium interpenetrating phase composite Int. J. Surf. Sci. Eng. 2 252–64
[146] Ramulu M, Paul G and Patel J 2001 EDM surface effects on the fatigue strength of a 15 vol% SiCp/Al metal matrix composite material Compos. Struct. 54 79–86
[147] Zhenlong W and et al 2014 Surface integrity associated with SiC/Al particulate composite by micro-wire electrical discharge machining Mater. Manuf. Process. 29 532–9
[148] Karthikeyan R, Narayanan P L and Naagarazan R 1999 Mathematical modelling for electric discharge machining of aluminium–silicon carbide particulate composites J. Mater. Process. Technol. 87 59–63
[149] Dev A et al 2009 Machining characteristics and optimisation of process parameters in micro-EDM of SiCp?Al composites Int. J. Manuf. Res. 4 458–80

[150] Wang Z et al 2018 Process characteristics of laser-assisted micro machining of SiCp/2024Al composites Int. J. Adv. Manuf. Technol. 94 3679–90

[151] Liu Y et al 2016 Effect of energy density and feeding speed on micro-holes drilling in SiC/SiC composites by picosecond laser Int. J. Adv. Manuf. Technol. 84 1917–25

[152] Li H et al 2017 Micro-EDM drilling of ZrB2-SiC-graphite composite using micro sheet-cylinder tool electrode Int. J. Adv. Manuf. Technol. 92 2033–41

[153] Paul G et al 2011 An investigation on electro discharge micro-drilling of SiC'20% BN composite Int. J. Mater. Struct. Integrity 5 348–61

[154] Gwon J Y et al 2018 Micro electrical discharge drilling characteristics of conductive SiC–Ti6CN composite J. Mech. Sci. Technol. 32 3351–8

[155] Liu C-C and Huang J-L 2000 Micro-electrode discharge machining of TiN/SiN4 composites Br. Ceram. Trans. 99 449–52

[156] Shirvanimoghaddam K et al 2016 Effect of B4C, TiB2, and ZrSiO4 ceramic particles on mechanical properties of aluminium matrix composites: experimental investigation and predictive modeling Ceram. Int. 42 6206–20

[157] Rajkumar K et al 2018 Experimental investigations on the Wire Electrochemical Micro Machining (WECM) integrity of AA6061-TiB2 composite Mater. Today: Proc. 5 6990–8

[158] Babu B et al 2015 Electrochemical micro machining on hybrid metal matrix composites Int. J. Chem. Tech. Res. 8 508–18

[159] Dharmalingam S et al 2014 Optimization of process parameters on MRR and overcut in electrochemical micro machining on metal matrix composites using grey relational analysis Int. J. Eng. Technol. 6 519–29

[160] Suresh R, Reddy K S and Shapur K 2018 Abrasive jet machining for micro-hole drilling on glass and GFRP composites Mater. Today: Proc. 5 5757–61

[161] Zhao B et al 2008 Research on micro-mechanism of nanocomposite ceramic in two-dimensional ultrasound grinding Key Eng. Mater. 359 344–8

[162] Baumeister G et al 2005 Microengineering of Metals and Ceramics: Part II: Special Replication Techniques, Automation and Properties (Weinheim: Wiley) pp 357–93

[163] Mohammad M M 2011 A review on micro fabrication methods to produce investment patterns of microcasting J. Nat. Sci. Res. 5 5–13

[164] Baumeister G et al 2011 New approaches in microcasting: permanent mold casting and composite casting Microsyst. Technol. 17 289–300

[165] Smart R and Critchley D 1995 Developments in investment casting Foundryman 88 115–7

[166] Baumeister G et al 2002 Production of metallic high aspect ratio microstructures by microcasting Microsyst. Technol. 8 105–8

[167] Baumeister G, Ruprecht R and Hausselt J 2004 Replication of LIGA structures using microcasting Microsyst. Technol. 10 484–8

[168] Baltes H et al 2008 Microengineering of Metals and Ceramics, Part I: Design, Tooling, and Injection Molding vol 30 (New York: Wiley)

