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STUDY ON THE EFFECT OF RECYCLED BRASS-FILLED EPOXY MOULD INSERTS FOR RAPID TOOLING

Rapid Tooling able to produce complex prototypes directly from three-dimensional CAD software using materials such as polymer, wax, and paper, but it is typically used for low-volume production. The current technology uses epoxy filled with metal fillers such as aluminum or copper to enhance the mechanical properties of rapid tooling molds. This study aims to investigate the effect of using recycled brass filler mixed with epoxy resin as mold inserts for Rapid Tooling in injection molding applications. An optimal ratio of brass filler particles will be evaluated to determine the best physical and thermal properties for the mold inserts. Significantly, this study will encourage the use of recycled materials such as metal waste from machining to offer great help in environmental sustainability.

Keywords: machining waste; rapid tooling; injection moulding; mould inserts; metal epoxy composite

1. Introduction

In the tooling industry, additive manufacturing (AM) and Rapid Tooling (RT) have traditionally been viewed as complementary technologies for faster tooling fabrication in various prototype applications. The end product requires stringent requirements, including dimensional accuracy and good surface finish. Therefore, the current method of producing tooling inserts, such as moulds (core and cavities), involves numerous manufacturing steps. Most mould components are made using Computer Numerical Control (CNC) or Electrical Discharge Machining (EDM) machines, which are expensive and time-consuming in fabricating the core and cavity of the mould for production-ready applications [1,2]. This trend has caused modern industries to gain enormous internal flexibility in order to meet customer expectations regarding product quality and price. As a result, current industrial trends are shifting from mass production to small volumes with a wide product range instead of high-volume and small-range manufacturing of products [3]. To overcome these issues, metal epoxy composites have been introduced. They reduce the cost and lead time of tool manufacturing by up to 25% and 50%, respectively [4]. However, the current challenges in using epoxy resins as a mould insert include issues with strength, accuracy, surface finish, and thermal properties. Moreover, epoxy moulds tend to break apart when subjected to repeated heating and cooling cycles. Usually, after more than 20 injection cycles, the surface of the epoxy mould chips, which can lead to fractures or cracks that spread quickly and consequently result in the failure of the mould insert [5]. Prior research on RT moulds has demonstrated that the mould lifespan is significantly affected by the level of stress it experiences during the injection moulding procedure [1,2,6,7]. Hence, considering these specific demands for distinct physical and mechanical characteristics, the appropriate choice of epoxy resins and curing agents could aid in satisfying these quality prerequisites. Another significant issue when employing epoxy resins as mould inserts is the heat transfer rate, primarily due to their low thermal conductivity [6,8,], which is approximately 6% of metal's thermal conductivity [6,8,9]. Furthermore, earlier investigations on the material traits of a metal epoxy composite were restricted to isolated values, with no extensive data available regarding the refinement of a metal epoxy composite's preparation [1,2,6,7]. Thus, there is a need to undertake an initiative to analyse the optimal parameter settings for mixing epoxy with particle fillers, as well as developing tool inserts for RT in injection moulding applications.

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2. Injection moulding process

Recently, injection moulding has become one of the primary forming processes for thermoplastic polymers, accounting for over 30% of all plastic parts manufacturing [10]. Examples include product casings and housings, computer monitors, mobile phones with thin shells, electrical and electronic devices, and food packaging [11]. Due to its ability to produce complex-shaped plastic products with good dimensional accuracy at relatively low manufacturing costs, injection moulding is the most preferred manufacturing process [12]. This method is also commonly used for producing a large number of plastic components. Fig. 1 depicts the plastic injection moulding machine used in the process, where hot molten polymer is injected into a cold, empty cavity with the desired shape and solidifies under high pressure [13]. Generally, three stages are required to complete the entire injection moulding cycle: injection time, packing (holding) time, cooling time and mould open stage. Due to the complexity of the moulding process, it is quite challenging to achieve the desired quality of the moulded part, which can cause difficulties in maintaining the quality of the part during production. Moreover, the process parameters in plastic injection moulding also have an impact on the quality and manufacturing cost of the moulded part. Therefore, it is essential to find the optimum process parameters for high-quality production. However, finding the optimal process parameters can be difficult due to the nonlinear phenomena involved. Traditionally, operators manually set the input of critical parameters in the injection moulding process using a trial-and-error approach. However, this approach is time-consuming and heavily relies on the experience of moulding operators [14]. Furthermore, the process parameters in plastic injection moulding have an impact on the quality of plastic products and the manufacturing cost. Therefore, finding the optimal processing parameters for high quality is essential. Some researchers have applied various optimization methods to enhance the quality of the moulded parts by determining the best injection moulding parameter settings [15-17]. Recently, plastic injection moulding simulation coupled with optimisation methods have attracted a lot of attention in improving the quality of moulded parts [18]. Thus, for engineers to design a moulded part, it is important to have knowledge of the processing parameters that are associated with quality in the injection moulding process.

