Preparation, Performance and Issues Associated with Metal Matrix Composites that are Produced by Additive Manufacturing Procedures

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Publication Date: 2026/07/17

Abstract: Metal matrix composites (MMCs) are widely used in a variety of advanced industrial fields because of their high modulus and strength, in addition to other desirable properties at high temperatures, such as wear resistance and corrosion properties. These properties encourage the material to be used in a variety of applications. MMCs possess these qualities, which is why this is the case. For the past few decades, the method of additive manufacturing (AM) has been the focus of interest as one of the prospective technologies that can be applied to construct MMCs. This attention has been directed toward the manufacturing approach. The field of additive manufacturing (AM) for metal-metal composites (MMCs) is the subject of this article, which examines the current advancements and activities that have taken place in this field. The various additive manufacturing (AM) technologies that are currently available, the various types of reinforcement, the preparation of feedstock, the fundamentals of synthesis in the AM process, typical AM-produced MMCs, the strengthening mechanisms of MMCs, the challenges that are required to fabricate MMCs, and potential interests in the field are all highlighted in this article. The AM method of manufacturing MMCs displayed mechanical properties that were equivalent to or even superior to those of the conventionally manufactured ones. This was proved when compared to the MMCs that were created using the regular MMC production procedure. This occurred as a result of the reinforcement being distributed uniformly throughout the material and the tiny microstructure. In addition, the technology of additive manufacturing can be applied to construct MMC lattice structures and geometrically complex components of MMC items. Additionally, it can be utilized to generate bulk MMCs with a substantially lower porosity. According to what was stated earlier, it has been noted that a significant number of AM-fabricated MMCs have been made. These MMCs include titanium matrix composites, aluminum matrix composites, nickel matrix composites, and iron matrix composites, amongst others. Both the technology and the parameters of additive manufacturing (AM) are highly dependent on the types and contents of reinforcements that are chosen. This, in turn, has an impact on the qualities of the MMCs that are produced by AM. Orowan strengthening, load transfer strengthening, dislocation strengthening, and Hall–Petch strengthening are all examples of different sorts of strengthening processes that have been identified in such MMCs. These four separate pathways have been identified as strengthening mechanisms. There are, however, a number of drawbacks that exist between the AM technologies and the regular manufacturing techniques, and these drawbacks can be solved for the properties of MMCs. Nevertheless, there are a lot of opportunities for improvement. Despite this, there are still more challenges to overcome: concerns about AM-produced MMCs, including their intrinsic properties in connection with AM technologies, new methods and tools for studying them, and AM process problems. Only these are some of the issues being addressed at this critical time. Thus, the paper finishes by examining AM of MMCs' difficulties and future interests. This concludes the paper. This article mentions additive manufacturing, feedstock, metal matrix composites, microstructure, and performance.

How to Cite: Maaz Bahauddin Naveed (2026) Preparation, Performance and Issues Associated with Metal Matrix Composites that are Produced by Additive Manufacturing Procedures. *International Journal of Innovative Science and Research Technology,* 11(6), 3546-3585. https://doi.org/10.38124/ijisrt/26jun2045

I. INTRODUCTION

The term "metal matrix composite" (MMCs) is used in composites to describe the close relationship between reinforcement and continuous metal matrix. MMCs can be classified by matrix material (titanium, aluminium, magnesium, copper, nickel, and cobalt) and reinforcing material (particles, fibres, whiskers) [3–5]. MMCs can be classified this way, making this classification method practical. MMCs can be made from many materials, each with a category. Over the past few decades, MMCs have garnered worldwide interest. Most of this is due to their ability to maintain the reinforcements' stiffness and strength while improving the metallic matrix's toughness and ductility. Their prosperity stems from this. High modulus, strength, wear resistance, and high-temperature performance are typical of MMCs. Only few of their features are listed. Another benefit of MMCs is their wear resistance. It has been shown that most circumstances have these traits. According to [1, 6-10], MMCs are used in many industrial applications.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

They are widely used since they have been rigorously tested as a material choice. This is partly due to their exceptional traits. Discontinuously reinforced Al matrix composite fans are used in many applications [9]. These applications use these fans. These fan exit guide vanes are used in many applications. The Boeing 777 uses the Pratt & Whitney 4000 series. The series is an application.

[11-15] MMCs are often made using these methods. Learn more about these methods here. Powder metallurgy, stir casting, forging, diffusion bonding, and infiltration are used. These are some technologies used. Additional procedures include infiltration. The fabrication processes outlined in the previous paragraphs require many stages to complete the manufacturing process. The machining process must be considered alongside the MMC process when evaluating the item's shape and dimensions [16]. For goal achievement, this is crucial. For the requisite manufacturing cost increase, MMC component production costs must be increased. This is necessary for the desired increase. Some MMCs, especially those with titanium matrix, may have moderate thermal conductivity but high chemical reactivity. This is especially true for titanium matrix ones. This applies notably to titanium matrix-based products. This is possible. In other words, undesired chemical processes during machining do not improve the material's machinability [17]. Powder metallurgy is used to make metal matrix composites (MMCs). Throughout this process, many problems arise, especially in the reinforcement-metal matrix interactions. [14] Insufficient bonding across surfaces and uneven reinforcement distribution in the metal matrix are two of these issues. Both issues are related. Both circumstances are difficult. To increase MMC properties after manufacturing, post-processing procedures include surface and thermal treatments [18, 19]. Thus, these methods are widely used. These treatments improve MMCs. This is essential to achieving success. Recently, attempts have been undertaken to overcome these limitations and reveal MMCs' potential. These attempts aim to do both. These efforts aim to illuminate the issue. These continued efforts achieved the desired results without any issues. MMCs could be made using additive manufacturing (AM), an alternative manufacturing method [20]. The advancement of additive manufacturing led to this technology. A lucky turn of events led to our current situation.

In 1986 [21], additive manufacturing (AM) technology were introduced. These technologies allow the direct manufacture of 3D components from CAD models without intermediate steps. AM technology is also called additive manufacturing. AM technology is also called additive manufacturing. These additive manufacturing processes enable more complex component forms. This wasn't before. These technologies also lessen the obstacles in conventional production processes, reducing their need. This would considerably reduce energy and material waste involved with producing the intended components [22–25]. The benefit would be significant. These technologies could eliminate labour-intensive post-processing, benefiting the environment. In general, additive manufacturing technologies can eliminate these processes. High-level designs for lean production can be made without losing quality. This is possible because CAD models are easy to build. Many applications require these benefits, and additive manufacturing is an appropriate fabrication method [26–31]. These applications show that these benefits are needed. These applicants want these perks.

It is vital to note that additive manufacturing processes for MMC development offer additional benefits beyond their basic features. Reinforcements can be added to additive manufacturing in two ways. These two methods are incompatible. Pre-mixing the reinforcement and metal matrix powder can be done in several ways to ensure homogeneity in additive manufacturing feedstock. This allows goal achievement. Ball milling and mechanical mixing are popular methods. Popular methods include ball milling. The additive manufacturing approach yields MMCs with consistent reinforcing distribution [32]. This conclusion is reasonable. It is possible to get this conclusion. Reinforcements can be absorbed into the powder by powder feeders, integrated or fused into the metal matrix powder, or inserted via an additive manufacturing method. After mixing, the particles can be melted with heat. This additive manufacturing method allows control over the proportional mass of the reinforcement and metal matrix powder [33]. There are other additive manufacturing methods, but this one is superior. This can be achieved by adjusting the powder feeder feed rate. This strategy achieves this purpose. Due to this advantage, functional gradient MMCs [34] are conceivable. Doing so has many benefits, including this. In-situ reactions create specific reinforcements during MMC manufacture. The manufacturing process aspect being considered is important. Effective and efficient in-situ reaction management is essential for making reinforcements. Because of the above reason. Additive manufacturing (AM) allows energy input to be adjusted by modifying production parameters [35]. Changes to processing settings enable this. Thus, preventing undesired chemical interactions between the additive and matrix is possible. Because the additive and matrix interact, this happens.

Many thick MMCs have been produced via additive manufacturing [6, 18, 19, 36–38]. There are MMCs made of titanium, aluminium, iron, nickel, and cobalt, among others. These MMCs' capabilities offer hope for the future. The PM generated by AM of MMCs has garnered attention for most of the past few years. Individuals are fascinated by this curiosity. As confirmed, a detailed investigation into AM-produced MMC developments and research has been conducted. The latest scientific discoveries and achievements are described in this field overview research. In this concept, additive manufacturing (AM) technologies are used to make metal-metal composites (MMC). This category includes MMC feedstocks, reinforcements, characteristics, and applications. This category also covers MMC. This research also examines M MC strengthening processes. This topic is being researched. This analysis also considered these findings' opportunities, challenges, and prospects. AM-produced MMC research results informed this review. This comprehensive assessment also considers research results.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

➢ *Available AM Technologies for Producing MMCs*

There have been a number of different additive manufacturing (AM) technologies that have been developed and applied in the process of constructing MMCs throughout the course of the past few decades. (6) [6] In order to guarantee the creation of MMCs that have superior performance attributes, it is essential to fulfill the requirement of achieving a homogeneous distribution of reinforcement. Nevertheless, the manufacturing of MMCs is not feasible with all AM technologies since each AM technology operates on a different processing principle. This is the reason why MMCs cannot be produced. When it comes to additive manufacturing technologies, the most typical types of feedstocks that are utilized include sheets, wires, whiskers, fibers, and particles. In situations in which wires and sheets are used as feedstocks, it is of the utmost importance to incorporate potential reinforcement, such as particles, fibers, or whiskers, prior to the production of the wire or sheet.

During the manufacturing process of wire or sheet feedstock, there is always the risk that plastic deformation will take place. This might result in reinforcement in the material that is not uniform [40]. In order to participate in the production of the Al–7Si–Cu–Mg composite ingots, which were then extruded and re-drawn into wire feedstocks, Deng et al. [41] developed in-situ Ti B2 particles as a reinforcement. These particles were used in the process. The purpose of this action was to address the matter that was being addressed at the time. It was not possible to find any forms of reinforcing that were dispersed in an optimal manner within the consecutive wire feedstocks. In the fabrication of high-performance MMCs, it is strongly advised that the reinforcement be distributed in a manner that is not equally distributed throughout the material. Powder-based additive manufacturing technologies have been the most straightforward way for the creation of MMCs up until this point since they were first introduced. We will explore the numerous powder-based additive manufacturing techniques that can be utilized in the following sections, as well as the applications that can be applied in the case of the fabrication of MMCs. These procedures and applications will be discussed in detail.

➢ *Powder Bed Fusion (PBF)*

Additive manufacturing is a way of shaping components that involves the selective melting of powder layer by layer using heat sources such as a laser or the energy beam associated with an electron gun (e-beam) [39, 42-46]. PBF can also be used for additive manufacturing, which is another means of shaping components. There are two major groups that may be distinguished within the PBF technologies. These groups are determined by the heat source that is utilized in the additive manufacturing process. Laser PBF, which is also known as selective laser melting (SLM), and electron beam PBF, which is also known as electron beam melt-ing (EBM) [47-50] are two examples of the groups that fall under this category. When it comes to LPBF fabrication methods, this is typically performed by utilizing a protective atmosphere that is made of argon (and occasionally N2) [48, 51-53]. Alternatively, when it comes to EBPBF operations, this is accomplished by operating under vacuum circumstances [47, 54]. The powder layer goes through a process of rapid fusion after the pre-deposition of the powder layer, which is based on a CAD model that has already been generated. This process involves scanning the powder layer with either a laser or an electron beam until the powder layer is completely scanned. There are a number of processing characteristics that can be used to control the effect of balling, porosities, and cracks. These parameters include layer thickness, beam power, scanning speed, scanning methods, hatching space, and the temperature at which the platform is preheated. Furthermore, the influence can be reduced by setting the process parameters in the most optimal manner so as to achieve the best possible results [55, 56]. In the body of research that has been conducted, it has been extensively recorded that parts that were made by PBF and had a porosity of less than 0.5% have been utilized, for instance [57–63]. During this interim period, PBF has the potential to be exploited for a wide range of materials, including metals [64, 65], ceramics [66], and composite materials [36, 67]. Nevertheless, this list does not contain everything. In comparison to the precision of parts generated by other additive manufacturing technologies, the accuracy of the parts that are developed by this technology will be considerably higher. As a consequence of this, the PBF approach is a method that is both good and prospective for the manufacturing of metallic plastic composites.

Depending on the PBF processes, the feedstock materials could be a composite powder or a mixture of substances. Both of these variations are possible. It is possible to use either of these two arrangements. In many cases, it is possible to state that the reinforcements are included exactly as they were before the PBF procedure [68]. This is because all of the reinforcements are included in the same manner. Obviously, there are a few instances in which this rule is not followed. High-energy heat sources that are produced by PBF technologies can be exploited to provide aid to in-situ reactions and, as a result, to provide in-situ reinforcement. This is possible because of the possibilities that these technologies present.

Several reports [36, 69] suggest that this phenomena occurs between the metal matrix powder and additions. These reports imply that this phenomenon occurs. Additionally, the reinforcements can be produced in the processing chamber by utilizing reactive gasses and interacting with the matrix particles of a metal [70]. This is another possibility. One more possibility is shown here. PBF is well known for its high level of accuracy in its manufacture, despite the fact that it has a relatively low production rate. Consequently, PBF is especially helpful for components that have a convoluted shape because of its simplicity. To add insult to injury, the PBF process makes it possible to reuse all of the feedstock materials, which in turn makes it possible to achieve a high level of material utilization [71]. As a result of the considerable cost of the feedstock for the composite, it is of the utmost importance to minimize the production cost, which is necessary in recycling. It is essential to reduce the costs of production as much as possible. In addition to the powder-based fabrication (PBF) technique, there are other additive manufacturing (AM) methods that are accessible that can be

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

applied in the creation of MMCs.

- *Direct Energy Deposition (DED)*

DED technology is distinct from PBF technologies, which involve the construction of components by the utilization of blasted powder as feedstock material with a high energy source [72-74] and the scanning of the components in accordance with a pre-designed computer-aided design (CAD) model [75]. Additionally, this method is considered to be an advanced laser cladding approach in the literature [76 - 78]. When the DED process is carried out, the feedstock that has been deposited is subjected to melting in an environment that is shielded by inert gas, and a "active melt pool" is created. Approaches that utilize several nozzles allow for the simultaneous deposition of multiple materials [72]. Therefore, DED can be utilized for a wide range of materials, including composites, ceramics, and alloys [72, 73, in addition to 79–81]. On the other hand, DED brought up a number of problems, such as a low build accuracy, a poor surface polish, and the presence of partially melted powder on the components. Powder on the connected surface that has been partially melted may have an effect on the surface smoothness and, as a result, provide the surface a longer fatigue life [82-84]. Because of this, it is often necessary to apply post-processing treatment, such as hot isostatic pressing (HIP), heat treatment, and machining, in order to improve the performance of the parts that are generated by DED [85-87].

There are a number of benefits that are linked with the utilization of DED technology in relation to the manufacturing of MMCs. In DED technology, one of the most important features is the ability to deposit multiple materials simultaneously from multiple nozzles. This allows for the importation of many materials. Along with the feeding of metal matrix powder, this technique allows for the precise control of the quantity of reinforcement. This is accomplished by managing the amount of reinforcement that is fed into each feeding machine. This allows for the ratio of various materials to be monitored and adjusted accordingly. Especially during the DED process, the potential of adding numerous reinforcements can be added, and as a result, the creation of MMCs that contain multiple reinforcements might be made. The DED technique allows for the easy creation of FGMs of MMCs [34]. This is made possible by the strategic management of the powder feed rates that are accomplished during the process. As a result of the fact that the energy input density of DED is typically higher than that of PBF, the production rate of DED is typically higher than that of PBF [89]. Technology such as PBF and DED make use of a high energy source, which causes the materials to melt while the process is being carried out. Different additive manufacturing (AM) technologies, on the other hand, do not make use of a heat source but rather a liquid binding agent. This binding agent is responsible for mixing ingredients and generating MMC pieces through bonding.

- *Binder Jetting (BJ) Printing*

When it comes to the manufacturing process, there are two different methodologies that are applied. One of these methodologies is the BJ printing technique, which is the same process as the PBF technique and also utilizes the powder bed. During the BJ printing process, a liquid binding agent is applied to the surface of the surface that is being printed. This is done while the surface is being printed.

The powder bed in order to produce a pattern that gives the impression that it is presented in two dimensions [90-92]. The successive addition of the deposition of the binding agent results in the production of a three-dimensional component as the final consequence of the process. When it comes to the construction of components, the BJ printing approach can be applied to make use of any powder-based feedstocks, including but not limited to metals [93], ceramics [94], polymers [95], or composites [96]. Furthermore, a binder could be utilized as a binding agent in some situations. Furthermore, in contrast to other additive manufacturing techniques, BJ printing can be carried out in air, which considerably improves the AM's performance in terms of both speed and economies. This is because BJ printing can be done in air. On the other hand, in order to remove the binder from the final product, post-processing techniques (such as sintering, de-binding, infiltration, and powder removal) are required [98-101]. These treatments are necessary because of the binder. The binder leaves were removed from the parts that were formed by BJ in order to create pores. As a consequence, the parts that were created had pretty substantial porosities thanks to this removal. As a consequence of this, the employment of HIP for the objective of lowering porosity is acknowledged as a common process [102]. Additionally, it is not possible to obtain a theoretical density of one hundred percent in components that have been printed using the BJ printing process. This is because the BJ printing technique is not viable to achieve. Not only that, but even with a component that has been meticulously built, the mechanical qualities are not as good as those predicted by their numerical models [103].

Nevertheless, it is not feasible to carry out in-situ reactions throughout the entirety of the manufacturing process in BJ. Furthermore, in many circumstances, reinforcements are required to be pre-integrated in the feedstock. As a result of the fact that BJ contains this attribute, it is a superb pre-alloyed powder that has the potential to be exploited in the production of MMCs that have favorable performance characteristics. Despite the fact that the binder is lost during the post-processing (sintering) steps, it is still possible for in-situ reactions to occur after the binder has been removed. The BJ method, which involved the utilization of a carbon-containing binder in the production of the Inconel 625 alloy, was responsible for the generation of the carbides. In the course of the sintering procedure, Do et al. [101] made this discovery. Carbides were formed as a result of a reaction that took place between carbon and metals that were present in the alloy. More specifically, the elements that were responsible for the development of the carbides were Fe, Ni, and Cr. Additionally, the binder should be removed from it, which will lead to pores in the final goods and a reduction in the mechanical properties [103]. This is something that should be done. When it comes to the use of a binder in order to bond materials together, it is feasible to consider BJ to be analogous to PBF. This is because both

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

procedures include the utilization of a binder. BJ, on the other hand, makes use of a high-power heat source in order to make the process of bonding the materials together easier. Despite the fact that both the PBF and BJ technologies have shown extremely great capabilities in terms of manufacturing components with intricate geometry, the production rate for both of these technologies is somewhat lower than it is for the other technology.

- *Spraying Technology*

Compared to PBF and BJ, the production rate per unit of technology is high when it comes to the manufacturing of components, notably metals and MMCs. This is the case when comparing the two technologies. Especially in the case of metals, this is certainly the case. The strategies and procedures that are utilized for spraying may be broken down into two categories: heat spraying techniques and cold spraying techniques [105–107]. Both of these categories are referred to as spraying techniques. For the purpose of producing MMC components, the composite powder is utilized as the feedstock in each of these several processes. Heat sources such as flames, electric arcs, and plasma arcs are some examples of the types of heat sources that are utilized in thermal spraying tactics. It is possible to spray the powder in a partially fused state while it is in a gas that is moving at a high velocity using these procedures [108-110]. When the temperatures of these high-speed gases are between 1500 and 15,000 degrees Celsius, the temperature range of these gases is determined by the heat sources that are utilized [108, 110]. The powder particles are subjected to acceleration within a critical velocity range, which is between 500 and 1200 meters per second, while the cold spray process is being carried out. Next, this acceleration is put to use in the formation of a component by the utilization of a supersonic gas jet, all the while ensuring that the gas temperature remains relatively low during the spraying process [111]. There are two temperatures that can be used for spraying: room temperature and a low temperature (pre-heated), which is normally lower than 600 degrees Celsius [112]. As an additional point of interest, the impact and the deformation can be observed in the manufactured parts, which might result in pores and lamellar borders that have a negative effect on the performances [113, 114]. This is in addition to the processes of spraying with heat and spraying with cold. As

On the other hand, there are circumstances in which post-treatments, such as remelting or heat treatment, are necessary [109, 113]. When cold spraying is performed, the energy of the particles that are in flight is significantly boosted. This is another benefit of cold spraying. It is sufficient to break through surface oxides and build clean interfaces as a result of this process, which results in the formation of strong particle-substrate interaction as well as particle-particle interaction [115-117]. When compared to the components that are sprayed with heat water, those that are sprayed with cold water have a lower probability of having flaws. This is because cold water spraying provides a lower temperature. When it comes to the selection of the appropriate spraying method, on the other hand, it is necessary to do a thorough analysis of the numerous types of feedstocks that could be applied in order to achieve the highest possible level of performance from the MMCs.

Through the usage of thermal spraying or cold spraying techniques, pre-alloyed powders have the potential to be utilized as feed-stocks in the production of MMCs and mixed powders [115, 118]. This is a possibility that can be utilized in the production of MMCs and mixed powders. It is feasible to carry out reactions in-situ while the process is being carried out, as indicated in [119]. This is made possible by the employment of a heat source. In particular, additives have the ability to react during the spraying process, which can lead to the production of reinforcements in the parts that are made. This can be detrimental to the quality of the parts. Not only that, but it has also been reported that there have been instances of reactions of the spray gases that took place during the process of thermal spraying, in which the spray gases transformed into reinforcements [120]. Reactive gases, on the other hand, have a propensity to have a negative impact on thermal spraying equipment, particularly with regard to the anode nozzle. This is because reactive gases have the ability to react with other gases.

The spraying additive manufacturing technique, on the other hand, is distinct from the other additive manufacturing technologies in a number of ways, the most important of which being the precision with which things are manufactured. Nevertheless, the manufacturing of coating is quite effective, and as a result, it is more ideal for applications of this kind. CAD can also be used in the context of spraying additive manufacturing (AM); however, the things that are made are often less accurate than those that are generated through the use of other AM technologies like as PBF and DED. Spraying additive manufacturing (AM) is a form of additive manufacturing using spraying. Molten pools are always discovered on the surface of the part during the PBF and DED procedures, and they can also be noticed during the manufacturing process [121]. Molten pools always appear on the surface of the part. When spraying in the morning, on the other hand, there are no pools of molten water on the surface of the water. The feedstock material is either molten or semi-molten when it reaches the nozzle of the additive manufacturing equipment that is used for spraying, and the molten or semi-molten in-flight particles are sprayed onto the "sub-strate" in accordance with a path that has been pre-designed [122]. As a result, it is not possible to provide an assurance that the in-flight particle deposition that is envisioned in the design will actually take place.