[169] Kasanická B et al 2005 Analysis of microstructure, surface topography and mechanical properties of microcast specimens made of the dental gold alloy Stabilor G Microengineering of Metals and Ceramics. Part II (Weinheim: Wiley-VCH) pp 523–54

[170] Kasanická B et al 2009 On the relationship between microcasting process, material states and mechanical properties in the gold alloy Stabilor® G Mater. Sci. Eng. A 501 70–80

[171] Rögner J et al 2011 Microstructure and mechanical properties of micro tensile specimens made of CuAl10Ni3Fe2 produced by micro casting Microsyst. Technol. 17 301–11

[172] Baumeister G, Okolo B and Rögner J 2008 Microcasting of Al bronze: influence of casting parameters on the microstructure and the mechanical properties Microsyst. Technol. 14 1647–55

[173] Auhorn M et al 2002 Quasi-static and cyclic testing of specimens with high aspect ratios produced by micro-casting and micro-powder-injection-moulding Microsyst. Technol. 8 109–12

[174] Kauzlarič D et al 2008 Integrated process simulation of primary shaping: multi scale approaches Microsyst. Technol. 14 1789

[175] Gokhale A and Patel G 2005 Origins of variability in the fracture-related mechanical properties of a tilt-pour-permanent-mold cast Al-alloy Scr. Mater. 52 237–41

[176] Türk A, Durman M and Kayali E S 2003 The effect of Cu and Al on the mechanical properties of gravity-cast hypoeutectic Zn–Al-based alloys Z. Metall. 94 1001–5

[177] Buezezi-Ahmeti D et al 2013 Metal-ceramic-composite casting of complex micro components Microsyst. Technol. 19 159–65

[178] Liu Y et al 2002 Micro-powder injection molding J. Mater. Process. Technol. 127 165–8

[179] Mez L et al 2004 Powder injection molding of metallic and ceramic microparts Microsyst. Technol. 10 202–4

[180] Rata A, Duong T and Hartwig T 2002 Micro powder metallurgy for the replicative production of metallic microstructures Microsyst. Technol. 8 323–5

[181] Rata A et al 2005 Micro MIM approaches mass production Met. Powder Rep. 60 16–20

[182] Ye H, Liu X Y and Hong H 2008 Fabrication of metal matrix composites by metal injection molding—a review J. Mater. Process. Technol. 200 12–24

[183] Kim S-W et al 2005 Micro metal powder injection molding of W-Cu nanocomposite powder Metals Mater. Int. 11 205–8

[184] Kim S-W, Suk M-J and Kim Y-D 2006 Metal injection molding of W-Cu powders prepared by low energy ball milling Met. Mater. Int. 12 39

[185] Simchi A, Rota A and Imgrund P 2006 An investigation on the sintering behavior of 316L and 17–4PH stainless steel powders for graded composites Mater. Sci. Eng. A 424 282–9

[186] Sin H et al 2015 Hybrid manufacturing of stainless steel and zirconia micro components using laser micromachining and powder injection molding 2015 11th Conf. Lasers and Electro-Optics Pacific Rim (CLEO-PR) (Piscataway, NJ: IEEE)

[187] Zauner R 2006 Micro powder injection moulding Microelectron. Eng. 83 1442–4

[188] Zhou Y N 2008 Microjoining and Nanojoining (Cambridge: Woodhead)

[189] Fuhrer M et al 2000 Crossed nanotube junctions Science 288 494–7

[190] Menz W, Mohr J and Paul O 2008 Microsystem Technology (New York: Wiley)

[191] Harman G G 1997 Wire Bonding in Microelectronics Materials Processes, Reliability and Yield (New York: McGraw-Hill)

[192] Onda N, Jaecklin V and Arsalane S 1998 High frequency wire machining of TiN Br. Ceram. Trans. 17 61–2

[193] Shirzadi A A, Assadi H and Wallach E 2001 Interface evolution and bond strength when diffusion bonding materials with stable oxide films Surf. Interface Anal. 31 609–18