2.1. Important parameters in injection moulding process

In order to produce high-quality moulded parts, the setting of processing parameters is one of the most crucial factors [19]. Therefore, many studies have been conducted over the years to optimise processing parameters to minimise shrinkage and warp defects [7,9,10,12]. Moreover, it has also been reported that several significant processing parameters, such as melting temperature, cooling time, packing pressure, mould temperature, and packing time, affect the quality of the moulded parts produced [7,11,15,18,20].

i. **Melt temperature** – also known as the temperature required to melt the plastic material in pellet form. The heater heats the screw barrel in the injection moulding machine before the injection phase to fill the mould cavities [21]. A few researchers have reported that the melting temperature is a significant processing parameter that causes warping on the moulded parts [14,16,17,22]. The results show that the melting temperature affects the amount of material flowing into the cavities [23].

ii. **Cooling time** – cooling time in injection moulding is a critical part of the production process. It is the duration for which the molten plastic takes to solidify. When the molten plastic hits the mould cavities' walls, it begins to cool down and continues to solidify. The mould will remain closed until the moulded part reaches the ejection temperature. Increasing the cooling time can improve shrinking quality and reduce warpage defects [24]. However, it is necessary to determine an appropriate cooling time to produce good quality moulded parts within the optimum cycle time.

iii. **Packing pressure** – the pressure used to inject and compact the molten plastic material into the moulding cavities until the gate freezes is significant. Previous researchers have reported that packing pressure is a critical processing parameter that affects the accuracy and quality of the moulded parts produced [25-27]. Moreover, packing pressure is also

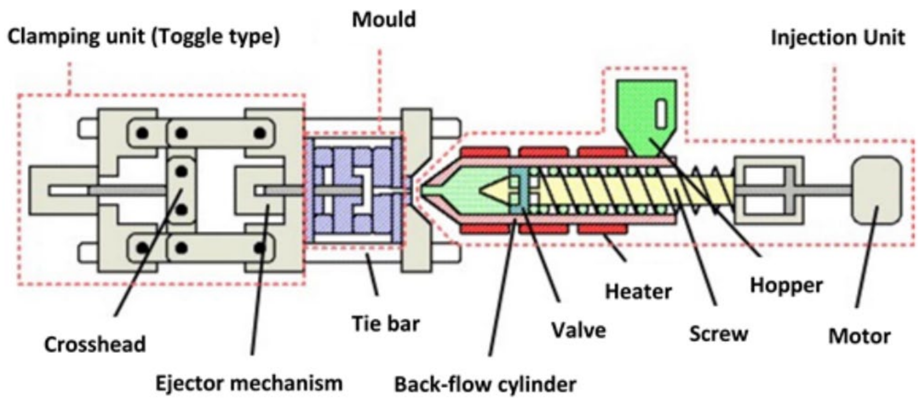

Fig. 1. Plastic injection moulding machine [13]

a significant processing parameter after packing time, which greatly impacts the shrinkage and flexural strength of the moulded parts produced. Any change in packing pressure will result in the degradation of the mechanical properties of virgin and recycled plastic moulded parts for different compositions [28].

iv. **Mould temperature** – the temperature needs to be controlled to solidify the molten plastic material that flows into the mould cavities towards the ejection temperature. Previous studies have shown that the mould temperature is one of the significant processing parameters that affect the moulded part's warping and shrinking [23,29,30]. This result is consistent with a study conducted by Alkaabneh et al. [23] which suggested that the mould temperature would affect the shrinkage in both the transverse and longitudinal directions of the molded parts produced.

v. **Packing time** – Packing time is the time required to fill the mould cavities without pressing the mould or flashing the finished parts entirely with additional material [31]. The packing time is usually determined by the time it takes for the gate to freeze. When the gates freeze, the material is no longer able to flow into the mould cavities. However, if the packing time is too short, the molten material may flow back into the feed system, causing a backflow phenomenon. Previous studies have demonstrated that simulation studies can be used to determine appropriate processing parameters, which can then be integrated with optimization methods [21,32]. Indeed, appropriate processing parameters are essential for the moulding industry to be identified to produce high-quality products [33,34]. Another factor in producing high-quality moulded parts is the selection of suitable mould design types.

3. Injection mould design

In injection mould design, there must be a gate or aperture to allow molten plastic to be injected into the mould cavity [8]. The gate type, design, and position of gate can affect part packing, gate removal or vestige, the visual look of the moulded part, dimensions, and its warping condition [8,14]. There may be differences in shrinkage rates between materials. Moreover, the material used for the mould base and mould insert part is determined by the product to be manufactured [8,14,17].

3.4. Materials for injection iould

Each material's shrinkage and mould flow rate must also be considered. These criteria affect the part's dimensions, tolerances, and surface state and can reduce undesirable flaws, such as warpage, sink marks, and colour streaks. It is essential to examine the shrinkage rate of injection moulding materials. Changing materials for subsequent manufacturing cycles can impact the size of a part made of a different plastic material during the initial production cycle. There may be a difference in shrinkage rates between different materials. Furthermore, the selection of material for the mould base and mould insert parts depends on the product that needs to be manufactured.

3.4.1. Mould insert iaterial

Mould insert material has a considerable influence on the cooling time, which, in turn, has an impact on the total cycle time. Tool Steel takes longer to cool than other materials, i.e., the insert material used for testing. The thermal conductivity of pure copper and beryllium copper (BeCu) is higher, making the heat-removal material more similar to Tool Steel. Before mould insert fabrication starts, the use of material with high thermal conductivity must be considered. When BeCu is utilised in the core insert, it has a higher thermal conductivity than steel, allowing for faster heat extraction and a more consistent temperature distribution from the cavity side to the core. As shown in TABLE 1, the BeCu insert decreases cycle time by roughly 3 seconds compared to Tool Steel, resulting in increased productivity, consistent shrinkage throughout the item, and fewer warps [35].