On the other hand, any technology will have a limited number of benefits and drawbacks, and it is crucial to select the method that will result in improved MMC production. Both of these aspects are important to consider. In the following table, a selection of the additive manufacturing (AM) technologies that are applied in the fabrication of MMCs as well as the processing mechanism are presented.

II. FEEDSTOCKS AND REINFORCEMENTS

- *Feedstock*

Powders are the main feedstocks for modified molecular compounds [38, 6]. Despite using powder, wire,

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

and sheet in additive manufacturing to create metals and alloys. Definitely, this attracts a lot of attention. Due to additive manufacturing, many composite powder materials have been used [18, 123-126]. These procedures include satellited, gas-atomized, mechanically combined, and ball-milled powdering. Figure 1 shows that these four powders are most commonly utilised. Mixing reinforcing and metallic powders creates gas-atomized powder (figure 1(a)) [18]. Making composite ingots includes melting and gas-atomizing them.

Table 1 Different Powder-Based Additive Manufacturing Technologies for Fabricating Metal Matrix Composites, the Feedstock Used, the Processing Mechanisms, Advantages, and Disadvantages.

Technology	Processing mechanism	Advantages	Disadvantages
Powder bed fusion	The powder is partially melted or fully melted in a powder bed, and the melted or semi-melted powder is solidified at a significantly fast cooling rate	High accuracy, high material utilization, and minimal machining; some reinforcements can be *in-situ* synthesized	Low production rate, the even-distributed reinforcements may not be reached using the mechanically mixed feedstock
Direct energy deposition	The blown powder is supplied into a scanning laser path and melted to produce a component	High production rate; additives can be added during the process with controllable content; some reinforcements can be *in-situ* synthesized	Relatively high production rate, poor surface finish, and low accuracy
Binder jetting	The jetted binder bonds the spread powder layer-by-layer; no heat source is used; post-treatments are always required.	It can be conducted at room temperature and in an atmospheric environment	High porosity, poor surface finish, and low accuracy; parts have limited shapes and extra adhesive residue
Spraying technology	The powder is sprayed at a high velocity; the powder is deformed and melted depending on the heat resource used	High production rate; it can be conducted at room temperature and in an atmospheric environment	High porosity, poor surface finish, very low accuracy; parts have limited shapes; the even-distributed reinforcements are very difficult to achieve using the mechanically mixed feedstock

Composite powder. Gas-atomized powder generally exhibits good flowability and sphericity but is expensive [37, 127]. Mechanically mixed powder is generated by rotating a mech-anical mixer for several hours, resulting in unevenly distrib-uted reinforcements in the MMCs due to the non-attached or detached particles (figure 1(b)) [123, 128–131]. Mechanically mixed powder often shows poor wettability, resulting in the instability of the melt pool during the AM process [132]. The ball-milled powder subjected to ball milling is obtained through hardened milling balls, which are processed via either a planetary ball mill or a ball-tube mill. The process is strictly controlled to prevent deformation or non-attachment of rein-forcements in the final composite powder (figure 1(c)) [133, 134]. It has been reported that gases can become trapped inside the particles during the powder atomization process, forming pores [135]. Ball milling is effective at sealing these pores [20]. However, ball milling can adversely affect the surface finish of MMC components. AlMangour *et al* [136] also found that ball-milled powder exhibits more extensive and severe cracking than directly mixed powder. However, the directly mixed powder demonstrates the presence of deep grooves and pores.

Satellited powder, also known as wet granulation, is pro-duced by adding a small amount of binder, such as polyvinyl alcohol, to the blender of metal particles and reinforcements, followed by gyroscopic mixing to obtain the desired powder (figure 1(d)) [125, 137]. Although satellited powder exhibits a higher level of reinforcement attachment, the poor adhe-sion of the binder can still result in unsatisfactory adhesion of reinforcements. Mechanically mixed powder, ball-milled powder, and satellited powder have inferior flowability and sphericity compared to gas-atomized powder. Therefore, the gas-atomized composite powder is a good choice for fab-ricating high-performance MMCs. However, the production cost of gas-atomized powders is significantly higher than those of other composite powders, necessitating consider-ing the performance-cost tradeoff. Table 2 lists the advant-ages and disadvantages of these types of composite powders.

International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165
https://doi.org/10.38124/ijisrt/26jun2045

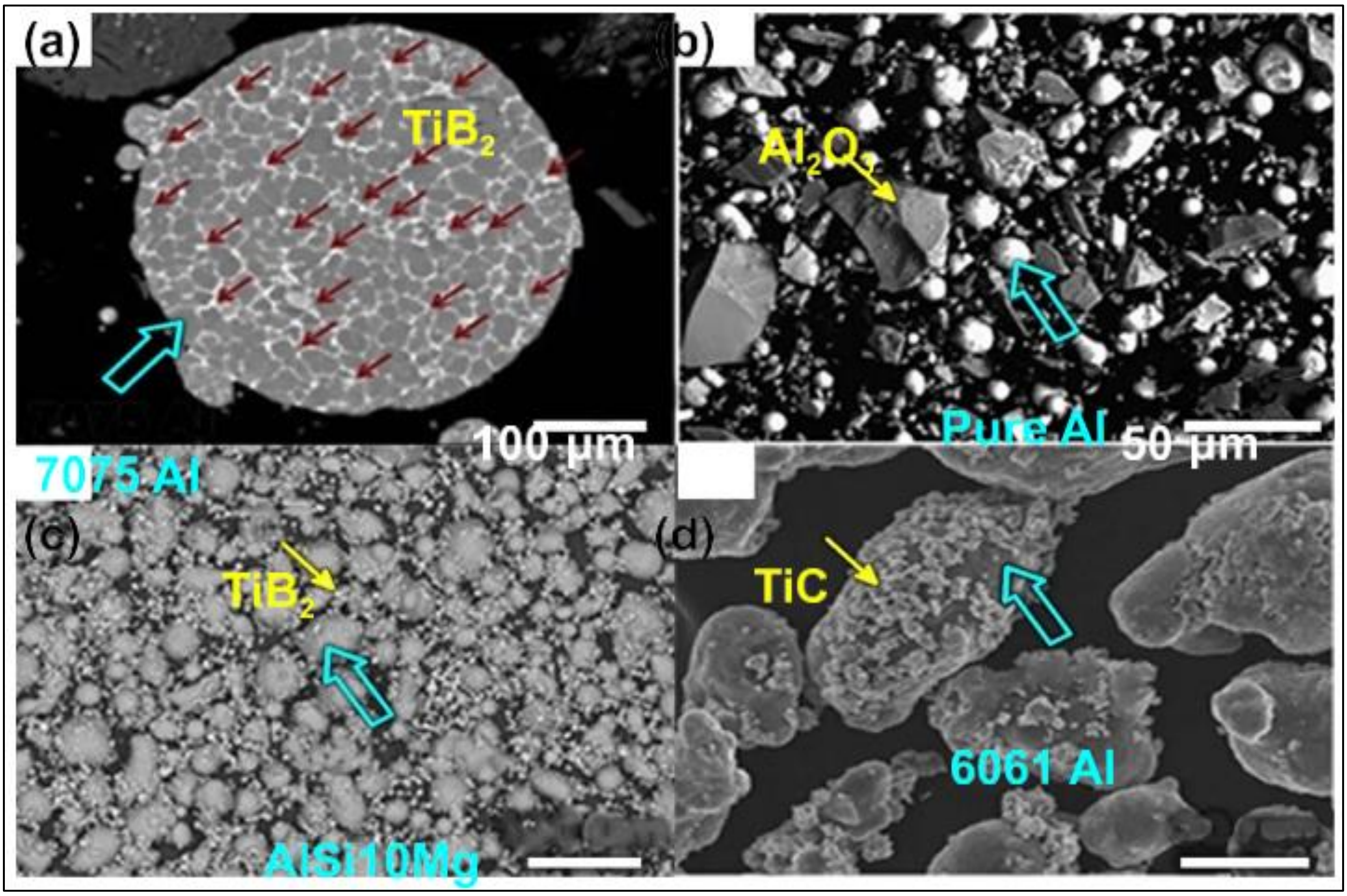

Fig 1 Four types of composite powders available for additive manufacturing processes: (a) gas-atomized powder, (b) mechanically mixed powder, (c) ball-milled powder, and (d) satellited powder. (a) Reprinted from [18], © 2019 Elsevier B.V. All rights reserved. (b) Reprinted from [123], Crown copyright © 2010 Published by Elsevier B.V. All rights reserved. (c) Reprinted from [124], © 2021 Elsevier B.V. All rights reserved. (d) Reprinted from [125], © 2019 Published by Elsevier B.V.

Table 2 Various Feedstocks Used for Producing Metal Matrix Composites, Methods, Advantages, and Disadvantages.

Feedstock	Method	Advantages	Disadvantages
Gas-atomized powder	Gas atomization	Evenly distributed reinforcements, strong bonding of the reinforcement and matrix, high flowability, and sphericity	High cost
Mechanically mixed powder	Mechanical blending	A wide range of the content of reinforcement, simple operation, low-cost	Particle size limitation, almost no interface bonding, non-uniformly distributed reinforcements, poor wettability, inferior flowability
Ball-milled powder	Mechanical ball milling	Good controllable weight fraction, dimension, and distribution of reinforcements, a good interfacial bonding, sealing of pores in powder	Impurities possibly introduced during milling, complex than mechanical blending, particle morphology change
Satellited powder	Wet granulation	Increased level of reinforcements with even distribution	Complex than mechanical blending, binder remained, poor interface bonding, inferior flowability

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

These composite powders employ distinct methods to integ-rate the metal matrix powder and reinforcements. The specific approaches vary in their techniques for achieving a homogen-eous mixture, ensuring proper distribution of reinforcements within the metal matrix. The subsequent section will delve into the unique characteristics of these reinforcements, exploring their role in enhancing the properties of the resulting MMCs.

- *Reinforcements*

Incorporating reinforcements is an important factor that influ-ences the fabrication and properties of MMCs, as it serves to refine their microstructures and inhibit the formation and propagation of cracks [129, 138–140]. For MMCs to exhibit high performances, the reinforcements should possess high thermal stability and hardness and be compatible with the metal matrix. Successful MMC design of the AM proced-ure requires the consideration of numerous factors, including the chemical composition of reinforcements, the natural oxide film, the flowability of feedstock, and processing parameters during the AM process. MMCs produced using AM and con-ventional methods can be categorized based on two methods of introducing reinforcements: *ex-situ* and *in-situ* [38, 141]. The *ex-situ* method involves adding the reinforcements to the metal matrix before the AM process. In contrast, the *in-situ* method produces reinforcements during the AM process via the *in-situ* reaction between the metal matrix and additives.

Compared with the *ex-situ* method, the *in-situ* method can promote the nucleation and growth of reinforcements and prevent the formation of interfacial products [128, 142]. *In-situ* reinforcements are also more uniformly distributed. The *in-situ* reinforcements can be exemplified by the pro-duction of TiB/Ti composites, where TiB is generated by the *in-situ* reaction between TiB_2 and Ti matrix [143]. The mixture powder comprises TiB_2 particles surrounding the Ti particles (figure 2(a)). During the process, the *in-situ* reaction results in the generation of TiB (figure 2(b)). Although some unreacted TiB_2 particles remain, the resulting TiB particles are evenly dispersed.

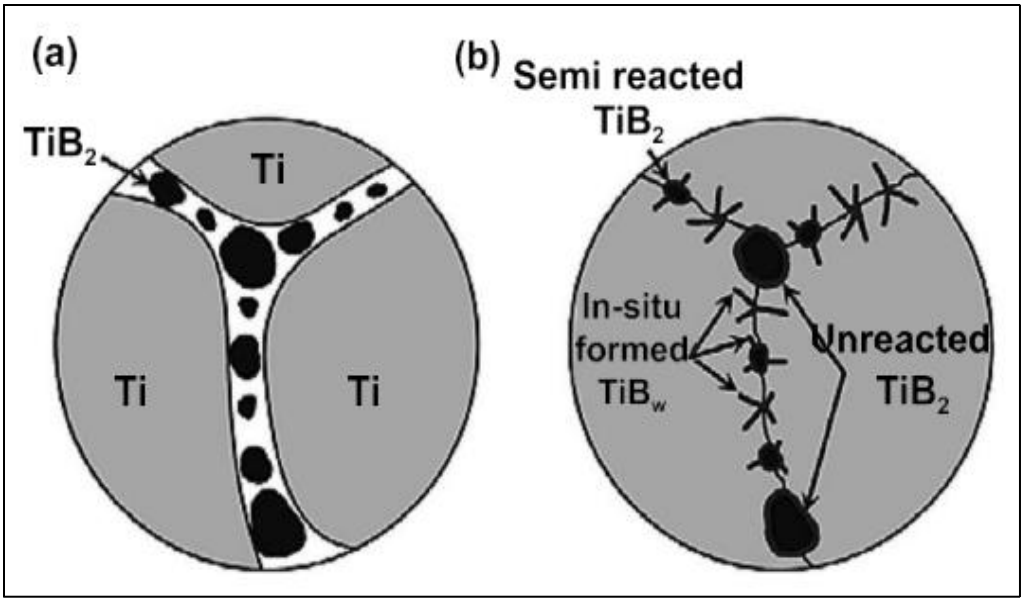

Fig 2 Illustration of the generation of TiB particles via the *in-situ* reaction between Ti matrix and TiB_2: (a) TiB_2 particles surrounding the large Ti powder in the powder mixture (b) *in-situ* formed TiB, semi-reacted TiB, and unreacted TiB_2 particles [143]. [8 January 2017], reprinted by permission of the publisher (Taylor & Francis Ltd, www.tandfonline.com).

Notable is the fact that the processing settings have the potential to influence the reaction that occurs in situ. The in-situ approach also has an intriguing advantage for the construction of MMCs, which is that it allows for the realization of strong interfacial adhesion between the reinforcements and the metal matrix. This is accomplished as a result of the in-situ reaction, which is documented in a number of references [144, 145]. This indicates that MMCs that are manufactured in-situ are generally superior in terms of their qualities when compared to those that are manufactured using the ex-situ method [144,145]. However, this is accompanied by instability of the melt pool of materials during the in-situ reaction of AM, which causes the addition of additional heat, which in turn results in excessive evaporation and powder splash [36, 146]. As a result, the metallurgical process, the thermal history of the materials that are going to be joined, and the composition of the additives and matrix should all be taken into consideration and properly specified throughout the materials system design process for in-situ composites during additive manufacturing.

When choosing the type of reinforcements that will be utilized with MMCs, it is important to take into consideration a broad variety of parameters, such as size, morphology, the coefficient of thermal expansion (CTE), and the elastic modulus (EM).

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

Table 3 Characteristics of Widely used Reinforcements or Additives.

Reinforcement or additive	Crystallographic structure	Thermal expan-sion coefficient ($\times 10^{-6} \cdot K^{-1}$)	Elastic modulus (GPa)	Melting point (K)	References
TiB_2	Hexagonal	$\alpha_a = 6.6$, $\alpha_c = 8.6$	560	3498	[154]
LaB_6	Cubic	4.9	227	2988	[155]
CaB_6	Cubic	6.5	379	2373	[156]
TiB	Orthorhombic	8.6	550	2333	[157, 158]
TiC	Face-centered cubic	7.42	400	3340	[159]
SiC	Cubic	3.8	430	3243	[160]
B_4C	Rhombohedral	4.5	450	2723	[159]
TiN	Face-centered cubic	9.4	250	3223	[161]
AlN	Hexagonal	4.5	310	2500	[162, 163]
BN	Hexagonal	1.1–8.6	44–68	2973	[164]
Si_3N_4	Hexagonal	2.4	320	2173	[159, 163]
Al_2O_3	Hexagonal	8	400	2316	[159]
B	Icosahedron	8.2	400	2573	[165]
Hydroxyapatite	Hexagonal	9.9–10.6	60–100	1887	[166–168]

A number of significant aspects to take into consideration include the crystalline structure, the wettability, and the in situ reactivity with the metal matrix. The size and form of the reinforcement is a significant issue for the ex-situ process [147]. This is because it has an effect on the dispersion of the reinforcement in the mix, and as a consequence, it has an effect on the characteristics of the composite materials that are created as a result of the process. [147] Saba and colleagues carried out study with the purpose of determining the effect that the size of the diamond powder had on the titanium matrix. An average-sized diamond powder with a size of 5 nanometers was found to be capable of greatly improving the strength and ductility of in-situ composites, according to discoveries made by the researchers. Interactions with structural flaws and the reduction of grain development from the powder were the means by which this was accomplished. A mismatch in the CTE and elastic moduli of the reinforcement and the matrix can also result in the formation of dislocations that are known as geometrically required dislocations (GNDs). These dislocations are generated when the reinforcement and the matrix do not match up. It is possible that the strength of the composites could be further improved by these dislocations [148, 149]. It is important to take into account the fact that the reinforcement and the matrix have different coefficients of thermal expansion (C.T.E.). This is something that should be taken into mind. This disparity has the potential to cause residual stresses at the interfaces, which can play a role in the development of fractures [150]. The crystallographic structure of the reinforcement is able to exert control over the heterogeneous nucleation of the melt during the solidification process [151]. This is made feasible by the lattice mismatch with the metal matrix, which also makes it possible for the reinforcement to have this control. In order to illustrate this point, the TiB2 ceramic particles have the ability to build a structure that is homogeneous. The TiB2/Al-12Si composite that was manufactured by LPBF is the component that makes up this structure. It is composed of extremely minute equiaxed grains that have random orientations. The formation of this structure takes place when the lattice is matched with the Al matrix to the fullest extent that is considered practicable [151]. It is feasible to improve the interfacial strength between the reinforcement and the metal matrix by employing an ideal wet-tability for molten metal matrix [152]. This can be accomplished by utilizing the ideal wet-tability. Finally, but certainly not least, the reinforcements that are obtained in the composite are defined by the reaction that takes place between the additives and the metal matrix during the in-situ processing approach [153]. This is the most important aspect of the composite.

In table 3, the characteristics of the additives and/or reinforcements that are utilized the most frequently are presented, and in table 4, the characteristics of the metal matrix that is utilized the most frequently are listed and discussed. The features of the additives and the metal matrix can be taken into consideration when designing new MMCs. This is something that can be done. In order to optimize the chance of achieving MMCs through additive manufacturing techniques, it is essential to make a well considered choice for a metal matrix that is appropriate and to contain the necessary additives. Either work integration is now taking place or it is being facilitated at this same moment. The development of additive manufacturing technology is currently experiencing the implementation and/or realization of a considerable number of successful work integration examples. This is currently taking place.

This type of printing has the capability and potential to be used in the production of advanced composite materials, as evidenced by the fact that it has been reported that MMCs can be printed.

- *Matrix Materials*

Metallic powder are the main feedstocks for AM process. Through the powder characteristics like particle size distribution, the flowability and the sphericity a pivotal role in influencing the spread ability and recoat ability during the AM process has been played by the consistency of the printing. These factors can significantly affect the parts densifications, microstructures and performances. Except for pre-alloyed composite powder, other composite powders, such as mechanically mixed powder, ball-milled powder or satellited powder, all come from the powder of matrix

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

material. Therefore, the properties of the metal powder used as matrix for the fabrication of the composite feedstocks are very crucial including particle size distribution, the sphericity, flowability and the chemical composition of the metal matrix powder. The particle size distribution is the proportionality of particle size of different particle sizes in the powder, which affects the amount of packing, melting of the particles, and particle flow [172-174]. There are unique requirements for the particle size parameters of powders in AM technologies [175]. Sphericity is a measure of the closeness of the particle geometry to the spherical shape where there is minimal surface friction traction; this will result in improved flowability of the particle to the solids, spreading behavior and packing density, which will be optimum in the spherical geometry [176]. Powder mobility (flowability) is also a characteristic of flowability which greatly affects the homogenous powder deposition, thus the regular layer thickness, density and uniform energy assimilation, augmenting the density and functional attributes of the product generated [177]. The chemical composition of a composite material is therefore of the highest importance as it can cause dramatic changes in density, phase distribution and perform-ance even with changes as small as a few per cent [178]. Therefore, the Every single one of the aforementioned properties of the metal matrix powder has a big influence on the qualities of the feedstock that is utilized in the material that is employed to make the composite. Without a doubt, when compared to the impact that the metal matrix powder with a wide particle size distribution has on the characteristics of the matrix composite products [179], it is evident that the preparation of feedstock by the metal matrix powder with a restricted particle size distribution is distinct from the previous example.

Table 4 Characteristics of Frequently Employed Metal Matrix Materials.

Metal matrix	Crystallographic structure	Thermal expansion coefficient ($\times 10^{-6}\cdot K^{-1}$)	Elastic modulus (GPa)	Melting point (K)	References
Pure Ti	Hexagonal	9.4	116	1923	[165]
Ti6Al4V	Hexagonal (α-Ti)	8.8	115	1951	[169]
Al	Face-centered cubic	23.2	25	933	[165]
Fe	Face-centered cubic	12.2	200	1808	[170]
Ni	Face-centered cubic	13.1	207	1728	[165]
Co	Hexagonal	12.5	211	1766	[165]
Cu	Face-centered cubic	18.7	117	1356	[171]

MMCs make use of a wide variety of metal matrices, such as aluminum, titanium, nickel, cobalt, and a variety of metal alloys, as was previously mentioned. Powder of metal matrix can be produced using a variety of techniques, the most common of which are gas atomization [180], electrode induction melting gas atomization [181], and vacuum induction melting gas atomization [182]. Centrifugal atomization [185], plasma rotating electrode technique [186], and even water atomization [184] are some of the other processes that can be utilized. However, regardless of the processes that are used to generate powders, there is a broad consensus that the price of powders that are utilized in AM printers is fairly high [71]. This is the case regardless of the procedures that are utilized. In light of this, the substantial potential to reduce the cost of the powders continues to be a crucial stage in the process of fabricating the powders in order to achieve cost efficiency. This is because the powders are required for the manufacturing process. It is possible to reduce the costs that are associated with powder by reusing the powder once the additive manufacturing process has been finished. However, it is vital to bear in mind that the recycled powder may display a variety of physical and mechanical characteristics, such as differences in chemical composition, particle size distribution, and flowability [187, 188]. This is something that must be kept in mind at all times. During the additive manufacturing process, it is believed that the shift that takes place is due to the interaction that takes place between the powder and the heat resource involved in the process. As a consequence of this, it is absolutely necessary to take extreme caution when making use of recycled powder for the purpose of incorporating composite feedstock. This is because the result may be different from that of composite feedstock that is generated using virgin powder. This is the reason for this.