[194] Shirzadi A A et al 2018 Gallium-assisted diffusion bonding of stainless steel to titanium: microstructural evolution and bond strength Mat. Sci. Eng. A 4 115–26
[195] Ide E et al 2005 Metal–metal bonding process using Ag metallo-organic nanoparticles Acta Mater. 53 2385–93
[196] Akada Y et al 2008 Interfacial bonding mechanism using silver metallo-organic nanoparticles to bulk metals and observation of sintering behavior Mater. Trans. 49 1537–45
[197] Tatsumi H et al 2005 Sintering mechanism of composite Ag nanoparticles and its application to bonding process-effects of Ag2CO3 contents on bondability to Cu Adv. Mater. Res. 26 499–502
[198] D’Hondt T and Corbin S F 2006 Thermal analysis of the compositional shift in a transient liquid phase during sintering of a ternary Cu-Sn-Bi powder mixture Metall. Mater. Trans. A 37 217
[199] Turriff D M and Corbin S F 2006 Modelling the influences of solid-state interdiffusion and dissolution on transient liquid phase sintering kinetics in a binary isomorphous system Metall. Mater. Trans. A 7 1645–55
[200] Becker M et al 1994 Laser micro-welding and micro-melting for connection of optoelectronic micro-components Laser in Engineering (Berlin: Springer)
[201] Naeem M, Lewis S and Chinn J 2008 Microwelding performance comparison between a low power (125W) pulsed Nd:YAG laser and a low power (100–200W) single mode fiber laser Pacific Int. Conf. on Applications of Lasers and Optics (LIA)
[202] He X, Elmer J and DebRoy T 2005 Heat transfer and fluid flow in laser micro welding J. Appl. Phys. 98 074909
[203] Gajapathi S S, Mendez P F and Mitra S K 2010 Micro welding process using electron beam under high Peclet number Proc. ASME 2010 Int. Mechanical Engineering Congress & Expo IMECE2010 pp 377–83
[204] Gajapathi S S, Mendez P F and Mitra S K 2010 Analytical method to study the temperature distribution of a moving heat source electron beam micro-welding HEFAT 2010
[205] Zhou Y, Dong S-J and Ely K 2001 Weldability of thin sheet metals by small-scale resistance spot welding using high-frequency inverter and capacitor-discharge power supplies J. Electron. Mater. 30 1012–20
[206] Ely K and Zhou Y 2001 Microresistance spot welding of Kovar, steel, and nickel Sci. Technol. Weld. Joining 6 63–72
[207] Böhm S et al 2006 Micro bonding using hot melt adhesives J. Adhesion Interface 7 28–31
[208] Hasan M et al 2012 Fabrication of thinner anodic aluminum oxide based microchannels Adv. Mater. Res. 550 2046–50
[209] Hasan M et al 2012 Anodic aluminum oxide (AAO) to AAO bonding and their application for fabrication of 3D microchannel Nanosci. Nanotechnol. Lett. 4 569–73
[210] Kasi A K et al 2012 Fabrication of low cost anodic aluminum oxide (AAO) tubular membrane and their application for hemodialysis Adv. Mater. Res. 550 2040–5
[211] Kasi A K et al 2012 Bending and branching of anodic aluminum oxide nanochannels and their applications J. Vacuum Sci. Technol. B 30 031805
[212] Passeport A and Muolo M 2000 Joining technology in metal-ceramic systems Mater. Manuf. Process. 15 631–48
[213] Zhou Y N 2008 Microjoining and Nanojoining (Cambridge: Woodhead) ch 16 p 480
[214] Zhou Y N 2008 Microjoining and Nanojoining (Cambridge: Woodhead) ch 10 p 266
[215] Gu D et al 2018 Laser additive manufactured WC reinforced Fe-based composites with gradient reinforcement/matrix interface and enhanced performance Compos. Struct. 192 387–96
[216] Worts N, Jones J and Squier J 2019 Surface structure modification of additively manufactured titanium components via femtosecond laser micromachining Opt. Commun. 430 352–7
[217] AlMangour B, Grzesiak D and Yang J-M 2017 Selective laser melting of TiB2/316L stainless steel composites: the roles of powder preparation and hot isostatic pressing post-treatment Powder Technol. 309 37–48