TABLE 1

Simulation results three inserts [35]

	Time to reach ejection temperature, TRET (s)	Mould core insert temperature, *T* (°C)	Volumetric shrinkage, VS (%)	Warpage (mm)
Pure copper	8.8	28.10	1.605	0.1602
Beryllium copper	9.5	41.62	1.160	0.1614
Tool steel	12.4	76.82	1.759	0.1700

4. Rapid Tooling

Rapid Tooling (RT) is most commonly associated with additive manufacturing methods, and specific techniques have been recommended using various technologies. A uniform framework can be constructed for all CAD-based manufacturing concepts, with tool parts developed in less time using automated procedures. However, the created tools frequently require hand assembly or finishing. As a result, traditional tooling development techniques, such as CNC cutting and machining methods and EDM, can be included in RT processes. In many cases, these techniques are used to create prototype tools that can be used as bridge tools. Standard base assemblies can be used to define the moulding core and cavity and to allow for mould inserts. RT is employed in developing these inserts, along with CNC machining. In some simpler manufacturing methods, the rapidly generated components can be used alone for the moulding operation, and there is an alternative in fabricating mould inserts in RT applications, such as Metal Epoxy Composite (MEC) mould inserts.

4.2. Metal Epoxy Composite (MEC) as mould insert materials

The performance of epoxy mould inserts in the injection moulding process using MEC has been widely explored. Fig. 2 illustrates the MEC mould insert assembled onto a conventional mould base for use as a hybrid mould in Rapid Tooling [36]. Based on previous research, this type of tooling can mould 100 to 600 shots without any defects on the mould insert surface [35]. The appropriate parameters for material preparation have been investigated by adding aluminium, copper, and brass fillers to the MEC mould inserts to create an epoxy mould with good material properties.

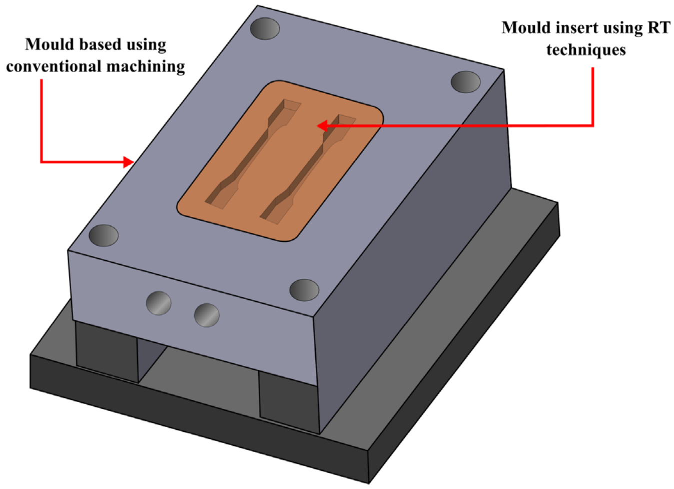

Fig. 2. illustrates the MEC mould insert assembled onto a conventional mould base for use as a hybrid mould in Rapid Tooling [36]

4.2.1. Aluminium metal filler in epoxy resin mould

Some researchers explored the application of aluminium metal filler in epoxy resin moulds, as summarised in TABLE 2. For instance, Fernandes et al. [7] investigated the mechanical and dimensional features of moulded parts in epoxy resin/aluminium RT mould inserts. The circular geometrical component used for the work had a diameter of 140 mm and five central cavities connected by a 2 mm diameter segment. There was also a 60 mm long runner with an entrance diameter of 6.5 mm and an angle of 2° in a draught. The variable parameters for this study were injection time, holding time, cooling time, clamping force, injection pressure, cooling water temperature, and injection flow rate. Simultaneously, the study analysed the strength of the parts' yielding tensile injections with epoxy/Al inserts. The metrological analysis of the moulds revealed that the injected parts were more likely to warp with the epoxy/Al insert than with AISI P20 steel. In addition, the different thermal conductivity of the moulding block materials used in the hybrid mould caused differential cooling on both sides of the mould, leading to further warping. As a result, the two sets of warpage data for the two mouldings were statistically significantly different. On the other hand, Kuo and Lin [37] investigated the manufacture of Fresnel lenses using rapid injection with liquid silicone rubber. The experiment was conducted with RT and LSR parts to develop horizontal LSR moulding equipment (Allrounder 370S 700-290, ARBURG). The variable parameters considered in this analysis were surface temperature of the moulding, heating time (minutes), injection speed, packing pressure, and packaging time. Simultaneously, the response was the plastic injection surface roughness measured with WLI (7502, Chroma Inc.). This study shows realistic results and provides a full scope for LSR applications in the moulding industry. The prospect of using an aluminium-filled