The majority of researchers have used virgin powder as a feedstock for the aim of making the composite. This is because virgin powder is easy to work with. Very never, if at all, is the utilization of recycled powder brought up in conversation. Powders that have been recycled are used more frequently, even after they have been commercialized [189, 190]. This is because recycled powders are more cost-effective than other powders. Following the advice given in reference [191], it is still beneficial to have an understanding of the distinction between fresh powder and recycled powder. Within the scope of their research [71], Huang and Yan investigated the particle size distribution, sphericity, and flowability of the powder that was put back into usage. Both an increase in the generation of spatters and a decrease in the amount of microscopic particles are two of the concerns that are associated with recycling and have the potential to impact the altered characteristics of the powder [192, 193]. Both of these issues are related to the problem of recycling. As a consequence of this, the flowability and sphericity of the recycled powders are lower than those of the fresh powder [71]. Additionally, the particle size distribution of the recycled powders is shifted onto the right. This occurs due to the fact that recycled powders are manufactured from recycled resources. Powders that have been employed in the past are typically sieved, or airflow is utilized, in order to

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

knock spatters that have become dislodged. This is done in order to lessen the influence that the spatters have on the environment. Under these circumstances, the particle size distribution of powders that have been reused would shift to the left, and the sphericity and flowability of the powders would have been restored [192, 194, 195]. As a result, recycled powders, which have been subjected to the necessary recycling processes, possess particular qualities that are entirely different from those of virgin powder. Regarding the process of preparing composite feedstock, it is essential to take into consideration the characteristics of the powder that will be utilized in the process. In addition to this, it is strongly recommended that the composite feedstock be subjected to enhanced quality control, and that the metal matrix powder be characterized in great detail.

III. AM OF MMCs

➢ *Aluminum Matrix Composites (AMCs)*

AMCs, on the other hand, have qualities that are comparable to those of both reinforcements and aluminum alloys. It is because of these qualities that they are able to be more durable and rigid than other forms of MPS, and they also have a certain degree of resistance to wear [68, 196–198]. As a consequence of this, AMCs have evolved into widely used lightweight materials that are utilized in a wide range of industrial sectors. In general, powder metallurgy or melt processing are two methods that can be utilized in order to produce classic AMCs [199-206]. In spite of the fact that they display prospective features, it has been discovered that conventional AMCs have a number of limitations, such as the non-uniform distribution of reinforcements, a poor link between the matrix and the reinforcement, and a large amount of porosity [207–209]. In recent times, the utilization of additive manufacturing (AM) technology for the production of particle-reinforced alumina matrix composites (AMCs) has been strongly proposed as a potential solution to these challenges. In contrast to conventional AMCs, AM-produced AMCs have a low porosity, a very uniform distribution of reinforcement, and a clear contact between the matrix and the reinforcement. These characteristics distinguish AM-produced AMCs from their conventional counterparts. SiC, TiC, AlN, BN, Si3N4, Al2O3, ZrO2, and TiO2 are some of the materials that are included in the list of materials that are utilized in AMCs the most commonly [38, 124, 210].

Among the several types of AMCs, carbides are the reinforcement that is utilized the most frequently. The tensile characteristics of LPBF-produced TiC/AlSi10Mg composite and LPBF-produced AlSi10Mg alloy were compared in the research that was carried out by Gu et al. [211]. Several comparisons and contrasts were made between the findings of this investigation. Their findings indicated that the TiC/AlSi10Mg composite that was made utilizing LPBF has a tensile strength that was 52MPa higher than the other composite. This was demonstrated during the course of their investigation. Greetings, Mr. Raj Mohan *et al* [212] prepared NbC/AlSi10Mg composites with different NbC particles by LPBF.

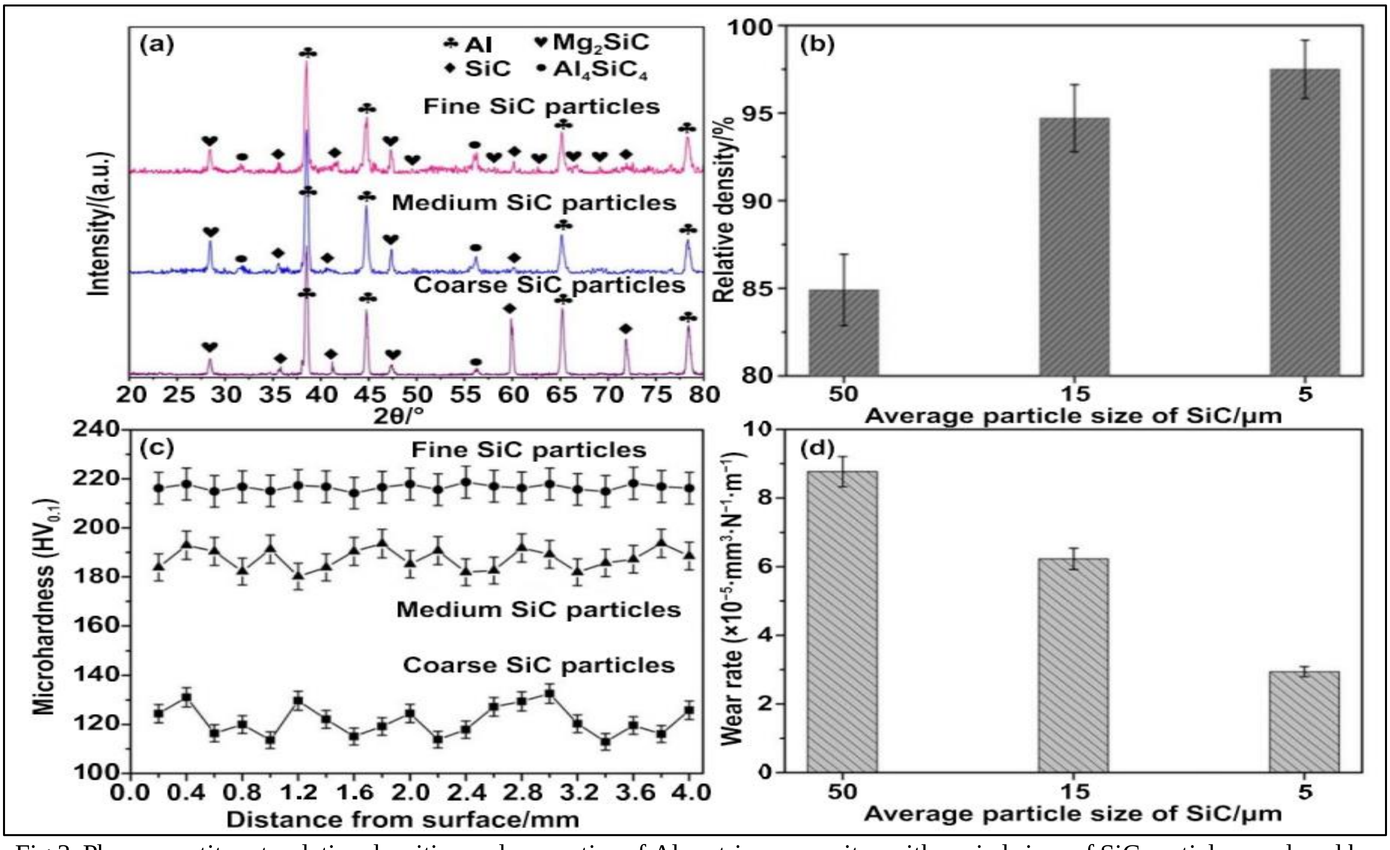

Fig 3 Phase constituent, relative densities and properties of Al matrix composites with varied sizes of SiC particles produced by laser powder bed fusion: (a) XRD patterns, (b) relative densities, (c) hardness, and (d) wear rates. Reprinted from [213], Copyright © 2015 Elsevier B.V. All rights reserved.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

Compared to the unreinforced LPBF alloy, the NbC/AlSi10Mg composites made with LPBF had better tensile strength, hardness, and wear resistance. The composites' improved mechanical characteristics showed this. The results shows that NbC incorporation does not reduce composite grain size. Furthermore, the dispersion strengthening mechanism was one of the main processes that strengthened mass-produced NbC/AlSi10Mg composites using the LPBF process. Careful analysis revealed this. The intriguing phenomenon Chang et al. [213] observed has been discovered. After that, they used SiC particles of various sizes (5 µm, 15 µm, and 50 µm) to create AMCs. These AMCs were combined with AlSi10Mg powders.

The LPBF method is used to manufacture these components to ensure quality. Figure 3(a) shows that only composite samples made with fine and medium-sized SiC particles show the in-situ reaction products, Al_4SiC_4. This shows that in-situ reaction products can be positively recognised. Despite having the same 20 weight percent SiC and LPBF process settings, the composite with the larger SiC particle size has a lower relative density (figure 3(b)). The composite's decreased relative density shows this. Thus, this composite material has reduced hardness and more wear (figures 3(c) and 3(d)). This is visible. Tiny particles (SiC) can be added to the melt to start an in-situ reaction, increasing interfaces [214]. Introduce SiC particles. In other words, the number of sections of the initial particle size amplifies in-situ processes that create additional reinforcements. Even though the laser only contacts with SiC particles briefly, they remain unmelted. Silicon carbide particles are huge. The laser will scan the molten tracks, disturbing them and creating discontinuities [214, 215]." The molten pool's viscosity and surface tension are high, so the melt flow is extremely turbulent. This melt flow is disorganised, resulting in a dispersed thermal energy and mass distribution. The melt pool is destabilised by the events that create huge holes near the SiC reinforcements and extensive balling. The melt pool becomes unstable. Thus, choosing the right reinforcing particle size for additive manufacturing is crucial.

More reports of in-situ reactivity in additively produced composites (AMCs) have been made. This is in addition to direct reinforcement. Yi et al. [69] started the LPBF method with CP-Ti, B_4C, and AlSi10Mg particles. Powder was made from this mixture. The composition of B_4C-Ti particles ranged from 0.7 to 17.2%. Both percentages were present. The local surroundings reacts strongly.

CP-Ti/B_4C interfaces cause AMCs to generate TiB_2 and TiC. CP-Ti and B_4C at 0.7 weight % increased the composite's tensile strength after unreinforced laser powder bed fusion (LPBF) of AlSi10Mg alloy. The composite's tensile strength rose after adding these components. Composites' tensile strength depends on CP-Ti and B_4C content. This connection is due to the two variables' relationship. According to the findings, adding additives increases the exothermic response of natural environmental responses. This phenomenon affects the remelting interface between melt pools and increases the viscosity of the molten pool to be melted. Increased melting temperature causes this viscosity rise [20]. These conditions cause a larger molten pool, higher liquid phase temperatures, and longer pool stays. It promotes consistent melt AlSi10Mg distribution and material densification [216]. Both perks are appealing. However, when operational temperature rises, reinforcements grow and become more numerous. This is because they operate at higher temperatures. Tensile stress causes brittle fracture, reducing tensile strength. This breakdown is easily caused by soft aluminium and harsh reinforcements. Crack initiation and spreading are easy in this interface.

Xi et al. [217] used LPBF to make (ZrC + TiC)/Al composites. These composites were created from aluminium, zirconium, and titanium carbide powders. The technique would produce a phase of (Ti, Zr)C from the LPBF's in-situ reaction between ZrC and TiC. This helps build a tight link to the aluminium matrix [218].

Figures 4(a)–(e) show that the LPBF-synthesised (ZrC + TiC)/Al composite had equally dispersed zirconia and titanium carbide particles. The figures show this. Figures 4(f) and (j) show TEM examinations of TiC and ZrC particles. These particles have good interfaces. The study developed alloys with a relative density of 99.5 ± 0.1 percent, comprised of Al-Cu-Ag-Mg-Ti-TiB_2. These alloys were crack-free. Samples were used in several ways. Figures 5(a) to (c) show that TiB_2 reinforcements, ranging from 0.1 µm to 1.3 µm, were mostly equally distributed throughout the sample. As seen in Figures 5(d)–5(f), the Al_2Cu phase is at grain borders and the TiB_2 particles are within grains. Coherent interactions with the Al matrix separate the Al_2Cu and TiB_2 particles (figures 5(g) and (n)). Table 5 shows more AMC properties created with AM and filled with a variety of reinforcement materials.

In addition to reinforcement-induced dispersion strengthening, the differential in thermal expansion coefficient between the metal matrix and reinforcements causes GNDs in MMCs. This is because reinforcements modify thermal expansion coefficient. Heat cycling causes matrix and reinforcement relative expansion and contraction [221]. Due to the complex interaction of the metal matrix and reinforcement, GND inclusion is critical when producing MMC microstructures and mechanical properties. Because the metal matrix and reinforcing are involved. After that, the freshly generated GNDs block the formation of other GNDs, reinforcing the metal matrix (dislocations). The equation [222] can be used to express dislocation strengthening:

$$\Delta\sigma_M = MBGb\rho^{\frac{1}{2}} \quad (1)$$

Where G is the shear modulus of the matrix, b is Burger's vec-tor, M is the Taylor factor, B is a constant coefficient, and ρ is the dislocation density. ρ is respectively derived from the mis-match in the CTE and EM, which could be given by [6, 223]:

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

$$\rho^{EM} = \frac{6V_P}{(br)^3} \qquad (2)$$

$$\rho^{CTE} = \frac{12\Delta T \Delta\alpha V_P}{br(1 - V_P)} \qquad (3)$$

Faces between the Al matrix and reinforcements, the Ti, Zr, and Al elements change gradually, as illustrated in figures 4(h) and (k). The mechanical tests conducted indicate that the pro-duced composites exhibit enhanced strength and wear resist- ance. Well-bonded interfaces between the matrix and rein-forcements resulting from *in-situ* reactions play a critical role in determining the performance of the composite. However, the *in-situ* reactions are often exothermic. Such heat input pro-duces an extra factor influencing the overall AM process [69]. Therefore, the design of MMCs should comprehensively con-sider all potential factors.

Other reinforcements, including multiple types, have been employed in the fabrication of AMCs by AM technologies. For example, Wang *et al* [124] used ball milling to prepare TiB_2/AlSi10Mg feedstock, which was subsequently used in the LPBF process to produce TiB_2/AlSi10Mg composites. The porosity levels of the produced composites are highly depend-ent on the milling dose, which indicates the milling progress and is regulated as the ratio of the impact energy transferred to the powder mixture from the mass of milled powder [219]. The resultant TiB_2/AlSi10Mg composite exhibits a density of 99% at the milling dose of 275 W s g^{-1}, improving tensile strength (450 MPa) and ductility (7.2%). Mair *et al* [220] used gas-atomized Al–Cu–Ag–Mg–Ti–TiB_2 powder in the LPBF

Where ρ^{CTE} and ρ^{EM} are the dislocation densities resulting from the mismatch in the CTE and EM, respectively, of the matrix and reinforcement, ΔT is the difference in the pro-cessing temperature and ambient temperature, $\Delta\alpha$ is the dif-ference in the CTE between the matrix and reinforcement. For $\Delta\sigma_M$, the calculations from ρ^{CTE} and ρ^{EM} are required, respectively. In [222], Gao *et al* used LPBF to produce a TiN/AlSi10Mg composite. They observed the generation of numerous dislocations within the Al grains, which interacted with intragranular TiN particles (figures 6(a) and (b)). The observed dislocations result from the thermal stresses from rapid solidification during LPBF and the mismatch in CTE between the metal matrix and reinforcement [224, 225]. High-resolution TEM images of the TiN/Al matrix and Mg_2Si/Al matrix interfaces (figures 10(c)–(f)) reveal various phases of TiN, Mg_2Si, and Si with different plane spacing, resulting in the production of GNDs that contribute to the dislocation

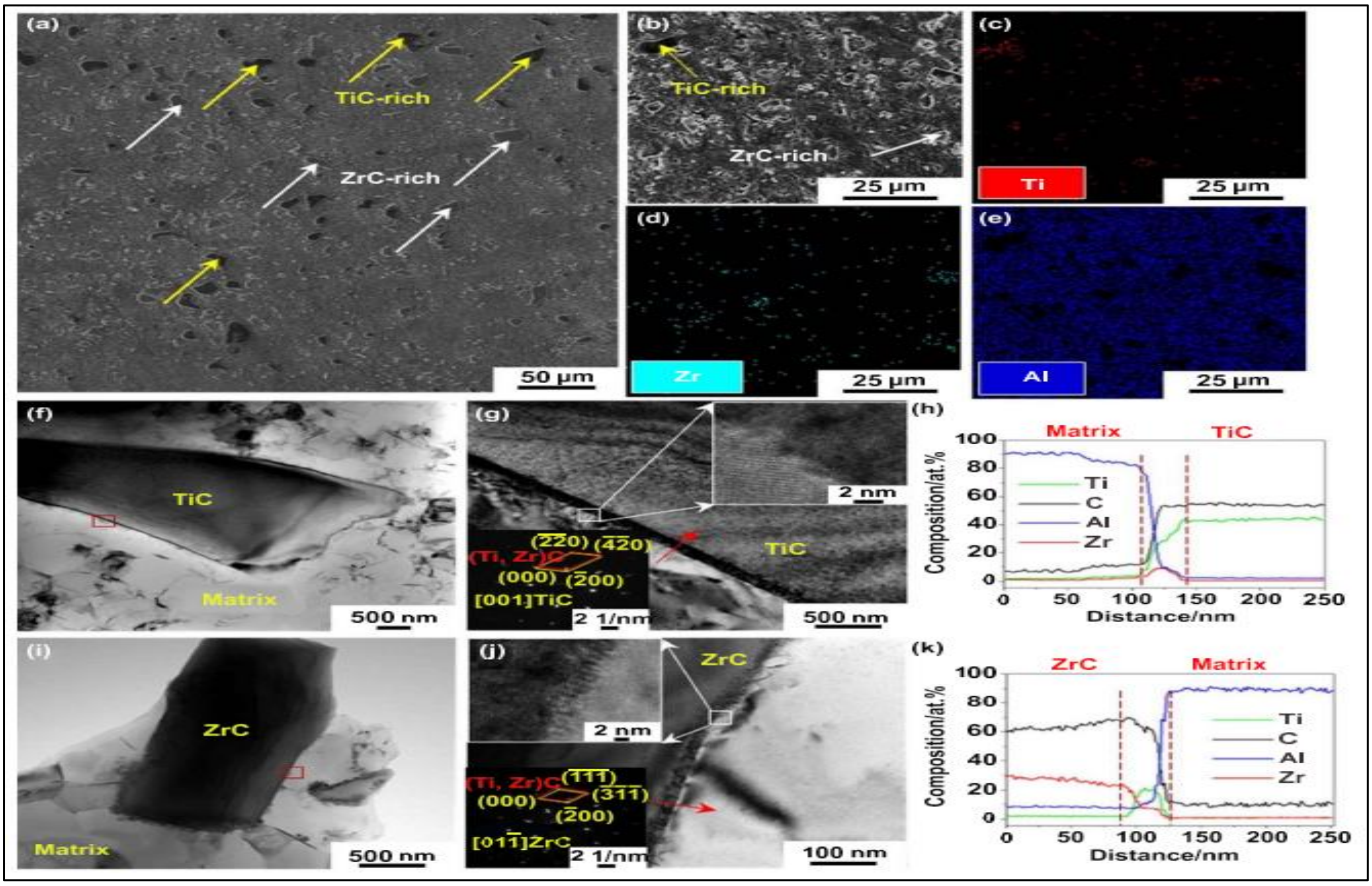

Fig 4 Microstructural features of (ZrC/TiC)/Al composites produced using laser powder bed fusion: (a) and (b) are SEM images, (c), (d), and (e) are EDS mapping of Ti, Zr, Al in (b); (f), (g), (i), and (j) are TEM images of TiC and ZrC particles in the Al matrix; the HAADF images of interfaces as marked by rectangular are indicated using the insets in (g) and (j); (h) and (k) are EDS results of line scan in (g) and (j) along with the red arrows. Reprinted from [217], © 2022 The Authors. Published by Elsevier B.V.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

AMCs are undergoing a strengthening process. For the purpose of determining the ΔσM in the TiN/AlSi10Mg composite that was generated, Gao et al. [222] employed the equation mentioned above. The value of M was determined to be 3.06 for the face-centered cubic crystal after careful consideration. In the case of aluminium, the value of ρ is determined to be 1.14 × 1014·m−2, the value of B is 1.25, the value of G is assumed to be 26.5 GPa, and the value of b for aluminium is 0.286 nm. The value of the TiN/AlSi10Mg composite that was made by LPBF was approximately 12 MPa, as determined by the computed ΔσM. The dislocation strengthening mechanism does play a significant role in the process of strengthening the MMCs; however, thermal stresses, which are caused by the differential CTE between the metal matrix and the reinforcements, have the potential to cause cracking and interlayer debonding. This is despite the fact that the dislocation strengthening mechanism plays a significant role in the process's overall success. This tendency is made worse by the fact that residual stresses are more pronounced in the direction that is orthogonal to the direction that is being scanned as opposed to the direction that is parallel to one another [226]. This has the effect of making this tendency considerably more severe. Because of this, it is essential to do so.