[218] Kumar S and Czekanski A 2017 Optimization of parameters for SLS of WC-Co and Cu Powders J. Manuf. Process. 23 1202–11
[219] Obuh I E et al 2018 Low-cost micro-fabrication for MEMS switches and varactors IEEE Trans. Compon. Packag. Manuf. Technol. 8 1702–10
[219] Prakash S and Kumar S 2018 Pulse smearing and profile generation in CO2 laser micromachining on PMMA via raster scanning J. Manuf. Process. 31 116–23
[219] Pacella M, Nekouie V and Badiee A 2019 Surface engineering of ultra-hard polycrystalline structures using a nanosecond Yb fibre laser: effect of process parameters on microstructure, hardness and surface finish J. Mater. Process. Technol. 266 311–28
[220] Hassanan H and Jiang K 2018 Microfabrication of components based on functionally graded materials Advances in Ceramic Matrix Composites 2nd edn (Amsterdam: Elsevier) pp 697–709
[221] Li N et al 2018 3D printing of Fe-based bulk metallic glass composites with combined high strength and fracture toughness Mater. Des. 143 285–96
[222] Jackson B et al 2018 Additive manufacturing of Ti-6Al-4V with added boron: microstructure and hardness modification Key Eng. Mater. 770 165–73
[223] Tarasova T, Gvozdeva G and Abyleva R 2018 Innovation in additive manufacturing of parts from aluminium matrix composites MATEC Web of Conf. EDP Sciences
[224] AlMangour B et al 2019 Novel TiB2-reinforced 316L stainless steel nanocomposites with excellent room- and high-temperature yield strength developed by additive manufacturing Composites B 156 51–63
[225] Vaézi M, Seitz H and Yang S 2013 A review on 3D micro-additive manufacturing technologies Int. J. Adv. Manuf. Technol. 67 1721–54
[226] Franchin G, Wahl L, and Colombo P 2017 Direct ink writing of ceramic matrix composite structures J. Am. Ceram. Soc. 100 4397–401
[227]Alias R 2014 Multilayer glass–ceramic components for microelectronics: processing and properties Advances in Ceramic Matrix Composites (Amsterdam: Elsevier) pp 587–610
[228] Vollertsen F 2008 Categories of size effects Prod. Eng. 2 377
[229] Ma X et al 2010 Deformation behaviour of ultrafine-grained copper: modelling and experiment J. Mater. Sci. 44 3807–12
[230] Stachowicz F, Trzepieciński T and Pjea T 2010 Warm forming of stainless steel sheet Arch. Civil Mech. Eng. 10 85–94
[231] Niklowski J and Sims G 2002 Size effects in composite materials Report National Physical Laboratory
[232] Wagner H D 1989 Statistical concepts in the study of fracture properties of fibres and composites Composite Materials Series ed K Friedrich (Amsterdam: Elsevier) ch 2 pp 39–77
[233] Wisnom M R 1999 Size effects in the testing of metal matrix composites J. Mater. Process. Technol. 59 1937–57
[234] Kim J-K and Mai Y-W 1998 Engineered Interfaces in Fiber Reinforced Composites (Amsterdam: Elsevier)
[235] Choi A, Heness G and Ben-Nissan B 2014 Using finite element analysis (FEA) to understand the mechanical properties of ceramic matrix composites Advances in Ceramic Matrix Composites (Amsterdam: Elsevier) pp 286–311
[236] Barai P and Weng G J 2011 A theory of plasticity for carbon nanotube reinforced composites Int. J. Plast. 27 539–59
[237] Haghgo M, Ansari R and Hassanzadeh-Aghdam M K 2018 Effective elastoplastic properties of carbon nanotube-reinforced
aluminum nanocomposites considering the residual stresses
J. Alloys Compd. 752 476–88

[240] Aghdam M and Morsali S 2014 Effects of manufacturing parameters on residual stresses in SiC/Ti composites by an elastic–viscoplastic micromechanical model Comput. Mater. Sci. 91 62–7

[241] Luo L et al 2014 Optimisation of size-controllable centroidal voronoi tessellation for FEM simulation of micro forming processes Proc. Eng. 81 2409–14

[242] Luo L et al 2015 An experimental and numerical study of micro deep drawing of SUS304 circular cups Manuf. Rev. 2 1–7