TABLE 2

Researches on Aluminium Filled Epoxy

Author	Material for Mould Insert	Experiment / Simulation	Parameter	Output Response	Result
Fernandes et al., (2016) [7]	Aluminium fillers	CAE simulation using the software Moldflow Insight version 2010	Injection time, holding time, cooling time, clamping force, injection pressure, cooling water temperature, injection flow rate	Mechanical properties of the parts	The epoxy/Al insert injected parts had a higher tendency to warp than with the steel AISI P20. By increasing the crystallinity and consequently a larger shrinkage, the slow cooling rate caused by the epoxy resin/Al insert leads to this result.
Kuo and Lin, (2019) [37]	Aluminium (Al)-filled epoxy resins (TE-375, Jasdi Chemicals Inc.)	Common horizontal moulding device for LSR (Allrounder 370S 700-290, ARBURG) was used manufacture of LSR parts.	Mould surface temperature, Heating time, injection speed, packing pressure, and packing time	The plastic injection parts surface roughness	For LSR injection moulding, the feasibility of an injection mould made from aluminium-filled epoxy resin is possible. After 200 test runs of LSR injection moulding, the average surface roughness of the Al-filled epoxy resin mould only increased by about 12.5 nm.
H. Radhwan et al., (2021) [35]	Aluminium filled epoxies, Resin PT100 and Hardener	The method was carried out using a conventional turning machine,	Density, and the percentage of filler	Compressive strength and hardness	When decreasing the compressive strength by increasing the filler (aluminium powder) at I the 40% weight percentage of filler with minimum compressive strength the cured is better than the lower temperature at high temperature (suggested by production), which can increase compressive strength and hardness values by 14% from room temperature.

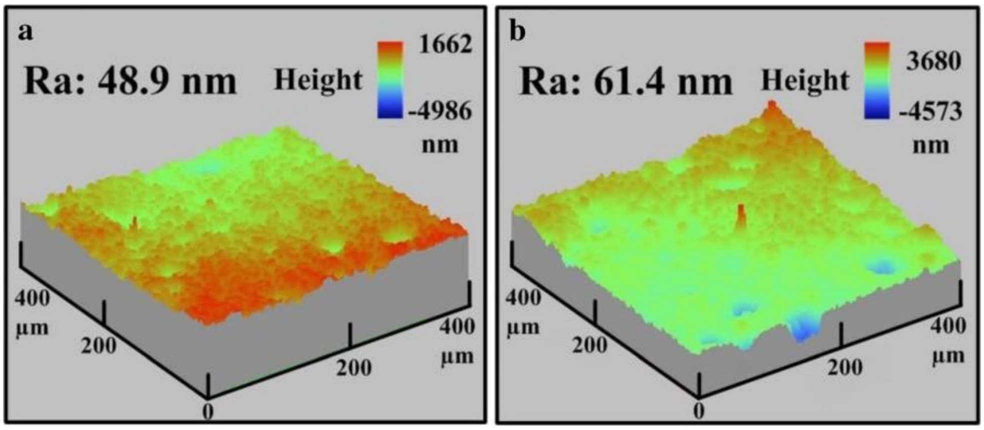

Fig. 3. Changes in the surface roughness of the mould surface a before and b after 200 test runs [37]

epoxy resin injection mould for LSR injection moulding is also presented. The average surface roughness of the Al-filled epoxy resins improved by approximately 12.5 nm, as demonstrated in Fig. 3, after 200 LSR injector test runs. Radhwan et al. (2021) [35] conducted an investigation into the experimentation of material properties on MEC. The variable parameters of this research were the filler particle materials, the type of epoxy resin, and the processes suitable for the application. Simultaneously, the response of the epoxy mould materials was measured by hardness, compression, tensile, thermal conductivity, and wear rate. The values increased when the percentage of filler added in the epoxy matrix increased. The hardness, density, and thermal conductivity tests showed an upward trend. However, the tensile test showed that the tensile value dropped gradually when the wt% of the filler composition increased. Compared to adding filler, the unfilled filler particle in the epoxy matrix showed higher tensile strength. The compression test showed that the composition of a filler had a nonlinear trend effect. The compression strength increased when the wt% of filler composition was added. The maximum compression value was at the composition of 20% filler, and the graph gradually dropped more than 25% when adding more filler composition. The wear rate testing indicated that the wear rate started at the maximum wear rate. When the filler ratio increased, the wear rate continuously decreased until a certain percentage of the filler wear ratio increased. The suitable selection of filler particles with the correct percentage composition was the most significant factor affecting the mould performance improvement in this study. Besides aluminium filler, some researchers also explored the copper-based filler in the application of RT.

4.2.2. Copper metal filler in epoxy resin mould

Some researchers have explored the application of copper metal filler in epoxy resin moulds, as summarised in TABLE 3, to improve the properties of the mould insert. For example, Singh and Pandey [38] investigated the rapid tooling of copper-graphene (Cu-Gn) composites using a novel rapid tooling technique. The variable parameter in this study is the change in density and hardness by adding graphene content to Cu-Gn composite samples. In comparison with CPS manufactured samples, UAPS samples showed improved performance. With the addition of a higher graphene content, the density of the rapidly manufactured parts was reduced by 4.48% in CPS manufactured samples and 6.79% in UAPS manufactured samples. This was due to the homogeneous blend of ultrasonic vibration between Gn and spherical particles during manufacturing. Furthermore, the CPS manufactured samples by UAPS had high particle diffusion and low surface porosity. In another study on the use of copper slag as a filler in glass-epoxy composites, Biswas and Satapathy [39] investigated improving the composites' wear resistance. The tensile modulus increased from 8.77 GPa to 9.64 GPa when up to 10 wt% of copper slag was used. However, when further adding copper slag (up to 20 wt%), the tensile modulus started to decrease down to 7.11 GPa. The trends observed in flexural strength and interlaminar shear strength were similar. Incorporating copper slag particles increased the impact strength by about 10-15%. This study involves processing, characterisation, and evaluation of erosion behaviour of copper slag-filled glass-epoxy composites using Taguchi's experimental approach. The results indicated that peak erosion occurred at a 60° impingement angle for unfilled composites and at a 45° impingement angle for copper slag-filled glass-epoxy composites. The possible use of copper slag as a filler material for preparing composite materials and added-value products like abrasive tools, cutting tools, and railroad ballast is considered in this paper. The mechanical properties, including flexural strength, tensile modulus, impact strength, and hardness, improved with the incorporation of copper slag. However, a slight decline in the composites' tensile and inter-laminar shear strengths compared to the unfilled case was observed. This study suggests that selecting the appropriate filler material and optimising its content in the composite system are critical for developing composite materials. The study conducted by Bhagyashekar [40] aimed to characterize the mechanical behavior of epoxy composites filled with metallic and non-metallic particles. Tensile, compression, and flexural tests were conducted on unfilled epoxy and its composites with metallic (Al and Cu) and non-metallic (SiC and Gr) fillers. Tensile properties such as strength and modulus were measured using