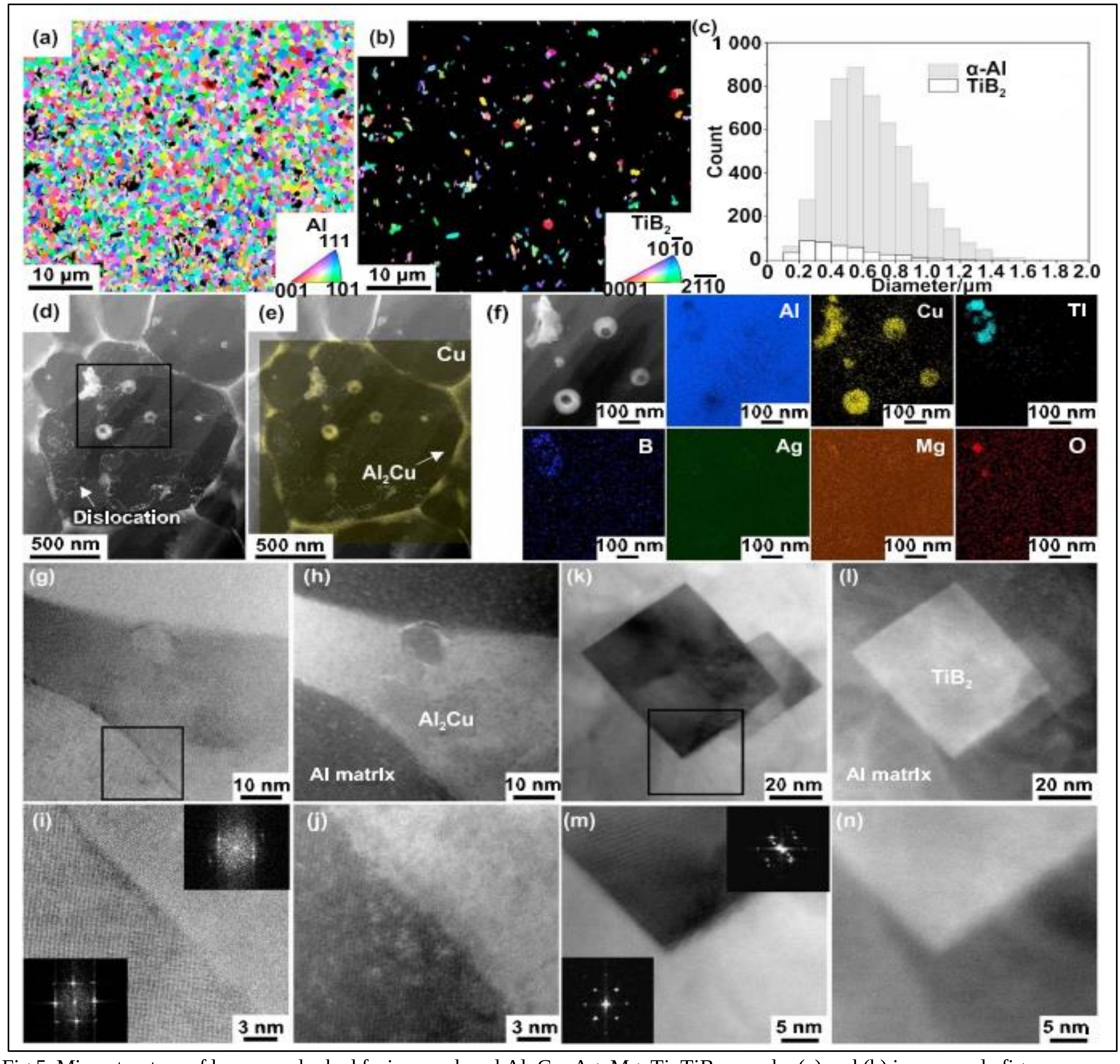

Fig 5 Microstructure of laser powder bed fusion produced Al–Cu–Ag–Mg–Ti–TiB_2 sample: (a) and (b) inverse pole figure maps of Al and TiB_2 grains; (c) size distributions of Al and TiB_2 grains; (d)–(f) scanning transmission electron microscopy (STEM) in high-angle annular dark field (HAADF) and energy disperse spectroscopy results of Al–Cu–Ag–Mg–Ti–TiB_2 sample showing the distributions of Al_2Cu and TiB_2 grains; (g)–(n) STEM in HAADF images of the interfaces of Al_2Cu and TiB_2 with the Al matrix; the insets in (i) and (m) are fast Fourier transforms from Al, Al_2Cu, and TiB_2 grains. Reproduced from [220]. CC BY 4.0.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

In order to lessen the amount of stress that is left over after processing, it is essential to make thoughtful adjustments to the processing settings.

Additionally, the manufacture of AMC coatings often includes the application of thermal spraying technology. This is a significant factor. Xie et al. [18] were able to create a novel coating for 7075Al that was enhanced with nano-TiB2 particles by employing cold spray additive manufacturing with atomised TiB2/7075Al composite powder. This allowed them to construct the coating. An improvement in the mechanical characteristics of the sprayed TiB2/7075Al composite coatings is brought about as a consequence of the uniform dispersion of TiB2 nanoparticles within the composite powder. Hardness, elongation, and tensile strength are some of the qualities that are included here. When the same spraying conditions are used, this improvement is in comparison to the attributes of the coatings made of 7075 aluminium that were sprayed. Zhang et al. [227] was able to construct in a manner that was comparable.

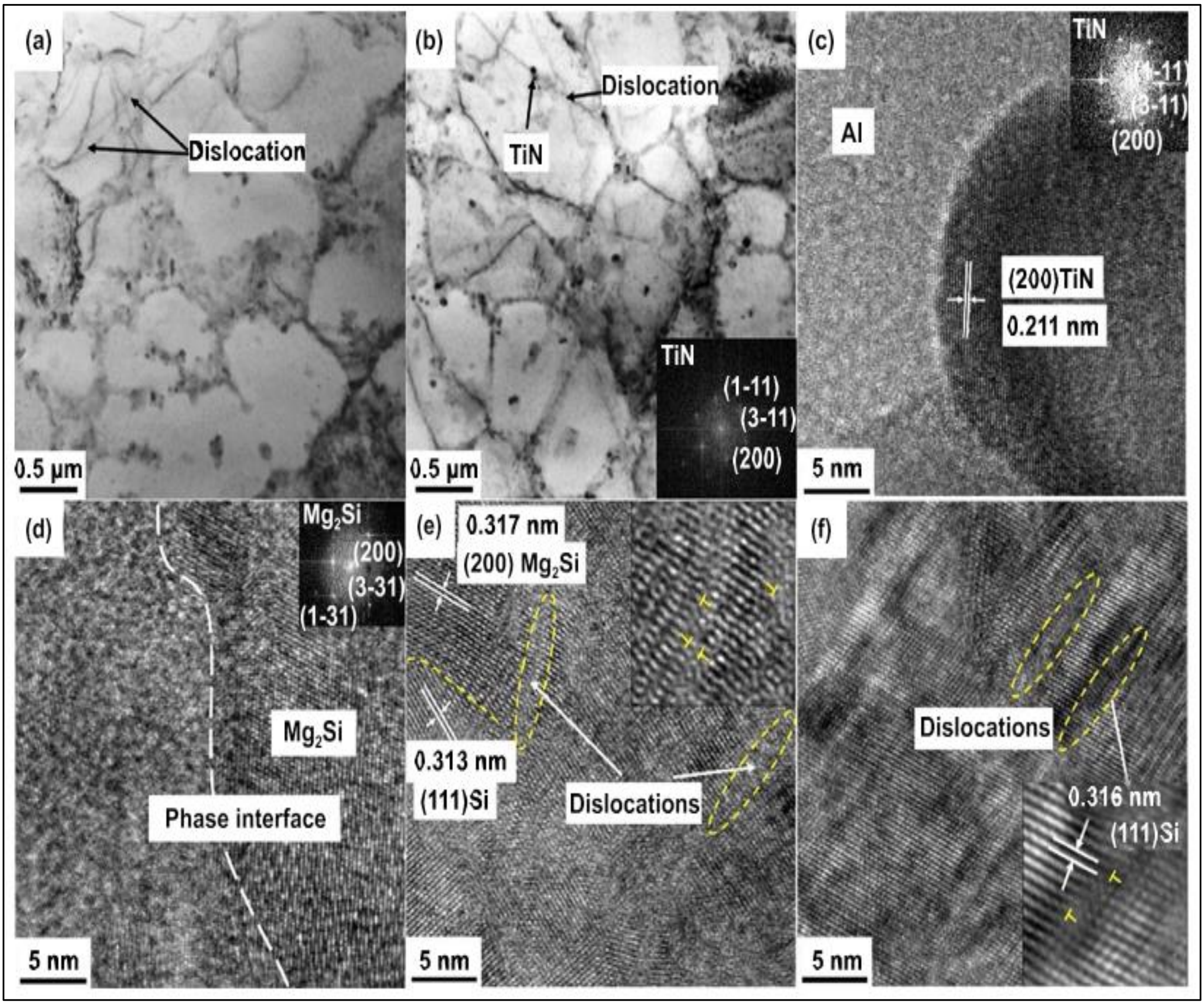

Fig 6 TEM images of microstructures of a TiN/AlSi10Mg composite produced by laser powder bed fusion: (a) bright-field images exhibiting the dislocation tangles in Al grains, (b) interactions of dislocations and TiN particles, (c) HRTEM image of the TiN/Al matrix interface, (d) HRTEM image of Mg2Si/Al matrix interface, (e) and (f) are HRTEM images of Mg2Si, Si, and Al phases with dislocations. Reprinted from [222],

The application of carbon nanotube (CNT)-reinforced aluminium composite coatings to AZ91 magnesium alloy was accomplished through the utilisation of ball-milled powder and cold spray additive manufacturing.

Al4C3 was produced in the powder mixture and MMC coatings in their initial condition as a result of the integration of carbon nanotubes (CNTs), which led to the formation of the powder mixture. During the course of their investigation, the researchers made the observation that the 'Al4C3' phase attachment was present in the end of the carbon nanotubes (CNTs) that were dispersed throughout the matrix. There is a possibility that the exposed carbon atoms, which are the source of the unclosed end of carbon nanotubes (CNTs),

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

could function as a rich source of carbon, which would result in the formation of the Al4C3 phase at the interface. In addition to this, the creation of the Al4C3 phase is a factor that leads to the formation of a "chemical bond" between the carbon nanotubes and the aluminium powder. On the basis of the tribology test, it has been observed that the wear resistance quality of the CNT-Al composite coating is higher than that of the Al coating. This was accomplished by comparing the two coatings. In Figure 7, we have an illustration of the sliding wear process that takes place in both the Al coating and the CNT-reinforced Al composite coating. The higher wear resistance is thought to be connected to the high hardness of the Al4C3 phase, in addition to the fact that Al debris is changed into Al2O3, according to the hypothesis. The amount of surface area that the CNT-reinforced Al composite coating has in contact with the friction pair is reduced as a consequence of this occurrence. The wear-resistant property was actually achieved through the creation of the tribofilm in the CNT reinforced Al composite coating. This was the way by which the property was achieved. During the course of the tribology procedure, carbon was deposited on the surface of the sample, which allowed for the successful completion of this task.

When aluminium composite coatings are subjected to thermal spray abrasion micromachining, one of the issues that makes it difficult to avoid premature failure is inadequate bonding between the particles [229-231]. This is one of the causes that makes it difficult to avoid premature failure. It is of the utmost importance to mention that this is one of the elements. Therefore, Post-FSP is frequently used after the production of coatings in order to further improve the qualities of the coatings. This is done in order to achieve the desired results. Through the utilisation of cold spray additive manufacturing, they were able to create composite components that were composed of AlSi10Mg and TiB2/AlSi10Mg. After friction stir processing was performed on the composite pieces, Xie et al. [229] carried out the procedure. As can be observed in figures 8(a) and (b), respectively, they made the discovery that the margins of the Al grains contain eutectic Si particles in addition to TiB2 clusters that are unevenly spread. This can be seen in both images. A homogeneous distribution of these extremely minute silicon nanoparticles is achieved through the precipitation process that takes place within the supersaturated aluminium. In the post-friction stir processing, silicon particles are dispersed both at the borders of the aluminium grains and among the aluminium grains themselves (figures 8(c) and (d)). This is the consequence of the processing. A large magnitude of deformation is experienced by the material in the stir zone, which leads to a high density of dislocations in the material. Every single one of the FSP tests exhibits this effect. The energy that has been stored in such dislocations makes it necessary for dynamic recovery and recrystallisation to take place while the deformations are still taking place. As a result of the assimilation of the fine Si particles, the size of the grains that are already present in the matrix will shrink. Enhanced UTS values of 295 MPa for the AlSi10Mg alloy and 365 MPa for the TiB2/AlSi10Mg composite are attributed to the fragmented TiB2 that was obtained after the post treatment of the parts (figure 8(e)). This factor is accountable for the increased UTS values.It is the"

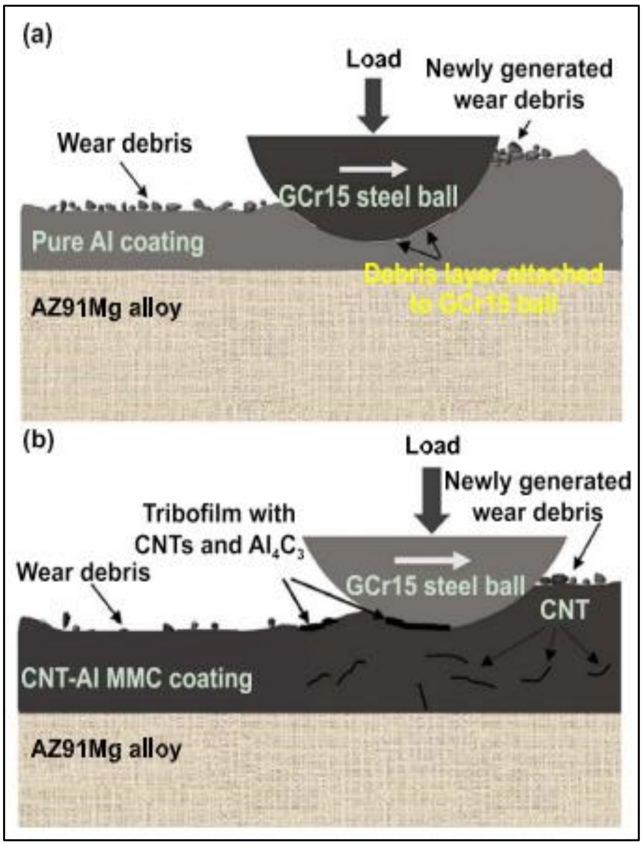

Fig 7 Schematic Illustration of Sliding Wear of (a) Al Coating and (b) Carbon Nanotube Reinforced Al Composite Coating. Reprinted from [227], © 2020 Elsevier B.V. All Rights Reserved.

As indicated in figure 8(f), TiB2/AlSi10Mg has slightly better work-hardening. Clearly, post-treated components have a great balance between ductility and stability. Similar investigations are done in [230, 231]. Cold-sprayed Al2O3/Al composite coatings have lower porosities due to post-friction stir processing, which homogenises their microstructures. [230, 231] This process homogenises coatings.

Steel is the most extensively used material in industry, but aluminium alloys are second. The most common material is steel. To address the aluminium alloy scarcity, aluminium metal composites (AMCs) have been extensively developed. In addition to the examples in this article, AM AMC manufacture has been investigated extensively. These investigations are documented. This table shows AM-produced AMC mechanical parameters and typical production behaviours. This table also displays its contents in a table. AMCs made from AM have a larger reinforcing content and are also increasing in strength [69, 232–239]. This is happening as AM-created TMCs become stronger. Notably, LPBF AMCs are stronger than DED AMCs [240–242]. Although it is crucial to emphasise the major impact that processing factors have on AMC properties, variations in processing parameters can result in material properties that are significantly different [211, 243–245]. Feedstock

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

preparation also affects composite performance [236–238, 246, 247]. Pre-alloyed powder is used to make composites, which perform better than manually mixed or ball-milled powder [236–238]. As noted, well-boned interfaces between the metal matrix and reinforcements reduce fracture nucleation locations. Information offered before supports this idea. Starting with feedstock preparation, well-boned interfaces between the metal matrix and reinforcements can be considered. This is possible.

- *Titanium Matrix Composites are "TMCs".*

Titanium metal Composites (TMCs) use titanium alloys and other reinforcing materials. TMCs are robust and strong in addition to being heat-resistant. These materials could replace titanium alloys in aeronautical, chemical, medical, maritime, and other domains [269-275, 126]. Conventional TMCs can be continuous or discontinuous reinforced, depending on the situation. However, continual strengthening is needed to withstand heat sources like lasers and electron beams. This reinforcement includes carbon and silicon carbide fibre. Additive manufacturing produces discontinuous reinforced thermomechanical composites (TMCs) such particle-reinforced TMCs [48, 276–278]. High-modulus, high-strength carbide, silicide, oxide, and boride are common reinforcements in thermomechanical composites (TMCs). Reinforcements include TiC, SiC, Y2O3, TiB, TiN, and Ti5Si3 [38, 161, 279-282].

TiC has similar density, Poisson's ratio, and thermal expansion to titanium steel alloys. TiC comes from titanium dioxide. However, titanium carbide has far better modulus and strength than titanium alloys [279, 283]. This suggests titanium carbide is better. The lack of a response between titanium and titanium matrix in standard or additive manufacturing processes encourages the use of titanium carbide particles to make titanium metal carbide (TMC) [280, 284]. This is achievable because titanium and titanium matrix do not interact. Gu et al. [285] created TiC/Ti composites with weight percentages of 7.5, 12.5, 17.5, and 22.5 wt% via LPBF. This composite was created from ball-milled TiC/Ti powder. Titanium carbon and titanium composites have lower relative densities as titanium carbon increases. Due to greater titanium carbon concentrations. The most comprehensive characteristics of TiC/Ti composites are achieved at 12.5% weight percentage. This includes the high microhardness (HV0.2) and low friction coefficient (0.19). LPBF was used by Gu et al. [132] to make the TiC/Ti composite. The composite powder was ball-milled or mechanically blended with TiC/Ti powder. Both methods were used. The ball-milled powder-produced TiC/Ti sample's flow and mechanical characteristics were compared. Flow attributes reduced relative density compared to mechanical qualities. This may be due to the significant densification of ball-milled TiC/Ti powder during LPBF. Ma et al. [286] used DED and ball milled TiC-Ti powder to make composites. In the composites, 10–50% by weight of various titanium carbide (TiC) forms were found. A semi-coherent contact is seen between the TiC particle and α-Ti matrix. Figure 9 shows the orientation relationships of 11¯20 /[110]TiC and ¯1100 / ¯111, distinguishing this interface.

This promotes titanium nucleation and a tightly bound particle–matrix interface. TiC increases TMC hardness and wear resistance, but it also reduces due to a trend that is on the other end of the spectrum in terms of both their tensile strength and their elongation.

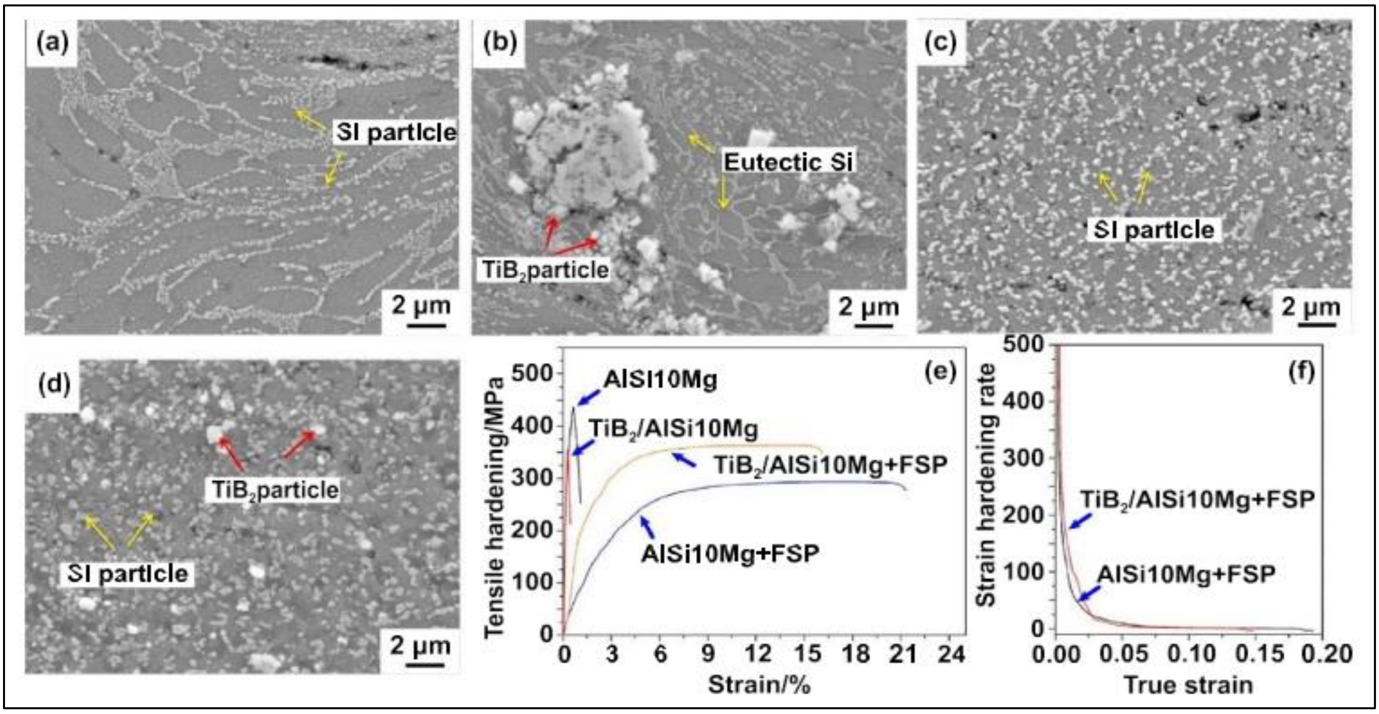

Fig 8 Scanning electron microscopy images exhibiting the cross-sectional morphologies of the cold spraying and cold spraying + friction stir processing samples: (a) and (c) AlSi10Mg; (b) and (d) TiB_2/AlSi10Mg composite; (e) tensile hardening and (f) strain hardening of the composites. CS denotes cold spraying, and FSP is friction stir processing. Reprinted from [229],

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

Through gas–liquid interactions and the use of CH_4, the in-situ laser additive manufacturing system that was recently created by Wei et al. [287] is able to produce nano-scale titanium carbide (TiC) without agglomeration. This is made possible by the utilisation of CH_4. The nanoscale TiC dispersions have a specific surface area that is substantially higher than that of conventional composite materials. As a consequence of this, the area of the interface between the particles and the matrix is significantly larger than it is in the typical composite materials.

A characteristic that is favourable to the formation of a pinning effect that is more intense [288]. As the quantity of CH_4 that is used increases, the mass fraction of TiC also increases. This, in turn, results in an increase in the yield strength of the composite material. On the other hand, it has been found that when the concentration of CH_4 is increased to 23 vol%, the composite material that is composed of TiC and Ti6Al4V experiences a decrease in its final compressive strength, as well as a reduction in its flexibility. The idea that an excessive amount of TiC addition results in a greater degree of brittleness in the composites is given more credence as a result of this tendency.

Through the utilisation of the succeeding reaction, TiB, in contrast to TiC, possesses the capability to engage in in-situ reactions during the creation of composites [289, 290]:

It is possible to calculate the product of Ti and TiB_2 as 2TiB (4).

- *A Total of Ti Plus B Equals TiB. (Five)*

Additionally, it is possible to achieve fine and homogenous TiB in the matrix through the in-situ production of TiB that takes place during the manufacture of composites [291]. This results in the construction of composites. In this way, the metal-lurgical bonding of the titanium dioxide (TiB) to the titanium matrix is guaranteed to be very effective. Because of this, there is a growing interest in the investigation of TiB in-situ reinforced AM-pieced thermomechanical composites (TMCs).

The rationale that was explained earlier is the explanation for this. An application of DED was employed by Hu et al. [289, 292] in order to manufacture TiB/Ti composites. In order to successfully produce a TiB/Ti composite, they made use of a mixture that included 1.6 weight percent B powder and 98.4 weight percent pure titanium powder with great success.