TABLE 3

Researches on Copper Filled Epoxy

Author	Composite Filled Material	Experiment / Simulation	Parameter	Output Response	Result
Singh and Pandey, (2020) [38]	Spherical copper powder	The indirect method of rapid production that combines three-dimensional. As rapid tooling, UAPS, and printing were used for Manufacture of Cu-Gn freeform composite shapes	Wear rate, and coefficient of friction	The rapid manufactured parts density	With the addition of a higher graphene content, the density of the rapid manufactured parts was reduced by 4.48 per cent in CPS manufactured samples and by 6.79 per cent in UAPS manufactured samples.
Biswas and Satapathy, (2010) [39]	Copper slag	Includes the processing, characterization and study of the erosion behaviour of a class of such copper slag filled glass-epoxy composites based on Taguchi's experimental approach	Density, and the percentage of filler	Tensile, Impact, and flexural tests	The tensile modulus increased from 8.77 GPa to 9.64 GPa when using up to 10 wt% of copper slag but on further addition of copper slag (up to 20 wt%), the tensile modulus started to decrease down to 7.11 GPa. Similar trends were observed in the case of flexural strength and interlaminar shear strength. With the incorporation of copper slag particles, the impact strength increased about 10-15%.
Bhagyashekar, (2010) [40]	Unfilled epoxy, epoxy with metallic (Al and Cu) fillers		Type epoxy resin, filler particle materials, and processes appropriate to the application	Tensile, compression, and flexural tests	As the filler loading was increased to 30%, the composites showed a maximum improvement in compression strength. The composites with SiC-Ep displays the highest improvement in compression strength. Increasing the filler loading decreased the flexural strength of the composites, whereas increasing filler loading increased the flexural modulus.

dog bone specimens, while compression strength was measured using cylinder specimens. Flexural properties such as strength and modulus were measured using a three-point bending test. The results showed that increasing filler loading to 30% led to a maximum improvement in compression strength, with SiC-Ep composites exhibiting the most significant improvement. Increasing filler loading decreased flexural strength but increased flexural modulus. Tensile strength decreased with filler loading, but the composites showed higher tensile modulus with more filler loading. In addition to aluminium and copper fillers, some researchers have also explored the use of brass metal filler in applying RT.

4.2.3. Brass metal filler in epoxy resin mould

Some studies have investigated the use of brass metal filler in epoxy resin moulds, as shown in TABLE 4, to improve the quality of the mould insert. For instance, Khdir and Hassan [41] investigated three different grades of brass debris with varying grain sizes (600 µm, 800 µm, and 1180 µm) as a strengthening agent in epoxy resin with varying weight percentages (2%, 4%, 6%, and 8%). The mechanical properties of the composites were evaluated using tensile and impact toughness tests. Fig. 4 shows the tensile test result and impact toughness test of brass debris epoxy. As a result, the best toughness value was obtained with the epoxy-BD600 and weight percentage of 8%. Thus, very low brass debris content did not significantly improve the toughness of composite samples, reducing the absorbed impact energy (toughness of impact). Therefore, to improve the tensile or impact properties of epoxy-brass debris composites, it is important to reduce the weight percentage of brass debris added to epoxy resin due to the coarse grain size of brass debris. In a while, Khushairi et al. [42] developed metal-filled epoxy inserts by fabricating aluminium-filled epoxy (EA) mixed with brass (EAB) and copper fillers (EAC) into moulding inserts to produce mechanical testing specimens of plastic material. Mechanical tests were conducted to compare the behaviour of specimens obtained from all inserts and those obtained from conventional metal moulds. EA moulded parts produced a higher yield tensile strength of 36.3 MPa and impact energy of 1.823J, compared to conventional metal moulded parts of 33.8 MPa and 0.002J. EAB and EAC inserts demonstrated high tensile modulus between 1640-1670 MPa, and their moulded parts had similar impact energy and strength to EA. Fig. 5 shows the tensile strength vs elongation for moulded parts from all inserts. The findings in this study can be used to improve the service of parts that require higher strength, depending on the moulded application. Adding metal fillers to EA composition improves the inserts' thermal conductivity and mechanical properties and provides new insights for future work. Based on Khushairi et al. [8], the inclusion effects of metal fillers such as copper and brass particles into the blended epoxy matrix were evaluated. 10%, 20%, and 30% of Brass and copper powders of their weight were added separately into the aluminium filled epoxy mix ratio. Physical and thermal properties such as density, thermal diffusivity, thermal conductivity,