The composite was made with TiB that had a volumetric content of 8.5%. This was used for the fabrication process. In the event that the TiB particles are arranged in a network that is entirely quasi-continuous, the mechanical properties and properties of the material are enhanced. This indicates that there should be no regions in which the TiB particles are not arranged in a network arrangement that is quasi-continuous over the whole surface.

Using TiB_2 as the additive, Cai et al. [290] were able to synthesise TiB/Ti–6Al–4V composites in a manner that was comparable to the previous example. While the LPBF process is being carried out, the TiB_2 is transformed into a needle-like shape. There is a correlation between the amount of titanium dioxide (TiB) in composites and the rise in the equivalent material (EM) and hardness values of the composites. Due to the fact that TiB is included into the composition itself, this is the result. It was Pan et al.'s intention to incorporate TiB_2 into the EBPBF process in order to achieve their objective of generating composites composed of TiB/Ti–6Al–4V. The in-situ reaction that takes place between TiB_2 and the matrix results in the production of a quasi-continuous network of nanosized TiB whiskers within the composite microstructure. This network is generated as a result of the reaction taken place. In a TiB/Ti–6Al–4V composite that was made utilising the EBPBF process, this type of microstructural texturing has the ability to increase both the tensile strength and the plasticity of the material (figures 10(a) and (b)).

Dispersion strengthening is used in conjunction with this process to achieve this goal. An investigation revealed that the composite that was produced by employing EBPBF has the potential to be categorised as a TiB/Ti–6Al–4V composite composition. It was also revealed that the formation of whiskers made of titanium boron (TiB) occurred along the grain boundaries of the metal matrix that was created. Due to the fact that this presents a unique mechanism of fracture, the rate at which cracks propagate is slowed down as a consequence (figure 10(c)). Cracks are created by a substantial number of dislocations building up at the grain boundary interfaces of the TiB/Ti--6Al-4V composite that was manufactured utilising EBPBF.

This, in turn, explains the production of cracks, which are caused by the dislocations. The microsized TiB whiskers, on the other hand, were put to stress for the forged counterpart, which resulted in the production of microvoids. This caused the whiskers to split into small segments. Cracks start to emerge at these microsized whiskers of titanium dioxide as a consequence of this, and it is essential to take into mind the role that these whiskers play in the material breaking through. The improved tensile strength and ductility that were demonstrated by the TiB/Ti–6Al–4V composites that were generated by EBPBF can therefore be attributed to the material. This may be the case because the material was formed by EBPBF.

Table 5 Mechanical Properties of Additively Manufactured Aluminum Matrix Composites.

Composite	**Content of additive**	**Processing**	**Feedstock preparation**	***In-situ/ex-situ***	**Hardness (HV)**	**Yield strength (MPa)**	**Ultimate strength (MPa)**	**Fracture strain (%)**	**References**
Al_2O_3/Al	4 vol%	LPBF	Ball-milled	*Ex-situ*	48	109^{T}	160^{T}	—	[248]
Al_2O_3/Al	7.1–67.2 vol%	CS	Mechanically mixed	*Ex-situ*	60–94	—	—	—	[232]
SiC/Al	23–71 vol%	CS	Mechanically mixed	*Ex-situ*	62–88	—	—	—	[233]
B_4C/Al	42 vol%	CS	Ball-milled	*Ex-situ*	58	—	—	—	[249]
CNT/Al	0.5–1.0 wt%	CS	Ball-milled	*Ex-situ*	131–172	—	—	—	[250]
TiB_2/Al–12Si	12 wt% Si + 2 wt% TiB_2	LPBF	Ball-milled	*In-situ*	142	247^{C}	—	30.0	[251]
TiB_2/Al–12Si	2 wt%	LPBF	Ball-milled	*Ex-situ*	142	225^{C}	—	—	[151]
SiC/Al–12Si	20–60 vol%	CS	Mechanically mixed	*Ex-situ*	145–205	—	—	—	[234]
TiC/Al–15Si	1–10 wt%	LPBF	Ball-milled	*Ex-situ*	146–177	—	313–578^{T}	2.2–7.9	[252]
TiB_2/2024Al (solution	0.5 wt%	DED	Ball-milled	*Ex-situ*	109–134	120–223^{T}	354–454^{T}	4.4–20.7	[253]
treatment or aging) TiB_2/2024Al	3 wt%	DED	Mechanically mixed	*Ex-situ*	—	163^{T}	284^{T}	18.7	[240]
TiB_2/2024Al	3 wt%	LPBF	Mechanically mixed	*Ex-situ*	—	237^{T}	336^{T}	8.0	[240]
TiN/7050Al	0.18–0.54 wt%	LPBF	Ball-milled	*Ex-situ*	—	—	60–111^{T}	0.9–1.1	[235]
(TiN + Ti)/7050Al	2–6 wt%	LPBF	Ball-milled	*Ex-situ*	—	—	408–613^{T}	8.6–13.2	[235]
TiB_2/Al–Cu	4.7 wt%	LPBF	Pre-alloyed	*Ex-situ*	—	317^{T}	391^{T}	12.5	[254]
TiB_2/Al–Cu	4 wt%	LPBF	Pre-alloyed	*Ex-situ*	113	—	401^{T}	17.7	[220]
CaB_6/Al–Cu–Mg	2 wt%	LPBF	Ball-milled	*Ex-situ*	132	348^{T}	391^{T}	12.6	[255]
(TiC + TiH_2)/Al–Zn–Mg–Cu	1 wt% TiC + 0.8 wt% TiH_2	LPBF	Ball-milled	*Ex-situ*	—	297–485^{T}	356–593^{T}	7.5–10.0	[256]
Al_2O_3/6061Al	25–75 vol%	CS	Mechanically mixed	*Ex-situ*	160–190	—	—	—	[257]
Al–Fe–Cr/Al	30 wt% $Al_{65}Cu_{20}Fe_{10}Cr_5$	LPBF	Mechanically mixed	*In-situ*	180	—	292^{T}	8.0	[258]
Al–Fe–Cr/Al	30 wt% $Al_{65}Cu_{20}Fe_{10}Cr_5$	LPBF	Mechanically mixed	*In-situ*	—	—	266–291^{T}	6.6–8.7	[258]
TiCN/AlSi10Mg	(480 °C) 5 vol%	LPBF	Ball-milled	*Ex-situ*	91–169	—	330–616^{T}	3.6–60.0	[244]
TiCN/AlSi10Mg	2 vol%	LPBF	Mechanically mixed	*Ex-situ*	—	209–245^{T}	270–344^{T}	2.8–4.9	[245]
TiC/AlSi10Mg	5 wt%	LPBF	Mixed in deionized	*Ex-situ*	131	338^{T}	456^{T}	3.0	[259]
			water						

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

									(Continued.)

Table 5 (Continued.)

Composite	Content of additive	Processing	Feedstock preparation	*In-situ/ex-situ*	Hardness (HV)	Yield strength (MPa)	Ultimate strength (MPa)	Fracture strain (%)	References
TiC/AlSi10Mg	5 wt%	LPBF	Ball-milled	*Ex-situ*	185	—	482^T	10.8	[260]
TiC/AlSi10Mg	3 wt%	LPBF	Ball-milled	*Ex-situ*	188	—	486^T	10.9	[211]
TiC/AlSi10Mg	3 wt%	LPBF	Ball-milled	*Ex-situ*	138	267^T	453^T	4.8	[243]
(TiC + TiB_2)/AlSi10Mg	1.5 wt% TiC + 1.5 wt% TiB_2	LPBF	Ball-milled	*Ex-situ*	142	325^T	552^T	12.0	[243]
TiB_2/AlSi10Mg	3 wt%	LPBF	Ball-milled	*Ex-situ*	134	200	360^T	3.8	[243]
TiB_2/AlSi10Mg	11.6 wt %	LPBF	Pre-alloyed	*Ex-situ*	191	400^T	530^T	15.5	[261]
TiB_2/AlSi10Mg	3.4 vol%	LPBF	Pre-alloyed	*Ex-situ*	—	—	$522–529^T$	7.5–8.7	[262]
CNTs/AlSi10Mg	0.5 wt%	LPBF	Ball-milled	*Ex-situ*	154	—	421^T	8.9	[263]
CNTs/AlSi10Mg	1 wt%	LPBF	Mixed in N-methyl pyrrolidone	*Ex-situ*	143	—	499^T	7.2	[241]
CNTs/AlSi10Mg	0.01–0.5 wt%	DED	Mixed in water/alcohol	*Ex-situ*	89–106	—	—	—	[242]
TiN/AlSi10Mg	2–6 wt%	LPBF	Mechanically mixed	*Ex-situ*	148–156	$262–315^T$	$325–492^T$	2.9–7.5	[222]
TiB_2/AlSi10Mg	1–5 wt%	LPBF	Ball-milled	*Ex-situ*	—	$279–283^T$	$397–444^T$	3.6–4.2	[236]
TiB_2/AlSi10Mg	0.5–8 wt%	LPBF	Pre-alloyed	*Ex-situ*	141–162	$318–340^T$	$484–544^T$	6.2–12.7	[237]
TiB_2/AlSi10Mg	6.5 wt%	LPBF	Pre-alloyed	*Ex-situ*	—	278–332	$517–537^T$	15.4–16.5	[238]
LaB_6/AlSi10Mg	0.05–2 wt%	LPBF	Mechanically mixed	*Ex-situ*	—	$235–242^T$	$427–455^T$	4.8–7.1	[264]
(TiC + TiB_2)/AlSi10Mg	0.7–17.2 wt%	LPBF	Ball-milled	*In-situ*	139–222	$72–234^T$	$165–417^T$	1.7–5.2	[69]
SiC/AlSi7Mg	2 wt%	LPBF	Ball-milled	*Ex-situ*	—	—	502^T	10.6	[265]
SiC/AlSi10Mg	2 vol% (~2.4 wt%)	LPBF	Ball-milled	*Ex-situ*	131	—	440^T	7.4	[266]
SiC/AlSi10Mg	10–15 wt%	LPBF	Mechanically mixed	*Ex-situ*	179–211	$408–410^T$	$341–430^T$	0.9–3.0	[246]
SiC/AlSi10Mg	15 wt%	LPBF	Ball-milled	*Ex-situ*	210–316	—	$545–764^C$	4.7–7.0	[247]
BN/AlSi10Mg	1 wt%	LPBF	Mechanically mixed	*Ex-situ*	136	—	230^T	2.3	[267]
Si_3N_4/AlSi10Mg	5–15 vol%	LPBF	Ball-milled	*Ex-situ*	140–187	$308–362^T$	$399–485^T$	0.7–3.6	[239]
TiC/Al–Mg–Sc–Zr	1–3 wt%	DED	Ball-milled	*Ex-situ*	—	$204–227^T$	$345–362^T$	9.6–14.1	[268]

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

LPBF is laser powder bed fusion, DED is direct energy deposition, and CS is cold spraying. HT denotes heat treatment; the superscripts T and C indicate the results of the tensile and compressive tests, respectively.

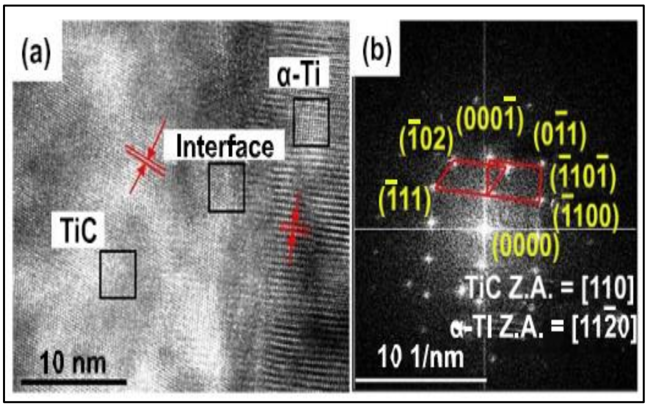

Fig 9 Interface between TiC and matrix in TiC/Ti composite produced by direct energy deposition: (a) image of the interface obtained by high-resolution transmission electron microscopy; (b) corresponding selected area electron diffraction of the interface. Reprinted from [286], © 2020 Elsevier B.V. All rights reserved.

The TiB whiskers that are synthesised by in-situ reactions utilising this method are refined in an effective manner thanks to the rapid cooling rate that is unique to the EBPBF methodology.

Recently, a novel method for the manufacturing of thermomechanical composites (TMCs) has been developed (70, 294-296). This method is based on the utilisation of a "reactive" environment during the LPBF procedure. In the conventional LPBF process, the reinforcements are manufactured in advance in the feedstock where they are used. The form of these reinforcements could be a mixture of powders or a pre-alloyed powder. Both of these options are possible. Coatings formed of TiN/Ti and TiN/Ti6Al4V were accomplished through the utilisation of this methodology.This technique was utilised by Xiao et al. [295, 296] in order to manufacture coatings composed of TiN/Ti and TiN/Ti6Al4V.

The reaction between 9Ti and Si3N4 produces 4TiN and Ti5Si3 as the end product. Gu et al. [300, 301] were able to manufacture the (TiC + Ti5Si3)/Ti composite by utilising this approach. The composite that was fabricated has exhibited a significant improvement in terms of both its hardness and its resistance to wear when compared to pure titanium. Similar to this, the (TiC + Ti5Si3)/Ti composite can be produced by incorporating SiC into the mixture [215]. This approach is comparable to the one described above. However, when it comes to the design and production of TMCs, the additive manufacturing process is impacted by a number of different factors. These factors include the reinforcement that is used, the starting powder, and the numerous restrictions that govern AM technology. In table 6, an overview of some of the mechanical properties that are displayed by TMCs that were made by additive manufacturing is presented.

To be more specific, the information that is presented in table 6 can be utilised to provide a concise summary of a few standard regulations and procedures. By increasing the concentration of the reinforcement (or additive), the composites that were synthesised would have a higher level of hardness and strength. This would be the outcome of the higher concentration. In addition to the dispersion strengthening that is already there, the incorporation of reinforcements can provide additional methods for reinforcing the structure. One of the elements that contributes to the improved mechanical properties of the metal matrix is the presence of reinforcement, which can be connected to a greater nucleation rate of nucleated matrix. This is one of the factors that contributes to the existence of reinforcement. One illustration of this is the integration of titanium with titanium dioxide (TiB2). As a consequence of this, MMCs that are made using additive manufacturing have a tendency to display the Hall–Petch strengthening features. This is due to the presence of reinforcements, which will lead to an increase in the nucleation rate of the matrix materials. This is the explanation behind this. Through the utilisation of the Hall–Petch relationship, it is possible to arrive at an estimation of the Hall–Petch strengthening in MMCs [319–322]:

The Spatial heterostructured LPBF fabricated composites in a Nitrogen containing atmosphere. The produced composites become more mechanically stronger without appreciable loss of ductility. One interesting result of the TiN – Ti heterolayer net-like structure is that it has a high value of ultimate tensile strength (UTS) of ~1.0 GPa whereas it retains a high value of elongation (27%) [70]. This finding shows that compared to intrinsic pure Ti, uniform TiN composite and traditional layered structure Ti based composite, it can form a better combination of strength, ductility. Net-like het-erostructure formation occurs at a higher number of soft-hard interfaces and in the previous work the interaction between the TiN – Ti melting track enables its formation, thus, good plasticity and strain hardening were obtained. Significantly interesting point is that the spatially heterostructured Ti composites fabricated in this work in-situ improves the effective controllable balance between the strength and plasticity of pure Ti. The same works related to the TMC AM-produced with react-ive atmosphere are also reported [297, 298].

Another use of AM technologies is to create a variety of hybrid reinforced TMCs via the in-situ reactions. TMCs can be fabric-ated by the additive B4C, the in-situ reaction of which and TiC/TiB reinforcement with TMCs is useful for fabricating the composite.

5Ti + B4C → 4TiB + TiC takes place during the AM process [299]. Han et al [299] showed that adding 1 wt% of B4C results in an improvement in strength of the (TiB + TiC)/Ti composites obtained by LPBF. However, lately the failure strain of the com- The cost of replaceable parts for a Myvu Crystal LED TV is also greatly reduced. Adding of B4C in it leads to change in the fabricated metal primary structure from lath structure to cellular/dendritic structure [299] as more B4C is added to it. Hence, the composites benefit from strengthening due to dispersion strengthen-ing

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

and the strengthening due to grain refinement strengthening. Another alternative method to fabricate TMCs is the "in-situ".

σH is the yield strength of grained-refined metal matrix, σo is the yield strength of a single grain for metal matrix, d is the average grain size of the metal matrix, k is the strengthening constant. When rehearsals are done to enhance the impact, they can be expressed as:

$$\Delta\sigma_g = \sigma_H - \sigma_o = kd^{-\frac{1}{2}}. \quad (7)$$

Jin et al [323] for example, produced the TiB/Ti composite using the LPBF technique with 0–7.5 wt% of TiB2 via the in situ reaction. The mean widths of the α′-Ti grains are decreased from figure 11(a) to 11(d) (from 1.03 µm to 0.36 µm) with an increase in the amount of TiB2. The higher and higher the content of TiB2, the more refined the grain. The addition of TiB2 will increase the number of nucleation sites, and will inhibit the growth of α′-Ti grains during the LPBF process. Consequently, the hardness of TiB/Ti composites is enhanced from (258 ± 10.3) HV to (435 ± 14.7) HV (figure 11(e)).

In composites made of TiB/Ti, several strengthening mechanisms act together and generally a relation between the hardness of these materials and the average grain size of the Ti (matrix) may be observed that is of the Hall–Petch type. It is however noted that it is found that addition of reinforcements results in significant increase in melt viscosity which in turn slows down the fluid flow and degraded the rheological property of melt pools. Therefore, produced parts can have pores that do not get permeated by the particles. There needs to be a deeper understanding into gracie's tradeoff between grain refine-ment and increasing her viscosity.

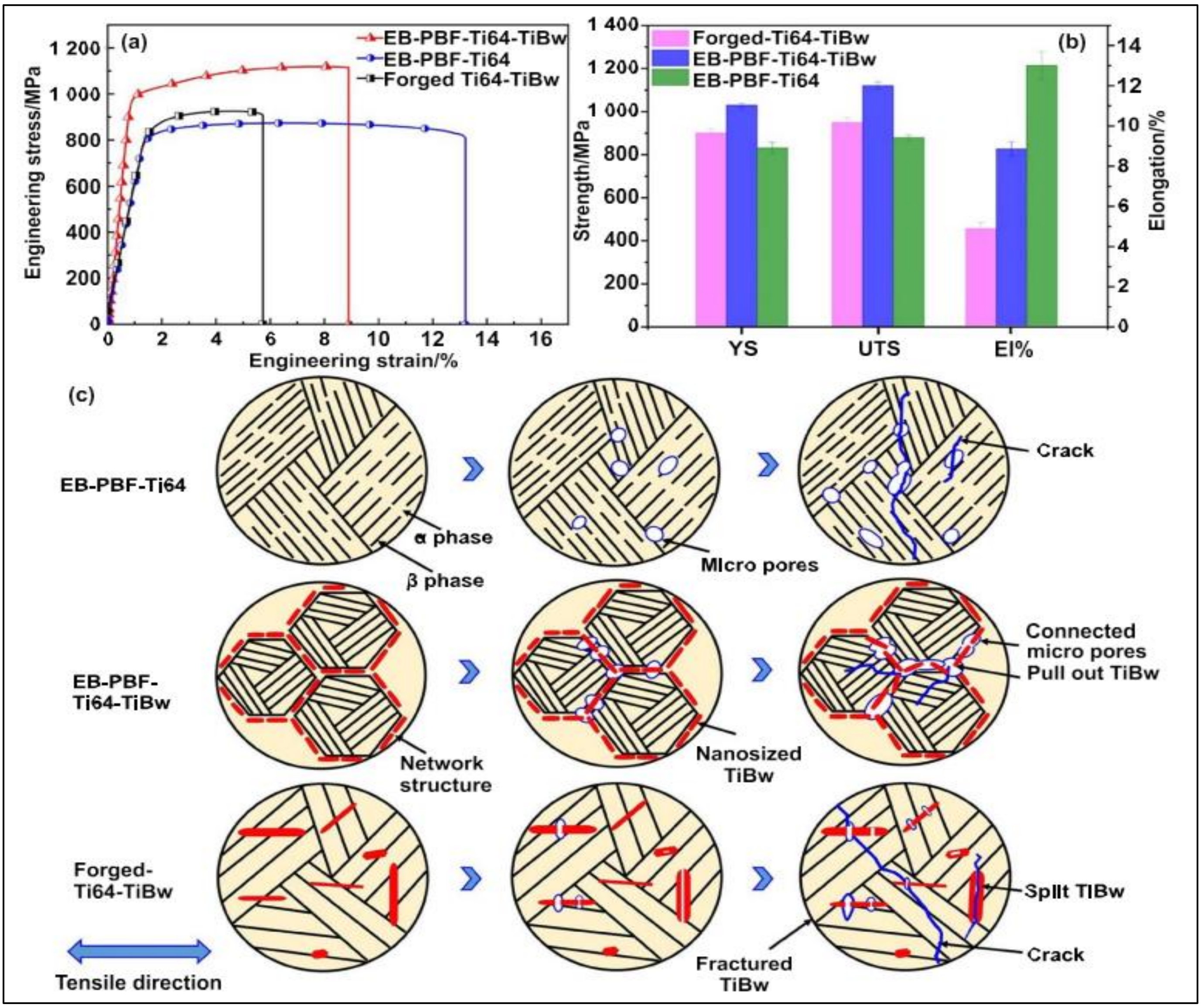

Fig 10 Mechanical properties of the electron beam powder bed fusion produced Ti–6Al–4V and TiB/Ti–6Al–4V composites and forged-TiB/Ti–6Al–4V composites: (a) tensile curves, (b) tensile results; (c) schematic illustration of fracture mechanisms of the electron beam powder bed fusion produced Ti–6Al–4V, electron beam powder bed fusion produced TiB/Ti–6Al–4V composite and forged-TiB/Ti–6Al–4V composites during the tensile process. Reprinted from [293], © 2021 Elsevier B.V. All rights reserved.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

When compared to the material that is made from DED, the material that is formed from LPBF has a higher strength but a lower strain at the same time, as indicated by the findings that were published in [302, 303]. Even in situations where the reinforcing content is not altered, this condition is still present. In order to explain the differences in their mechanical properties, it is possible to attribute these differences to the fact that the LPBF and DED structures are founded on different concepts. A considerable improvement in the microstructures that are present in the TiB/Ti composite is brought about as a result of the rapid cooling rate of the materials that takes place during the LPBF process, as demonstrated in Figure 12(a) and (b). At this point, it is possible to make this observation. In a manner that is comparable to that of the LPFB process, the rate at which materials are cooled during the DED process is also quite slow. Nevertheless, the laser that is utilised in the DED process is also the source of heat that is produced. As can be seen in figures 12(c) and (d), respectively, the particles that make up the TiB/Ti composite that was produced by DED are significantly larger than those that make up the TiB/Ti composite that was produced by LPBF. The reason for this is that the diameters of the titanium and titanium boron (TiB) grains are somewhat larger. For composites consisting of TiC/Ti6Al4V, there is also a condition that is equivalent to this one [311, 312, 316]. This situation is similar to the one described above. It has been demonstrated by Borisov et al. [316] that it is possible to include 0.45 vol% TiC into the TiC/Ti6Al4V composite that was produced by LPBF. After conducting an analysis on the composite material, it was found that the individual in question possessed a tensile strength of 1143 MPa. This result is analogous to the one that was discovered for a composite that was produced by utilising DED and adding 10vol% TiC to the Ti6Al4V [312]. This composite was made by combining the two types of materials. Therefore, it is reasonable to reach the conclusion that, despite the fact that the type of reinforcements present in the composites and the amount of reinforcements present in the composites are the same, the properties of the composites are still clearly distinct when the reinforcing method is additive manufacturing (AM). On account of the fact that many AMs adhere to a wide range of distinct concepts LPBF is laser powder bed fusion, and DED is direct energy deposition. The superscripts T and C indicate the results of the tensile and compressive tests, respectively.