TABLE 4

Researches on Brass Filled Epoxy

Author	Composite FilledMaterial	Experiment / Simulation	Parameter	Output Response	Result
Khdir and Hassan (2018) [41]	Brass debris	The brass debris which is obtained through matte smelting and refining of brass or different machiningprocess like grinding operation, to use as filler in epoxy-resin composites	Different grades with different grain size anddifferent weight percentages	Tensile tests and impact toughness test	Increasing the grain size of the brass debrisadded to pure epoxy matrix, it is suitable to decrease the amount of weight percentage added. Epoxy sample without any reinforcement has a higher toughness than the other samples
Khushairi etal., (2018) [42]	Brass and copper	Physical and thermal properties were analysed toevaluate the effects of inclusion of metal fillers such as copper and brass particles into the blended epoxy matrix.	Type epoxy resin, filler particle materials and processes appropriate to the application	Density, thermal diffusivity, thermal conductivity and compressive strength	Both filler compositions were increased from 10% to 30%, density, thermal diffusivity, and thermal conductivity valuesincreased linearly and higher composition of metal fillers leads to decrease in compressive strengthdue to the presence of porosity.
Khushairi etal., (2017) [8]	Aluminium filledepoxy (EA) mixed with brass (EAB), copper fillers (EAC)	The moulding inserts consisted of cavity and core blocks which are CNC machined into specific dimensions of the tensile strength and Izod test specimens based on ASTM standards.	Type epoxy resin, filler particle materials and processes appropriate to the application	Izod test and tensile tests	Moulded parts from EA insert displayed higher tensile strength and impact strength values, as compared to moulded parts from metal moulds.

and compressive strength were then analysed using calculations, the ASTM D 695 standard, and a thermal conductivity analyser. The result in Fig. 6 shows that density and thermal conductivity values increase linearly when filler compositions are increased from 10% to 30%. However, a higher composition of metal fillers leads to decreased compressive strength due to porosity. Further studies on the moulding process are necessary to evaluate the mechanical properties of the moulded part with different inserts.

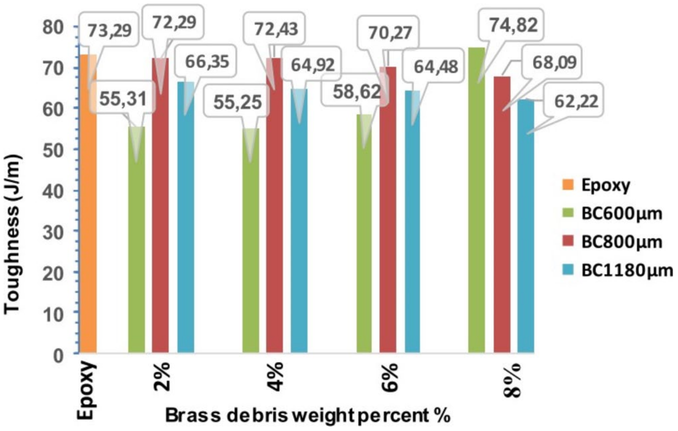

Fig. 4. Result of a) tensile test b) impact toughness test [41]

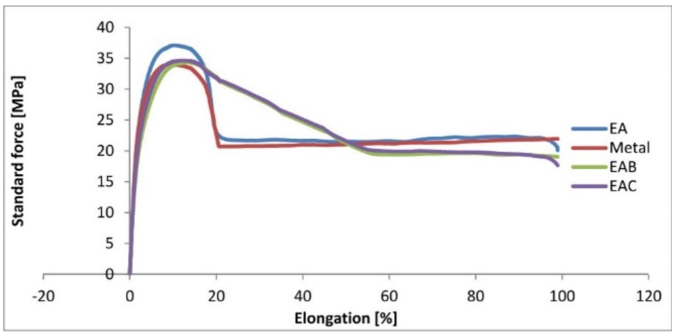

Fig. 5. Tensile strength vs. elongation for moulded parts [42]

5. Methodology proposal for Brass Metal Epoxy Composite as mould insert

The proposed methodology for the review comprises four phases: Phase 1 to Phase 4. It begins with an examination of the filler particles used in MEC production. The next step is the creation of test specimens using brass filler particles mixed with an epoxy resin to establish a new combination of filler particles. Before assessing the suitability of the manufactured mould inserts for use in the injection moulding process, mechanical and thermal conductivity tests must be conducted to analyse the physical properties of the newly developed brass metal filler epoxy composite. The mould inserts are then designed and fabricated using the new MEC insert composition. Finally, the mould inserts will be mounted on the mould base and subjected to testing using an injection moulding machine to validate the mould's performance.