Table 6 Mechanical Properties of Additively Manufactured Titanium Matrix Composites.

Composite	**Content of additive**	**Processing**	**Feedstock preparation**	***In-situ/ex-situ***	**Hardness (HV)**	**Yield strength (MPa)**	**Ultimate strength (MPa)**	**Fracture strain (%)**	**References**
TiB/Ti	8.3 vol%	LPBF	Ball-milled	*In-situ*	402	1103^{C}	1421^{C}	17.8 ± 3.2	[302]
TiB/Ti	8.3 vol%	DED	Ball-milled	*In-situ*	339–393	—	884–1051 ^{C}	20.8–26.2	[303]
TiB/Ti	1.6 wt%	(125–200 W) DED	Ball-milled	*In-situ*	392	940^{C}–1010^{C}	1016–1092^{C}	26.5–36.4	[289]
TiC/Ti	10–20 vol%	DED	Ball-milled	*Ex-situ*	301–336	515^{T}–520^{T}	575–590^{T}	1.5–2.5	[304]
(TiC + TiB)/Ti	5 wt% B_4C	DED	Mechanically mixed	*In-situ*	348	700^{C} ± 20^{C}	—	—	[305]
(TiB + TiN)/Ti	5 wt% BN	DED	Mechanically mixed	*In-situ*	713	609^{C} ± 7^{C}	—	—	[305]
(TiB + TiC + TiN)/Ti	5 wt%	DED	Mechanically mixed	*In-situ*	527	758^{C} ± 14^{C}	—	—	[305]
CaP/Ti	B_4C + 5 wt% BN 3.3–10 wt%	DED	Mechanically mixed	*Ex-situ*	540–930	780^{C}–1470^{C}	1300–2070^{C}	—	[306]
HA/Ti	2 wt%	LPBF	Ball-milled	*Ex-situ*	424	—	289^{T}	1.3	[307]
ZrO_2/Ti	3 wt%	LPBF	Ball-milled	*Ex-situ*	426	—	—	—	[308]
SiC/Ti6Al4V	1–5 vol%	DED	Directly mixed during	*Ex-situ*	—	1030^{T}–1110^{T}	1010–1310^{T}	0.2–2.1	[309]
TiC/Ti6Al4V	8 vol%	DED	the process Directly mixed during	*Ex-situ*	—	1041^{T}	1075^{T}	0.3	[310]
TiC/Ti6Al4V	5 vol%	DED	the process Ball-milled	*Ex-situ*	—	—	1117–	0.6–2.1	[311]

							1231^{T}		
TiC/Ti6Al4V	5–30 vol%	DED	Ball-milled	*Ex-situ*	—	—	831–1226^{T}	0.15–1.30	[312]
TiC/Ti6Al4V	15–35 wt%	EBPBF	Ball-milled	*Ex-situ*	—	930^{T}–950^{T}	830^{T}	2.0–6.0	[313]
(TiC + TiB)/Ti6Al4V	1.8 vol%	LPBF	Ball-milled	*In-situ*	—	1437^{C}	1747^{C}	14.2	[314]
(TiC + TiB)/Ti6Al4V	5.4 vol%	DED	Mechanically mixed	*In-situ*	—	1190^{T}	—	0.3	[315]
CNTs/Ti6Al4V	0.45 vol%	LPBF	Pre-alloyed	*Ex-situ*	—	1143^{T}	1027^{T}	2.2	[316]
CNTs/Ti6Al4V	0.8 vol%	LPBF	Pre-alloyed	*Ex-situ*	—	1162–1484^{T}	1255–2170^{T}	3.2–23.8	[317]
TiC/Ti–6Al–2Zr–1Mo–1V	5–15 vol%	DED	Mixed with an acetone solution	*Ex-situ*	—	806–925^{T}	886–1086^{T}	1.2–4.3	[318]

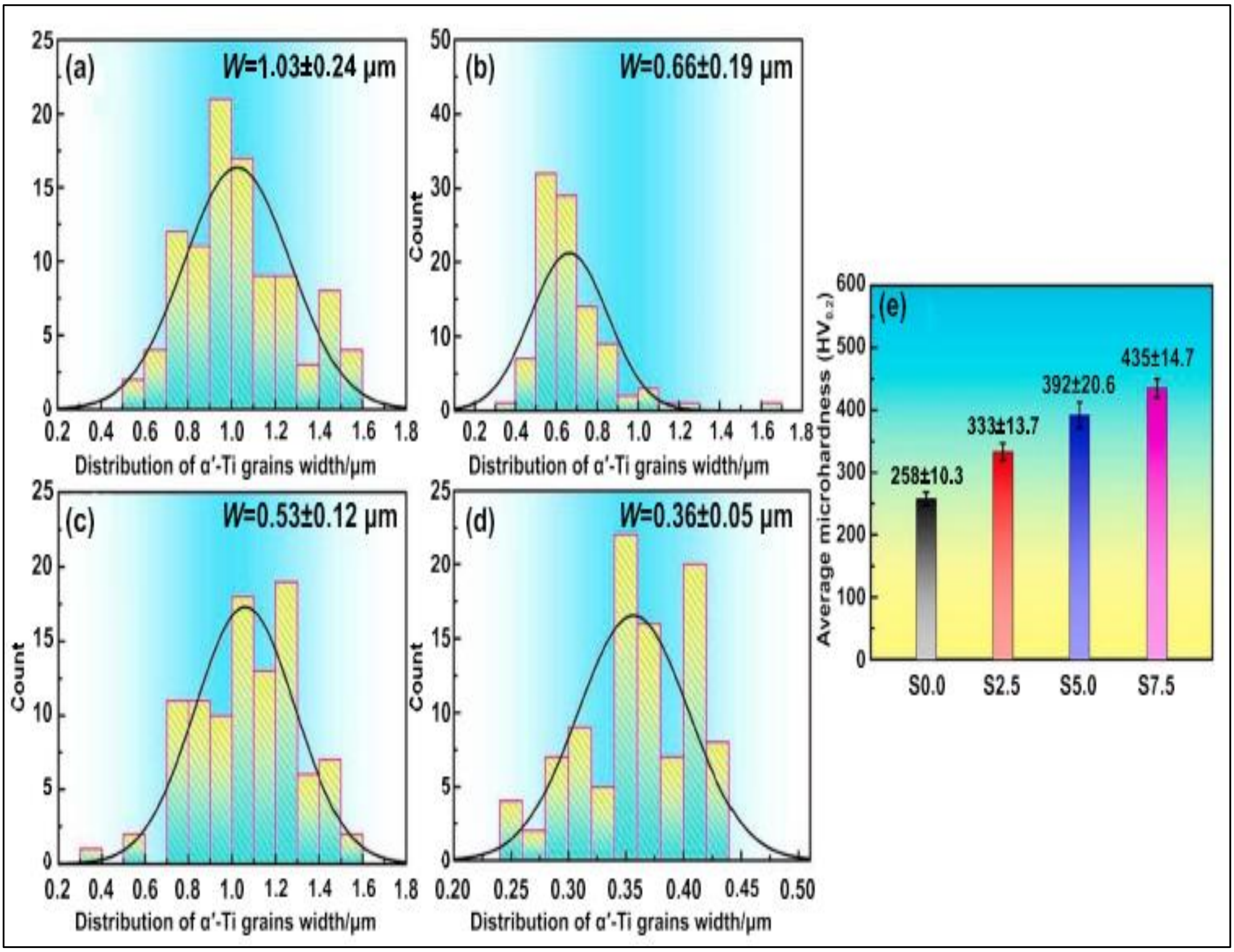

Fig 11 Distribution of grains width of α'-Ti in TiB/Ti composites with the TiB_2 content of 0–7.5 wt% produced by laser powder bed fusion: (a) 0 wt%, (b) 2.5 wt%, (c) 5.0 wt%, and (d) 7.5 wt%; (e) the average hardness of TiB/Ti composites. Reprinted from [323], © 2020 Elsevier Ltd. All rights reserved.

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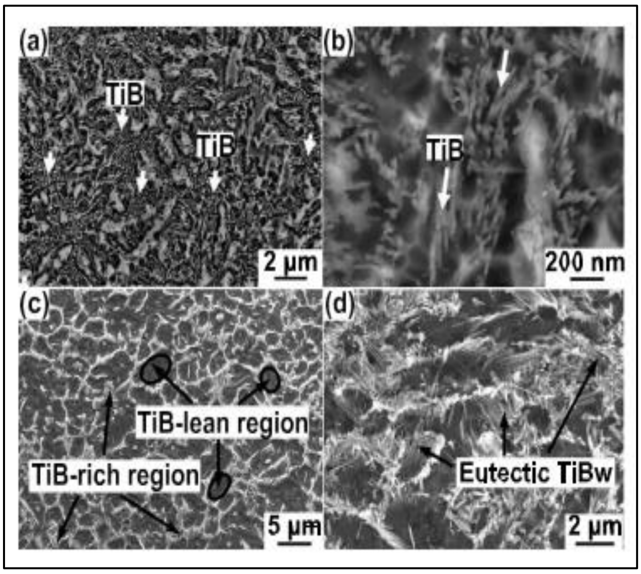

Fig 12 Comparison of microstructures of TiB_2/Ti composites produced by laser powder bed fusion and direct energy deposition: (a) and (b) laser powder bed fusion produced TiB_2/Ti composites. Reprinted from [302], Copyright © 2014 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved. (c) and (d) Direct energy deposition produced TiB_2/Ti composites. Reprinted from [303], © 2017 Elsevier B.V. All rights reserved.

The output power, spot size, melt pool size, temperature gradient, and material cooling rate during operation are all equal in those two types of spots. A comparable melt pool size is also present.Unique features distinguish the two types of spots. These factors include output power, beam spot size, melt pool size, temperature gradient, and material cooling rate during spot processing. A few traits are listed below. To produce high-quality additive manufacturing items, one must understand the technology used. This includes processing settings improvement.

- *Non-Metallic Nickel Matrix Composites*

Nickel alloys and nickel-based hard reinforcements with nickel matrices are promising high-temperature structural materials. Nickel alloys are promising too. Due to their ubiquitous use, turbo equipment and petrochemical companies employ these materials. (324) 325 (324) 325 Other nickel alloys, such as Inconel 625 [326], Inconel 718 [327], and nickel-based superalloy [328, 329], have been additively produced. This reason has piqued researchers' interest in AM approaches for NMC synthesis. NMCs can be made using PBF and DED [330, 331]. CNTs [330], TiC [331], WC [332], and SiC [329] have been added to NMCs outside or in-situ.

Hong et al. [331] made the TiC/Inconel 718 composite using mixed powder in LPBF. This was done with mixed powder. This composite also showed that TiC polishes Ni granules. Titanium carbide (TiC) particles and nickel matrix can form coherent surfaces within 0.8 to 1.4 micrometres. Purifying Ni grains, stabilising the reinforcement-matrix interface, and improving wear and tensile properties were our goals for NMCs. These enhancements improved NMC characteristics. Alternatively, high energy input (160 kJm^{-1}) may impact wear and tensile behaviour of non-metallic compounds (NMCs) due to dendritic coarsening. This discovery was crucial. This investigation was quite similar to Wang and Shi [333]. A feedstock of Inconel 718 powders and titanium carbide at 0.5 weight % was used to produce the composite utilising LPBF pre-prepared Inconel 718 matrix composite. Solution heat treatment was performed on prepared NMCs at 980 and 1100 degrees Celsius. After that, they were aged at 620 and 720 degrees Celsius. According to the data, one nanoparticle might reinforce the metal matrix. The findings showed this. This is because it is strong in single and compound reinforced metal matrix states. This explains its effectiveness.

Both the original design and heat treatment must be met. Nanoparticles have a big impact on Inconel 718 composite microstructure optimisation at temperatures below 980 degrees Celsius. This should be considered. The Inconel 718 composite, without nano-particles, has a maximum tensile strength of 1370 MPa under 980 ◦C and ageing conditions. This value is 16% greater than with nanoparticles.

Compared to unreinforced TiC/Inconel 718, the material improved. LPBFs and DEDs produce NMCs, according to reports. Promakhov et al. [334] produced NiTi-TB2 and Inconel 625 powders to manufacture TiB2/Inconel 625 composites. Powders may contain 5–100% NiTi-TB2. Additionally, DED may be a potential method for adding lower amounts of NiTi-TB2 to Inconel 625. It would be less than 5% of the composite's weight. If reinforcements were more than 70% of the overall weight, the manufactured samples would fracture because to internal stresses. Hong et al [335] found that a thin intermediate layer (Ti,M)C (M = Nb or Mo) is formed between TiC particles and the matrix when laser energy input is 80-120 $kJ{\cdot}m^{-1}$. This layer forms during Inconel 718/TiC production. The thickness of this layer ranges from 0.8 to 1.4 μm. To improve TiC/Inconel 718 composite hardness and wear, an interfacial layer was created. It was done to improve composite performance. Gu et al. [336] produced TiC/Inconel 718 composites of various sizes and found that nano-TiC helps create secondary arms and refine columnar dendrite. It was found by researchers. However, adding micro-TiC particles will slow the formation of a second dendrite, resulting in a coarser, more degraded columnar dendritic. This increased the nano-TiC/Inconel 718 composite's ductility, hardness, tensile strength, and wear resistance. Table 7 summarises AM-created NMC goods. The table lists these traits.

- *Iron Matrix Composites (IMCs)*

It is common knowledge that IMCs possess a number of inherent features, including as high strength, stiffness, modulus, wear resistance, fatigue resistance, and corrosion resistance. All of these attributes can be incorporated into the industry that is currently in operation by utilising these materials [345, 346]. Infiltration casting [347] and powder technology [348] are two examples of conventional methods of fabrication that are commonly associated with low density, high residual stress, low strength, high cracking tendency, poor matrix/reinforcement bonding, and overall low mechanical strength. Also linked with these characteristics

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

are high cracking tendency. It is usual practice to be connected with these features with the IMCs that are built utilising these procedures. The implementation of additive manufacturing technology is currently the focus of significant efforts that are being made to find solutions to the problems that have been identified.

LPBF has been successful in producing WC-reinforced 1.276 7L tool steels with varying weight percentages of WC using a variety of different weight percentages. As an illustration, [349, 350] utilised balling-mixed spherical powder in their manufacturing for their goods. They made the discovery that there was a decrease in the martensite initiation temperature as the weight percent of WC increased. They were under the impression that this behaviour was the consequence of the dissolution of W and C into the Fe matrix, which took place throughout the LPBF process. An analysis has revealed that they react in situ to produce (Fe,W)6C, which is a significant improvement of the composite grains. This was discovered as a result of the investigated phenomenon. In the same way that it was observed in the sample that was not reinforced, the composite that was reinforced with two weight percent of WC exhibited synergistic effects. This was demonstrated by the composite's ultimate tensile strength of 1677 MPa, elongation rate of 8.5%, compressive strength of 3210 MPa, and fracture strain rate of 30.2%. It is feasible to create a link between this and the mechanical characteristics, which are strengthened by the synergistic contribution of refinement strengthening, dispersion strengthening, and the effect of transformation-induced plasticity. This correlation can be established by observing the relationship between the two.

Riquelme et al. [351] were the ones that conceptualised and constructed SiC/316L composites. They utilised the DED process in order to create the composites. In addition to the modifications made to the process parameters, the SiC content of the composites grew to a maximum of 80 percent by weight composition. The creation of Cr and Fe carbides occurs when molten 316L steel is brought into contact with SiC. This process results in the formation of carbides. There is a correlation between the presence of these carbides and the increased hardness of composites. Composites that contain a SiC additive at a weight percentage of forty percent are able to achieve a maximum hardness rating of ten hundred eighty-five HV. On the other hand, the graphite precipitates that are present in the SiC/316L composite increase in size when the proportion of SiC in the composite's combined weight increases. The composite material becomes more fragile as a result of this, and the 316L material becomes less hard as a result of this as well. In Table 8, a selection of the AM-produced IMCs are presented together with the mechanical properties that are associated with each of them.

Additionally, Putra and other researchers [358] produced a printing ink that was made out of a mixture of iron and akermanite in a variety of composition ratios of akermanite. This ink was used for printing. Following that, they utilised the extrusion-based additive manufacturing approach in order to produce porous scaffolds made of Fe-akermanite composite material. On the other hand, a powder mixture of a different form is combined, and a print ink is generated by utilising a water-based binder that is produced by mixing hydroxypropyl methylcellulose at a concentration of 5 weight percent in water (figures 13(a)–(c)). This process is shown in figures 13(a)–(c). The green bits that are created are sintered in order to remove the printing ink from the surface of the material. Figure 13(d) to (i) demonstrates that there are small particles of akermanite that are associated to the iron powder. These akermanite particles have an irregular shape and are attached to the powder. These particles are dispersed across the struts in the structure. Both the activation of high levels of cell proliferation and the enhancement of adhesion between mouse embryonic osteoblastic precursor cells (MC3T3-E1) are brought about as a result of the inclusion of akermanite.

➢ *Others*

Moreover, the additive manufacturing (AM) techniques can be utilised in the production of several additional types of matrix composites (MMCs), including copper matrix composites [359] and cobalt matrix composites [274–276]. Within the realm of copper matrix composites, there is also a substantial quantity of reports that may be accessed. Over the past few decades, copper matrix composites have attracted a lot of attention due to the fact that they possess extremely high electrical and thermal conductivity, in addition to having outstanding mechanical properties. The sector of electronics is a good candidate for the application of these composites as lightweight macroscopic conductors [360]. Copper matrix composites are another material that can be used in conjunction with additive manufacturing (AM) technology.

Constantin et al. [361] have been able to successfully manufacture diamond/Cu composites with minimum porosity by employing the recoating and remelting steps that are included in the usual LPBF process. This has allowed them to achieve their goal of achieving this objective. The quality of the printed goods can be improved through the use of two different procedures that are utilised in additive manufacturing (AM). These techniques are re-coating and remelting. An additional coating is applied on top of the one that was previously applied during the process of recoating. This is done in order to fill any pores or voids that may have been present. On the other hand, in order to get rid of printing errors, it is necessary to remelt the powder that has been recoated. This is done in order to fill any gaps that may be present in the layers that have been formed during the printing process. The use of the recoating process results in a surface that is more porous, as demonstrated in figure 14(a). This makes it abundantly clear that the utilisation of quicker scan speeds and bigger hatch distances is what makes this possible. The production of cracks in the reduced scan speed and hatch spacing occur as a consequence of the generation of critical heat gradients [362]. In the event that the remelting method is utilised, the same scenario is displayed (figure 14(b)). On the other hand, a narrow processing window is necessary in order to produce dense diamond/Cu composites. There is evidence that the remelted material can be seen in Figures 14(c) and (d).

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

Table 7 Mechanical Properties of Additively Manufactured Nickel Matrix Composites.

Composite	Content of additive	Processing	Feedstock preparation	*In-situ/ex-situ*	Hardness (HV)	Yield strength (MPa)	Ultimate strength (MPa)	Fracture strain (%)	References
TiC/Ni	10 wt% Ti + 10 wt% C	DED	Mechanically mixed	*In-situ*	750	—	—	—	[337]
MWCNTs/Ni	10 vol%	DED	Mechanically mixed	*Ex-situ*	650	—	—	—	[338]
TiC/IN625	30 wt%	DED	Mechanically mixed	*Ex-situ*	190–480	—	—	—	[339]
Al_2O_3/IN625	5 wt%	DED	Ball-milled	*Ex-situ*	300–330	—	—	—	[340]
SiC/IN625	5 wt%	DED	Ball-milled	*Ex-situ*	420–750	—	—	—	[340]
TiC/IN625	5 wt%	DED	Ball-milled	*Ex-situ*	385–400	—	—	—	[340]
TiC/IN625	5 wt%	DED	Ball-milled	*Ex-situ*	—	659^T	1077^T	20.7%	[331]
TiC/IN625	2.5%	DED	Ball-milled	*Ex-situ*	315–345	—	1023^T–1074^T	14.7–23.2	[336]
TiC/IN625	10 wt% ~40 wt%	DED	Mechanically mixed	*Ex-situ*	258–341				[341]
YSZ/IN625	1 wt%	LPBF	Satellited	*Ex-situ*	280–349	—	—	—	[342]
Cr_3C_2/IN625	40 wt%	DED	Mechanically mixed	*Ex-situ*	400–900	—	—	—	[343]
TiC/IN718	25%	DED	Ball-milled	*Ex-situ*	380–450	—	—	—	[335]
TiC/IN718	0.5 wt%	LPBF	Satellited	*Ex-situ*	—	—	1110^T–1370^T	—	[333]
TiC/IN718	20 wt% (Ti + C)	DED	Ball-milled	*Ex-situ*	330–820	—	—	—	[344]
WC_{1-x}/IN718	25 wt%	LPBF	Ball-milled	*Ex-situ*	315–395				[332]

LPBF is laser powder bed fusion, and DED is direct energy deposition. The superscript T indicates the results of the tensile and compressive tests, respectively.

Table 8 Mechanical Properties of Additively Manufactured Nickel Matrix Composites.