5.1. Phase 1 – Investigation filler particle

The literature review highlights prior work on filler particles used as MEC material. Based on previous studies, MEC

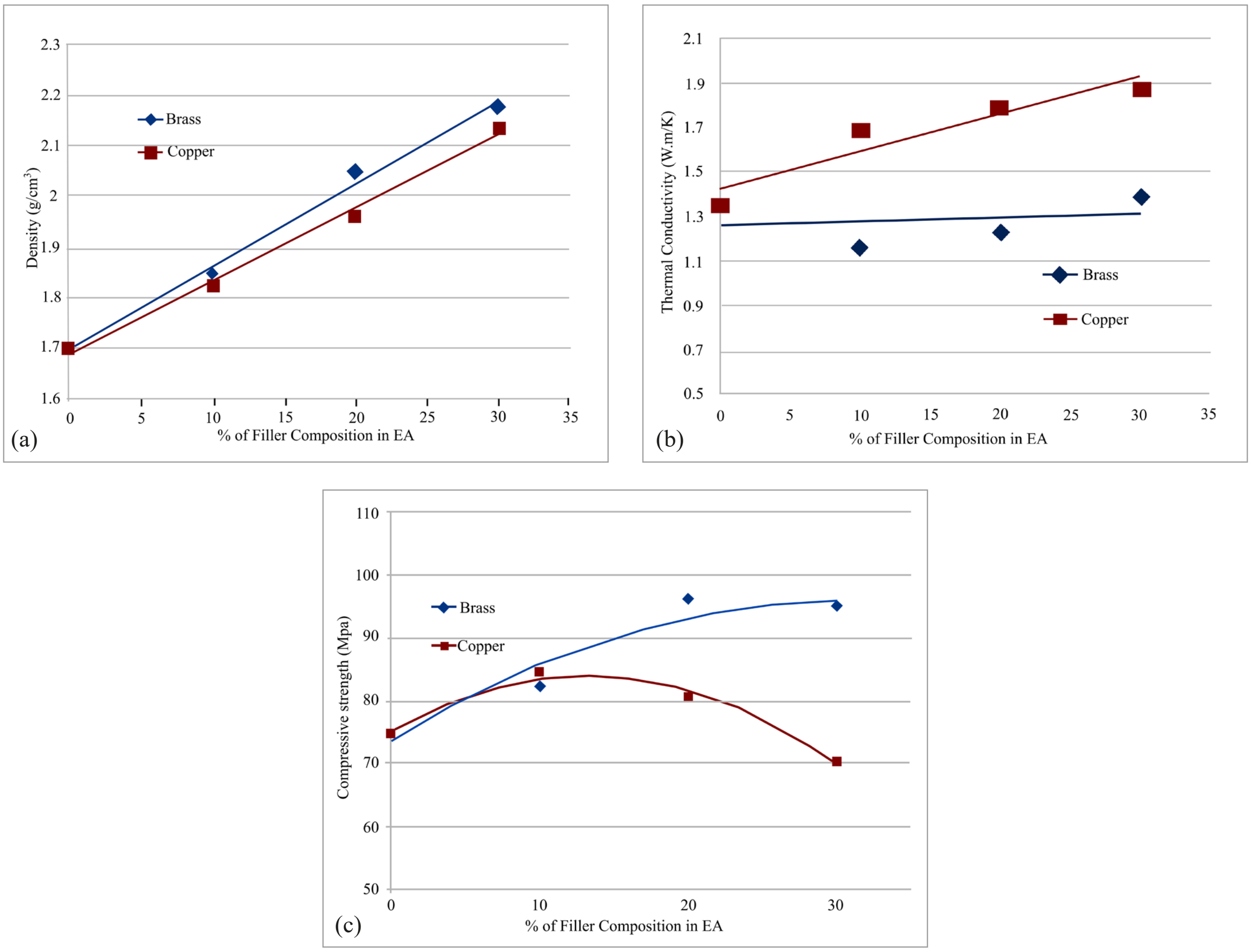

Fig. 6. Effects of fillers against: (a) density [8], (b) thermal conductivity [8], (c) compressive strength [8]

material has shown great potential for fabricating mould inserts for injection moulding [8,35-37]. Epoxy resin mixed with metal filler particles such as brass is believed to improve the durability and thermal conductivity of the produced mould inserts. Fig. 7 presents an image of brass in wire shape with a particle size of 2 mm, measured using a scanning electron microscope (SEM).

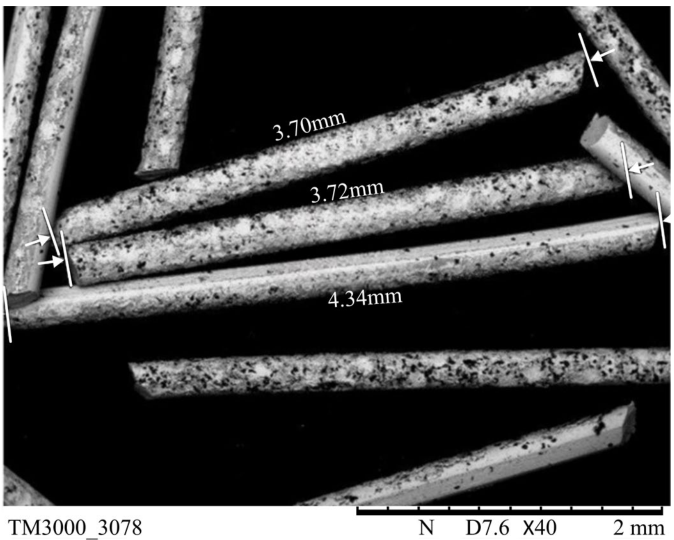

Fig. 7. Brass metal particles with cylindrical shape [41]

A smaller size of the brass filler could enhance the strength and thermal properties of the MEC mould insert [37]. Therefore, using a ball mill machine could crush the metal particles into powder form with smaller sizes.