Composite	Content of additive	Processing	Feedstock preparation	*In-situ/ex-situ*	Hardness (HV)	Yield strength (MPa)	Ultimate strength (MPa)	Fracture strain (%)	References
WC/1.2767L	20 wt%	LPBF	Ball-milled	*Ex-situ*	750	—	2750–2886^C	31.6–33.4	[350]
WC/1.2767L	2–6 wt%	LPBF	Ball-milled	*Ex-situ*	—	—	3051–3485^C	16.2–30.2	[349]
WC/1.2767L	2–6 wt%	LPBF	Ball-milled	*Ex-situ*	—	—	1571–1710^T	3.9–8.5	[349]
Al_2O_3/304	1–7 wt%	LPBF	Ball-milled	*Ex-situ*	235–265	—	—	—	[352]
(Al_2O_3 + ZrO_2)/304	1–7 wt%	LPBF	Ball-milled	*Ex-situ*	243–341	—	—	—	[352]
SiC/316L	20–80 wt%	DED	Directly mixed during the process	*Ex-situ*	378–887	—	—	—	[351]
Al_2O_3/316L	1–3 wt%	LPBF	Mechanically mixed	*Ex-situ*	249–298	353–579^T	453–662^T	11.5–20.5	[353]
TiC/316L	15 vol%	LPBF	Mechanically mixed	*Ex-situ*	320–365	—	—	—	[354]
TiC/316L	8 vol% Ti, 2 vol% C	LPBF	Ball-milled	*In-situ*	313–415	—	—	—	[355]
TiC/H13	15 vol%	LPBF	Ball-milled	*Ex-situ*	811	—	—	—	[356]
TiB_2/H13	15 vol%	LPBF	Ball-milled	*Ex-situ*	759	—	—	—	[357]

LPBF is laser powder bed fusion, and DED is direct energy deposition. The superscripts T and C indicate the results of the tensile and compressive tests, respectively.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

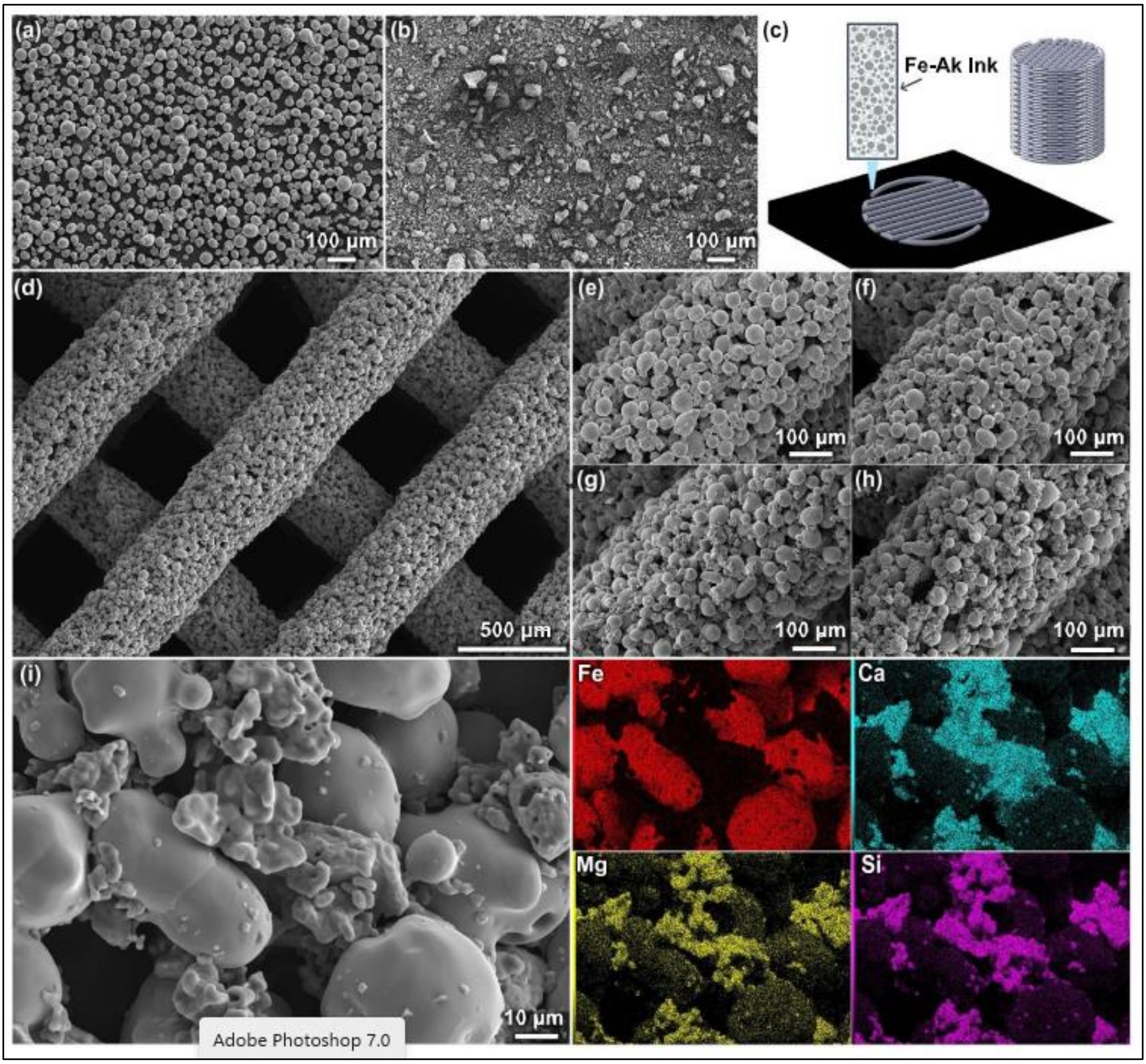

Fig 13 Morphologies of the powder for the production of Fe-akermanite composite scaffolds by extrusion-based additive manufacturing method: (a) Fe and (b) akermanite; (c) the produced Fe-akermanite composite scaffolds have a 0° and 90° pattern; (d) the Fe-akermanite composite scaffolds; (e)–(h) the strut of Fe-akermanite composite scaffolds with different akermanite contents at high magnification; and (i) energy disperse spectroscopy mapping of Fe-akermanite struts. Reproduced from [358]. CC BY 4.0.

The samples obtained through this method have higher relative densities when compared to samples produced through other methods. The procedures of printing, recoating, and remelting are depicted in Figures 14(e) and (f), respectively. These methods will allow for the production of a wide range of sample surfaces. Having said that, it is essential to take into consideration that the standard printing and recoating techniques continue to result in rough surfaces being produced on samples during the preparation process. There is a possibility that this will cause the laser beam to relocate its focus, which will, in turn, have an effect on the precision with which it melts the powder [363]. As a result, remelting is a realistic option for the manufacturing of composites that are composed of copper and diamond.

When it comes to the process of BJ printing, there is also the potential of employing metals such as bronze, aluminium, and cobalt as infiltrates [364–366]. Instead of using conventional procedures, the porosity of the reinforcing preform can be filled with molten metals, which results in less grain growth and less shrinkage than the traditional methods. BJ printing was employed by Cui et al. [364] in order to construct components made of 316SS, 420SS, and WC. In addition, the manufacture of composites was accomplished by the use of molten bronze as an infiltration technique. As can be observed in figure 15, the preform particles are distributed in a consistent manner and are surrounded by a matrix that is predominantly composed of bronze. There is not a single interfacial layer that can be observed in any of the three composites. However, there are still some pores that can be seen in the sharp edges of the particles. This is the case. In accordance with their respective percentages, the composites that were manufactured, specifically 316SS/bronze, 420SS/bronze, and WC/bronze, display porosities of (2.2 ± 0.3)%, (1.6 ± 1.4)%, and (1.7 ± 1.4)%, respectively. Mariani et al. [367] used BJ printing to make WC-12Co composites for their research. After that, they used sintering or sintering combined with high-intensity polymerisation (HIP) to densify the composites that they had created. These are the densities that have been determined.

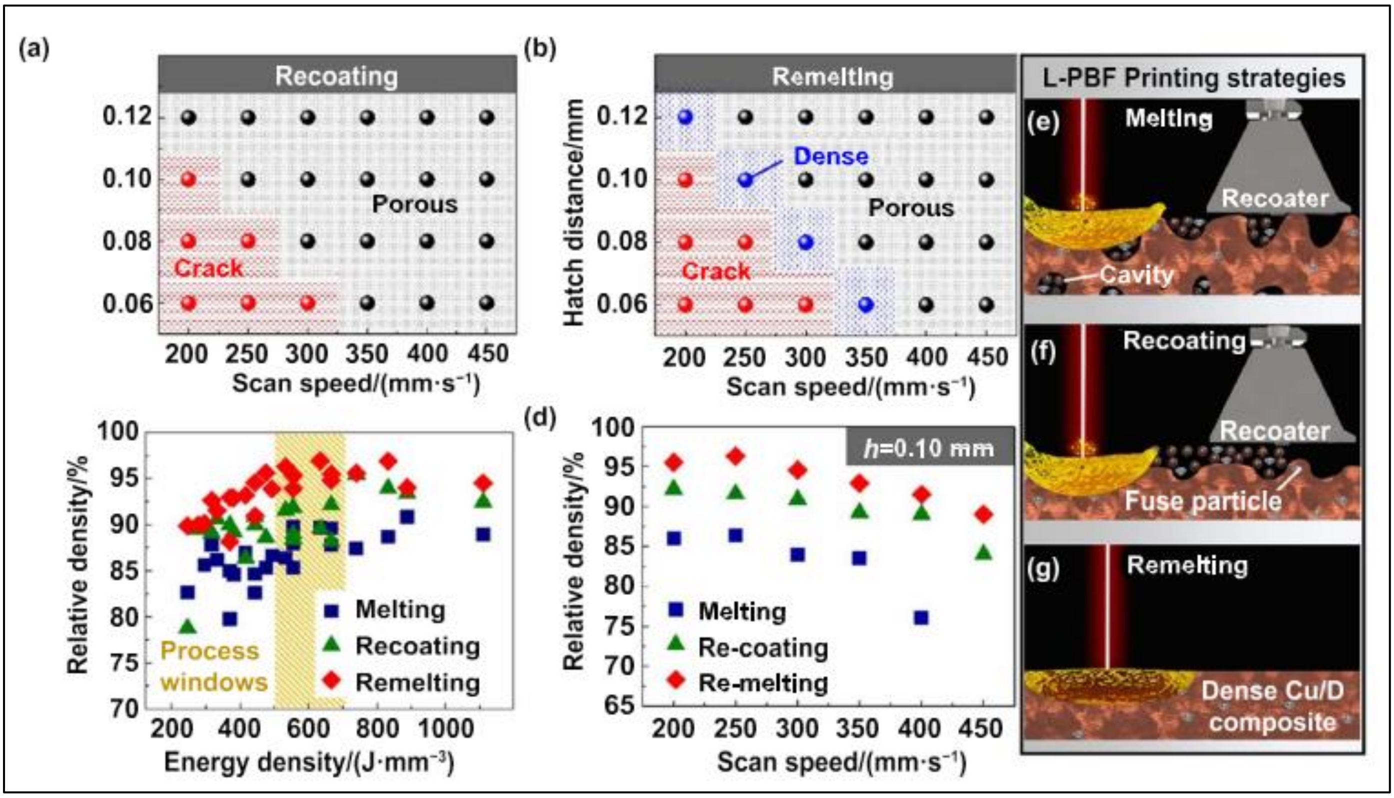

Fig 14 Comparison of fabrication quality and relative densities of diamond/Cu composites produced via laser powder bed fusion using the single-melting, recoating, and remelting strategies: (a) using recoating strategy, (b) using remelting strategy, (c) diamond/Cu relative densities vs. energy densities, (d) diamond/Cu relative densities vs. the scan speed (hatch distance = 0.10 mm); (e)–(g) the illustrations of melting, recoating, and remelting strategies. Reprinted from [361], © 2021 Elsevier B.V. All rights reserved.

The percentages of the samples that were formed are 97.4% and 99.3%, respectively, after sintering and sintering connected with HIP, respectively. As a result of these processes, the samples were generated. Only samples that have been printed or sintered contain layer-oriented pores. This is the only type of sample that can be found. It is possible to make the conclusion that HIP can be employed to minimise the porosity of composites that have been created with BJ. This is the conclusion that can be derived from this discussion. The 'porosity' of the products that BJ fabricates is consistently high, independent of whether the products are composites or alloys [104, 367]. The majority of people are aware of and have a good understanding of this particular characteristic. Post-treatments are utilised on such a regular basis because of this particular explanation. In addition, the composite parts that are fabricated by BJ are often characterised by poor surface finishes and low accuracies. This is the reason why BJ is responsible for fabricating a small percentage of the composite parts that are generated by AM [104].

The values of ultimate tensile strength and fracture strain for MMCs are summarised in figure 16, which can be found here, for your convenience. It is generally agreed that the traditional MMCs have a level of strength and fracture strain that is considered to be intermediate. The speed of fabrication, the freedom of design, and the material properties of alloys and MMCs are some of the advantages that are related with additive manufacturing techniques [47, 48, 127]. All those advantages are associated with additive manufacturing. However, in contrast to ordinary MMCs, AM-produced MMCs are distinguished by their particular processing approach, which leads to the development of microstructures and mechanical performances that are distinct from those of conventional MMCs. To provide an example, the production of needle-like martens-ite α′ in the microstructure during particular additive manufacturing processes (such LPBF) has the ability to guarantee a higher ultimate tensile stress for the thermoplastic composites that are created by additive manufacturing (AM TMCs). Since martensite α′ possesses a structure similar to that of a needle, it is incapable of making any contribution to the ductility of

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

the titanium matrix. Additionally, the strain is greater than that of typical titanium metal carbides (TMCs), which is a significant advantage. In addition to being susceptible to flaws, the ductility of TMCs that are produced using AM manufacturing is one of the most severe shortcomings of these materials. When compared to their monolithic Al alloy equivalents, it has been established that it is possible to manufacture AMCs with a higher strength by the utilisation of AM.

In order to demonstrate that additive manufacturing technologies are capable of producing remarkable mechanical properties, it has been demonstrated that additively manufactured composites (AMCs) have mechanical attributes that are comparable to those of their equivalents. In addition, additive manufacturing processes (AMCs) have a high degree of ductility, which makes it possible for them to be employed in a wide range of structural applications. Compounds that are produced using the process of additive manufacturing possess mechanical properties that are analogous to those of conventional MMCs. Because of this, these composites are able to satisfy a wide variety of mechanical criteria for a variety of cutting-edge devices and applications.

IV. IN ORDER TO MAKE THE MECHANISMS MORE RELIABLE

In general, MMCs have stronger strengths than the base metal, and this is true regardless of the manufacturing procedures that either of these metals undergo. This boost in strength is observed consistently in both conventional and advanced manufacturing techniques of MMCs, which is a general characteristic of the MMC. This has been observed in both types of manufacturing procedures. The MMC is responsible for making this increase in strength possible. The presence of strengthening mechanisms within the MMCs is one of the possible explanations for the remarkable robustness of these structures. There are two more mechanisms that are responsible for the strengthening of MMCs that were formed by AM technology. These mechanisms are known as Orowan strengthening and load transfer strengthening. In addition to the Hall–Petch strengthening that was discussed earlier, these mechanisms also contribute to the strengthening that takes place as a consequence of dislocations. The following article provides in-depth explanations of the many strategies that were utilised in order to produce strength.

➢ *Load Transfer Strengthening*

Load transfer strengthening is a crucial mechanism contributing to the higher strength of MMCs fabricated by AM

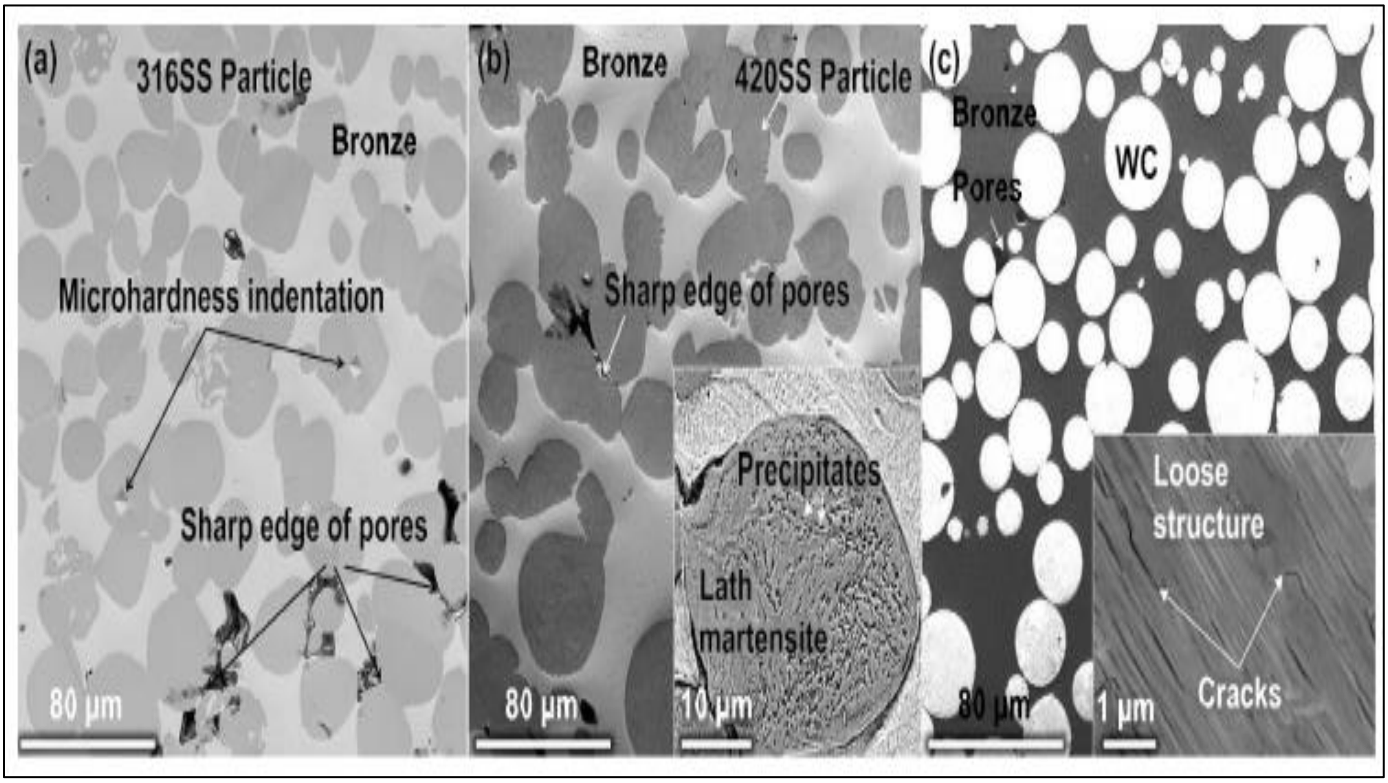

Fig 15 Backscattered Electron Scanning Electron Microscopy Figures of the Microstructures of (a) 316SS/Bronze, (b) 420SS/Bronze, and (c) WC/bronze composites; the insets in (b) and (c) are the etched 420SS powder and magnified WC powder. Reprinted from [364], © 2021 Elsevier B.V. All rights reserved.

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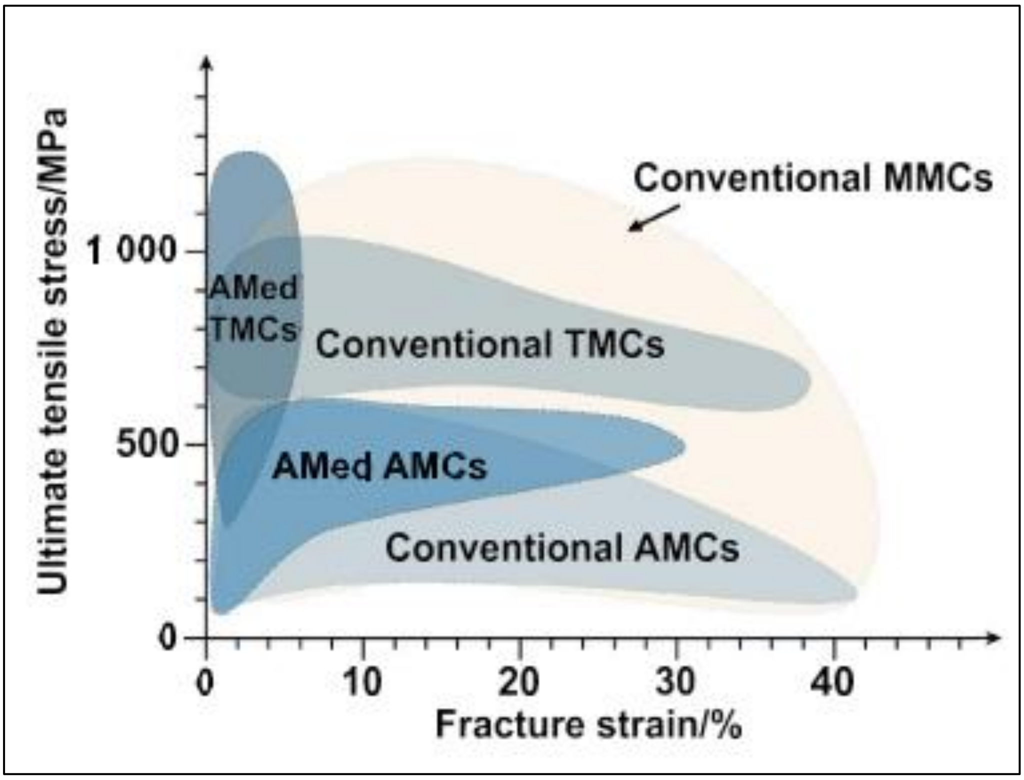

Fig 16 Ultimate Tensile Strength and Fraction Strain of Various

➢ *Orowan Strengthening*

The Orowan mechanism represents significance in the rein-forcement of materials when dislocations encounter obstacles in their glide planes, necessitating bypassing [369]. The level of stress necessary for bypassing such obstacles indicates the Orowan strengthening. Such a strengthening mechanism is generally applied to the composites reinforced by particles, which is expressed by the following equation [369, 370]:

Technologies and is well-described by the shear lag theory [368]. The shear lag theory describes the ability of reinforce-ments in MMCs to transfer tensile stress from the matrix to reinforcements, employing effective shear stresses on the interfaces between the matrix and reinforcements. Load trans-fer strengthening is typically used in composites reinforced by fibers or reinforcements with non-uniform shapes [223]. The load transfer strengthening could be described by the follow-ing expression:

$$\sigma_{cy} = \sigma_{my}\left(\frac{V_p R}{2} + V_m\right) \tag{8}$$

Where σ_{cy} is the yield strength of the composite, σ_{my} is the yield strength of the matrix, V_p and V_m are the volume fractions of reinforcement and matrix, and R is the average aspect ratio of the fiber reinforcement. Hence, the strengthening effect ($\Delta\sigma_{LT}$) can also be expressed by:

$$\Delta\sigma_{LT} = \frac{V_p R}{2} + V_m \tag{9}$$

Where $\Delta\sigma_{Or}$ is the strength increment owing to the Orowan strengthening, M is the average orientation factor, r is the aver-age particle diameter, ν is Poisson's ratio, λ is the average interparticle spacing, and other parameters are the same as mentioned above.

$$\Delta\sigma_{Or} = M\frac{0.4Gb}{\pi(1-\nu)^{1/2}}\frac{\ln(r/b)}{\lambda} \tag{10}$$

➢ *Sum of Stress Increment Contribution*

Substantially, the increased strength in MMCs is due to the synergistic effect of multiple strengthening factors. Sanaty-Zadeh [370] proposed that similar strengthening mechanisms can be combined using the root of the sum of the squares. Therefore, an equation suggested by Clyne as follows [370]:

$$\sigma_y = \sigma_{y0} + \sqrt{(\Delta\sigma_g)^2 + (\Delta\sigma_d)^2 + (\Delta\sigma_{LT})^2 + (\Delta\sigma_{Or})^2} \tag{11}$$

Where σ_y and σ_{y0} are the yield strength of the reinforced and unreinforced matrix, and the second term on the right is the

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

Table 9 Summarized Information on Strengthening Mechanisms in Additive Manufacturing Produced Metal Matrix Composites.