5.2. Phase 2 – Evaluation of Brass Metal Epoxy Composite specimen

The master patterns for the specimens must first be produced using AM or machined with a CNC machine. Using the RT process, the master patterns will then be cast in silicone rubber molds. The required mixture of epoxy resin and hardener is mixed and agitated with brass metal filler particles until evenly distributed before being degassed in a vacuum chamber to remove air bubbles. Therefore, it is important to control the mixing time during the preparation of the MEC mixture because the mixture viscosity increases in proportion to time. Based on the review that has been done, the percentage of metal filler composition plays an essential role in determining the brass MEC properties [35]. The brass MEC mixture will agglomerate if the percentage of metal filler particles' composition is too high. Therefore, appropriate mixing time and filler particle composition rate could be determined using optimisation methods such as Response

Surface Methodology (RSM) or other optimisation approaches. After the mixture is ready, the slurry will then be poured into a silicon rubber mould that has been custom-made to fit the shapes of individual specimens. The sintering and curing processes are carried out according to an epoxy resin manufacturer's standard data sheet. Before a test can commence, the specimen must undergo a finishing process based on ASTM standard dimensions. The mechanical, thermal, and microstructural analysis will be performed once the specimen is ready. In terms of mechanical testing, an Instron Universal Testing Machine would be used to perform a compression test based on the ASTM D 695 Standard Test Method, considering that the epoxy substance is a stiff thermoset material. Meanwhile, the Vickers hardness (HV) test will be conducted using the Matsuzawa hardness tester, with specimens being graded using the ASTM D2240 standard. The density test will be carried out following the ASTM D-792 standard. The materials will be broken into small sizes and weighed in air and water to determine their relative densities. The filler effect on wear will be assessed utilising the pinned-on disc technique during ASTM G99 wear rate tests. The thermal conductivity test will be performed using a Decagon kD2 Pro thermal conductivity analyser, and the ASTM C884 standard will be used to test the specimen. Microstructure analysis will be used to validate the filler dispersion in the epoxy matrix, and the microstructure of the composites will be observed. Finally, based on the prior research findings, an ideal value for the epoxy resin to produce the mould tooling insert was effectively estimated.

5.3. Phase 3 – Metal Epoxy Composite mould inserts fabrication

The suggested mould inserts (core and cavity) are made from a specific combination of materials (brass metal filler particles and epoxy resin) and are fabricated using the RT method. A hybrid filled epoxy composite with a combination of brass metal filler particles is recommended for the mould inserts. The cavity and cooling channel patterns must be set in the frames before the core and cavity inserts are cast with epoxy and metal particles. In order to analyze the processing parameters, including injection/fill time, packing time, packing pressure, and cooling time, it is necessary to use simulation software. The cooling time should be analysed using ANSYS software because, as a new composite material has been developed, its properties are not available in Modlflow software. On the other hand, Moldflow or C-MOLD softwares should be used to obtain other parameters such as injection/filling time, injection pressure, and injection speed. These parameters will be employed as settings on the injection moulding machine during the experimental work.

5.4. Phase 4 – Validation

The mould inserts made with brass MEC material must undergo testing using an injection moulding machine to be validated. The performance of the mould insert must be assessed in terms of durability, cooling time and total cycle time. The results obtained from simulation studies must be validated through experimental works by using the same set of processing parameters. Additionally, the quality of the moulded part, including surface roughness, shrinkage, and warpage condition, should also be evaluated.

6. Conclusion

RT is vital in manufacturing for its capability to provide faster production of moulds and tooling, reducing turnaround times and meeting market demands. It offers cost-efficiency by lowering tooling costs through additive manufacturing technologies. RT enables iterative design processes, allowing quick prototyping, testing, and adjustments to minimize errors. It also facilitates the production of customised or low-volume products and offers material flexibility to adapt to specific product requirements. In summary, RT provides significant advantages in speed, cost-efficiency, iterative design, customisation, and material flexibility, making it essential for enhancing manufacturing competitiveness and meeting industry demands. The review conducted indicates that brass can be used as a metal filler in metal epoxy composite to manufacture mould inserts for RT in the injection moulding process. Consequently, utilising recycled brass from machining waste as mould inserts in RT offers environmental and resource conservation benefits, such as reducing the demand for virgin materials, conserving finite resources, saving energy in production, and decreasing greenhouse gas emissions. Additionally, it leads to cost savings for manufacturers through material reuse and promotes waste reduction and responsible waste management practices. Furthermore, recycling brass contributes to the development of a more sustainable and circular economy. Therefore, a few future works are suggested to realise this potential, including:

i. the processing parameters, including the type and material of the jar and ball used in the ball milling process to convert recycled brass from machining waste into a powder form, need to be investigated.
ii. the mechanical properties (including density, compression, and wear), thermal characteristics, and microstructural analysis of recycled brass from machining need to be properly evaluated using appropriate international standard procedures.
iii. the performance of MEC fabricated from recycled brass needs to be properly evaluated in terms of the durability and quality of moulded parts produced. It is essential to compare the performance of MEC with the current technology available for mould inserts used in RT, such as MEC fabricated using copper and pure brass.
iv. an optimization method needs to be applied to obtain the optimum composition of metal fillers and epoxy for fabricating mould inserts for RT using MEC with recycled brass. However, there are some limitations that need to be con-

sidered. For instance, the brass waste from machining needs to be separated due to the different machining processes that may result in varying chemical reactions and defects on the brass waste, especially when machining involves the use of oil, grease, and coolant.

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