Mechanism	Cause	Contribution by AM	Comment
Hall–Petch strengthening	Reinforcements introduce nucleation sites, enhancing the nucleation rate within the metal matrix. This process leads to a finer grain structure in the solidified metal matrix. The high cooling rate of the material hinders the growth of grains of the metal matrix.	AM technologies promote the uniform distribution of reinforcements in the metal matrix. The materials such as LPBF and DED have high cooling rates during the AM process.	This enhancement in MMCs depends upon the grain size of the matrix, which is influenced by the dimensions and volume fraction of the reinforcements.
Dislocation strengthening	Geometrically necessary dislocations are generated during thermal cycling, owing to the differential expansion and contraction rates between the metal matrix and reinforcements. The produced dislocations impede each other, giving rise to the dislocation strengthening of the metal matrix.	The components are fabricated using a layer-by-layer method during the AM process, such as PBF, DED, and thermal spraying additive manufacturing, providing multiple thermal cycling of materials.	The influence of this enhancement becomes pronounced with the increase in temperature due to the growing disparity in expansion and contraction rates between matrix and reinforcements. This mechanism is less relevant at lower temperatures and can be disregarded at room temperature.
Load transfer strengthening	The reinforcements transfer tensile stress from the matrix to reinforcements, employing effective shear stresses on their interfaces.	AM technologies promote the uniform distribution of reinforcements in the metal matrix, providing more matrix interface areas and reinforcements.	This mechanism is substantially reliant on the interface quality between the metal matrix and the reinforcements, with reinforcements generated through *in-situ* reactions demonstrating more stable interfaces than *ex-situ* counterparts.
Orowan strengthening	The magnitude of stress that is necessary for dislocations to bypass the reinforcements.	AM technologies promote the uniform distribution of reinforcements in a metal matrix, providing a greater dispersion-strengthening effect.	This mechanism assumes significance only when the size of the reinforcements is less than 1 μm

In terms of their yield strength, MMCs have demonstrated a complete increase. At the yield strength, the increment contributions of refinement strengthening, dislocation strengthening, load transfer strengthening, and Orowan strengthening are represented by the symbols $\Delta\sigma g$, $\Delta\sigma d$, $\Delta\sigma LT$, and $\Delta\sigma Or$, respectively. These symbols are used to indicate the respective increment contributions. The approach that was described above is mostly applicable to the reinforcements or the matrix grains that are measured at the micrometre scale. This is due to the fact that it is possible that the procedure does not apply to nanocomposites. Getting closer to the nanoscale can cause significant changes in the properties and performance of composites and alloys [371–375]. This phenomenon happens as a result of the fact that these materials can suffer significant changes in their features and performance. A overview of the facts surrounding the strengthening mechanism in AM-produced MMCs can be found contained in Table 9. One of the elements that may be linked to the contribution that additive manufacturing methods offer to the mechanical properties of the material is the encouragement of uni-form distribution of reinforcements. Other factors that may be linked to this contribution include a high cooling rate throughout the process, several heat cycles of materials, and much more.

➢ *The Difficulties and Outlook*

The investigation of AM-produced MMCs has resulted in the development of novel methodologies and technologies. In terms of their design and processing, high-performance MMCs present a number of significant challenges that must be overcome. It is necessary to examine each and every aspect of the additive manufacturing process, from the careful selection of reinforcements and metal matrices to the thorough assessment of the additive manufacturing process itself. Despite the meticulous planning that goes into the creation of MMCs, there are still some instances in which the production fails to meet expectations. It is required to have a comprehensive understanding of the specific method in which numerous aspects interact with one another in order to attain the desired performance characteristics. This requirement must be met in order to achieve the intended results. Among these considerations are the compatibility of the materials, the parameters of the processing, and the distribution of reinforcement. In the past, the design of MMCs has typically been approached through the use of a single-step procedure, as illustration 17(a) demonstrates. The application of this methodology has been extensive. This linear strategy is consisting of a sequence of succeeding steps, each of which is in turn dependent on the outcomes of the phase that came before it. Despite this, there has been a trend toward the development of high-throughput technologies in

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

order to overcome the limitations of the single-step process. This is being done in order to overcome constraints. This change has taken place as a result of the fact that the procedure that consists of a single step is both time-consuming and economical. The utilisation of the material database as the foundation for high-throughput procedures is a typical practice. MMCs can have their composition, process, and performance optimised in a short amount of time thanks to all of these different ways. As can be seen in figure 17(b) [376], the high-throughput method offers a number of advantages in comparison to the single-step methodology. One of these advantages is the capability to carry out parallelisation, which is one of several advantages.

The design and preparation of MMCs are extremely difficult to accomplish because of the enormous number of variables that are involved. It is vital to take into account a variety of elements when designing MMCs. The characteristics of the reinforcements, as well as their kind, composition, size, and distribution, are included in these variables.

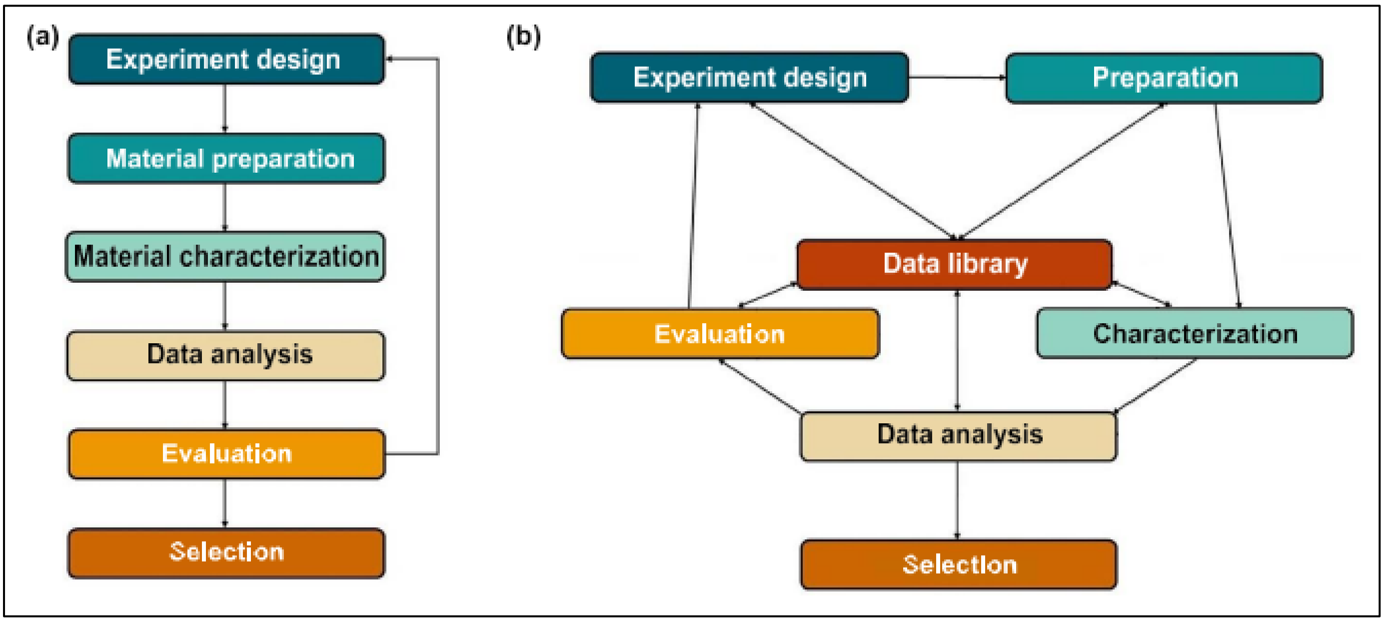

Fig 17 Comparison of the Processes in (a) the Single-Step Method and (b) the High-Throughput Method.

This covers the materials that make up the metal matrix as well as the characteristics of the interface that exists between the matrix and the reinforcement. In spite of the fact that these variables make it possible to have a greater degree of flexibility in the design and preparation of MMCs, they in addition create challenges throughout the entire process, including the designing, the preparation, and even the process itself. High throughput preparational approaches are employed in order to accomplish the goal of overcoming the complexity. What this indicates is that the number of samples produced for each of the variables is increased by a factor of two on average. It has been stated that composites and alloys can be manufactured using high throughput laser additive manufacturing procedures. Some examples of these processes include laser cladding, laser cladding, and direct laser deposition. An example of the composite was provided by Shishkovsky et al. [270], who demonstrated that the graded TiBx/Ti–6Al–4V composite was created using laser additive manufacturing (LAM) with varying amounts of TiB2 addition. When the distance between the composite and the substrate grows, the particle content of the composite also gradually increases. The analysis of the performances and microstructures of MMCs that contain different percentages of TiB2 inside a single composite is made possible as a result of this. The need to take more samples is therefore rendered unnecessary as a result of this. The fabrication of a number of different TiC/Inconel 718 composite materials on a single plate was accomplished by Kong et al. [378] through the use of a high throughput dual-feed Laser Metal Deposition (LMD) technology. These composites were given the designations T0, T5, and T10, which stood for TiC/Inconel 718 composites that comprised 0 and 5 weight percent of TiC, respectively (figure 18(a)). It is feasible for the TiC/composites to have a variation of different amounts of TiC, and it is also possible to construct them in a batch (figure 18(b)). Both of these potential outcomes are achievable. The references [379, 380] offer illustrations of additional research that have been carried out using approaches that are comparable to those described here. Therefore, in order to produce bulk samples of MMC that have a variety of features, it is necessary to make use of the right additive manufacturing (AM) processes. In the following step, high throughput characterisation technologies ought to be employed in order to provide insights concerning the composition, microstructure, performance, and interfaces that are contained within the material. The high throughput production and design of MMCs that contain particular attributes is particularly appealing when they are generated utilising the high throughput technique [381, 382]. This is especially true when the MMCs are viewed as a whole.

For the purpose of gaining an understanding of the connection that exists between the processing, microstructure, and qualities of MMC that is produced using

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

additive manufacturing (AM), there is still a need for research, technological breakthroughs, and the development of materials and processes. When in-situ techniques such as aberration corrected transmission electron microscopy and synchrotron radiation x-ray microscopy are utilised, it is feasible to get powerful insights into the mechanism of defect development, distribution of reinforcement, and other subjects that are linked to these areas of study.

In addition to the development of the microstructure [316–318]. When it came to carbon fiber/epoxy composites, for example, Liu et al. [317] employed synchrotron radiation x-ray microscopy to observe the beginning and progression of fractures in the composite while it was being loaded. This allowed them to observe both the start and propagation of cracks. It was because of this that they were able to discover the complex mechanism that operates on a nanoscale and cannot be observed using traditional methods. In order to get a comprehensive comprehension of the metallurgical behaviour of the multiphase material in the molten pool of the AM process, it is possible to create a numerical model of the metal transfer in the AM process that involves the multiphase material. [319] This model makes it possible for energy, momentum, and mass to be transferred from one multiphase substance to another. It is vital to create a link with an AM monitoring system of some kind in order to obtain information in real time while the AM process is being carried around. This is the second step that must be taken. Through the application of cutting-edge technology and numerical simulation methods, it is possible to establish an approach that is both effective and efficient in tackling such challenges.

➤ *Intrinsic Nature of MMCs Coupled with AM Technologies*

One of the most important things that must be done in order to achieve the desired level of performance is to make certain that reinforcements are distributed evenly between MMCs. When it comes to the manufacturing of MMCs, it is of the utmost importance to make certain that the appropriate material is blended in a strategic manner at the appropriate location. The typical preparation processes that are used in the traditional manufacturing process, particularly the liquid-based approaches that are used for the production of MMC, have problems when it comes to generating a completely homogeneous distribution of the reinforcement in the matrix material [383]. On the other hand, additive manufacturing techniques provide the opportunity to include reinforcements in the metal matrix in a manner that is not only uniform but also individualised [132, 384]. It is feasible to receive this benefit if the feedstock is prepared in the appropriate manner in accordance with the instructions that are provided in section 3. It is possible to obtain a somewhat homogeneous dispersion of the reinforcements (or additives) in the metal matrix, as can be shown in table 2. This is made possible by the standard techniques that are used in the fabrication of the composite feedstock, in particular the pre-alloyed powder. Despite the fact that the mechanical blending method typically indicated a somewhat lower level of reinforcements that were spread in a homogeneous manner, it is nevertheless preferable than techniques that are based on liquids [245, 383]. The DED method can be utilised even in circumstances in which the composite feedstock is not prepared prior to the AM process. This is because the DED method is a flexible method. Allows several nozzles to inject reinforcements into the metal matrix melt pool, allowing precise reinforcement control [309, 310].

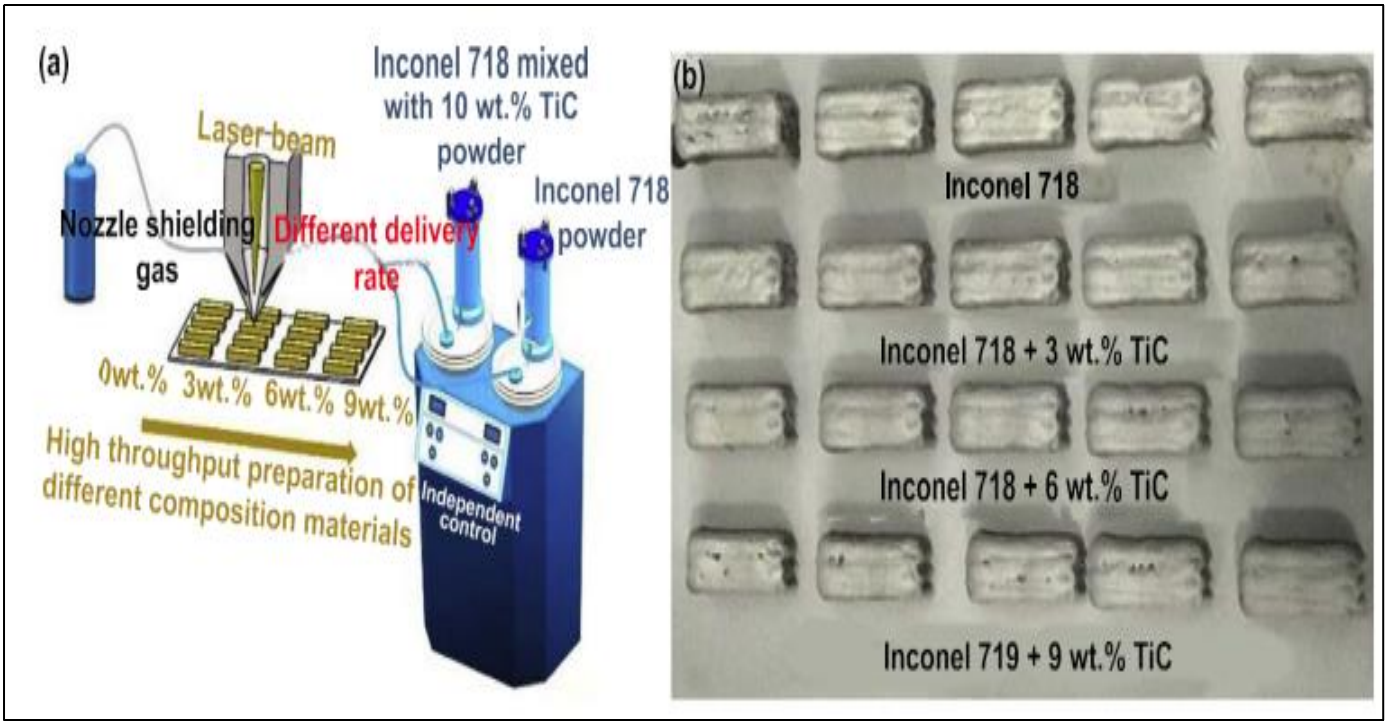

Fig 18 The high-throughput dual-feed laser metal deposition system for fabricating Inconel 718 alloy with different TiC weight percentages: (a) schematic illustration of the system and (b) the fabricated samples. Reprinted from [378], © 2019 Elsevier B.V. All rights reserved.

This has not been done with mechanically blended powder feedstock for the PBF process. It is widely accepted that pre-alloyed feedstock is the best way to produce MMC with uniformly distributed reinforcements, even though AM processes have advantages. Note that feedstock pre-alloying is still expensive. You should know about this. Producing cheaper, pre-alloyed feedstock materials is essential to addressing this hurdle.

AM technologies are interesting for MMC manufacturing due of their benefits, but they also have drawbacks. Additive manufacturing (AM) methods have high costs, limited feedstocks, limited capacity to create big components, anisotropic mechanical performances, and mass production challenges. These features contrast with low-cost conventional production methods. Whether using metals or composites, additive manufacturing has certain drawbacks. Because AM technologies depend on each other, developing AM-produced MMCs is difficult. As an example, MMC designs may need to be tailored to a feedstock that is not readily available to suit project needs.

High-resolution technologies like LPBF and EBPBF cost more and take longer to process. Because these methods are more precise. The chamber volume also limited the component size that could be manufactured using this process. Due to processing delays and high prices, additive manufacturing (AM) technologies struggle with traditional parts, which makes mass production impractical [385]. This makes additive manufacturing effective for constructing complicated MMC components such bionic design, topology-optimization, metamaterial design, and superstructure design [386-388]. This is good news.

- *Challenges During AM Procedures*

However, if SLM technology is to be widely used and have a bright future, defect-free parts must be produced. Some metal-lurgical defects on MMC parts are unavoidable. These faults include balling, porosity, and cracking. PFB, DED, BJ, and spraying technologies cause these issues. Four methods are presented in this article. Current research is aimed at finding solutions, although none have yet been found. PBF and DED procedures often experience "balling" faults. Due to the melt track failure or splash of molten metal, this flaw affects surface characteristics and quality and the uniform deposition of fresh powder layers [389, 390]. [20] [20] The quality of powder is largely controlled by its wetting properties during powder manufacturing, which accounts for a large portion of the phenomenon. This is the most critical factor in powder quality. Reinforcement often requires different processing conditions than matrix metals. This is because reinforcing alters material characteristics. The balling effect may be more noticeable in AM-produced MMCs due to these variances. Because of this, it is crucial to evaluate the quality of the materials' physical properties while choosing processing parameters.

Insufficient melting and gas entrapment in melt pools produced by AM technologies like PBF and DED (and in stacking for BJ and spraying technologies) are two of the most common drawbacks of AM-produced parts and major contributors to porosity [90, 122, 135]. AM parts have poor melting. Modifying additive manufacturing settings reduces poor melting and gas entrapment [391]. Gas entrapment and melt pool fluid flow instabilities can reduce melting. A well-tuned feedsock and post-treatment procedure can reduce particle stacking pores [392, 393]. This procedure has been shown to reduce holes. Due to the balling effect, adding reinforcements to MMC additive manufacturing might increase porosity. Dadbakhsh and Hao say Fe2O3 affects porosity. Additionally, [394] discovered that higher reinforcement percentages accentuate porosity. The previous paragraph covered both findings. Unfortunately, given that many

Few articles have covered compact part manufacture. However, almost compact components with 0.5% porosity are possible [161, 395, 396].

Hot cracking and cold cracking of fracture are additive manufacturing applications. The most popular categories are these two. Hot fractures occur when grain-based continuous skeletons arise later in solidification. This allows heated fractures. Considering this, thin equiaxed semi-solid microstructures may limit liquid entrainment. Grain rotation and deformation are impossible in dendritic microstructures [397], yet they may allow it. Due to the above rationale. This characteristic prevents cracks from growing throughout the semi-solid material when it absorbs tension. Nucleation site reinforcements can promote equiaxed structure development [261, 398]. Put reinforcements in the structure. AM procedures show this cold crack more due to residual tensions [399]. It forms because residual tensions result. These forces can produce cracks and material layer separation [226]. Cracks and separation are possible. These internal trainings are prevalent in multi-phase materials due to changes in thermal expansion coefficient [400]. Preheating the base substrate reduces the temperature differential, which can help manage residual stress. This is one method. Reinforcements in AM-fabricated MMCs can change melt pool flow due to the additively manufactured material's increased viscosity. Because of has increased viscosity. To minimise clumping and disperse particles equally, the manufacturing process may need more energy density. When the temperature is high, it reduces the effect of liquid mass viscosity on spreading out to generate a dense end product. (2) It speeds up liquid mass spread. It helps burn out cars and make a more consistent paste. Residual strains cause cracks when energy input and temperature gradient are high [401]. This creates a precise balance between viscosity and fine grain control. This requires more investigation to understand and manage the situation.

As previously stated, the faults and mechanisms that caused them in AM-made MMC parts would significantly affect their performance. However, those parts' performance would suffer. Since they are made using the same AM method and reinforcing material, certain MMC can have different qualities. Most of this is due to processing parameter changes [211, 243, 310, 311]. Thus, AM-fabricated MMCs still struggle to find the best conditions for reproducing features. This is important. Many AM-created MMCs contain in situ

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

reactions [36]. In additive manufacturing (AM), in-situ reactions between additives and metal matrix must be considered. Because these reactions occur during AM. The circumstances may make these reactions endothermic or exothermic.

Post-mounted ceramic reinforcement may cause rare LPBF, which can crack. Because AM's production methods cool quickly, this is the case. Therefore, it is crucial to carefully choose the type of reinforcements, their morphologies, and their amounts to prevent in-situ reactions and metal matrix cracking. Thus, processing parameters should be changed to prevent stress concentration and increase MMC performance. For in-situ generated reinforcements, which are essential for additive manufacturing, parameter optimisation is crucial.

Unfortunately, there is no complete processing parameter database to simplify AM-produced MMC manufacture. To simplify manufacturing. New additive manufacturing processes are still difficult to develop.

➢ *Future Interests*

There are two key research directions that should be taken into substantial consideration for AM-produced MMCs in the future. These directions should be taken into account. To get things started, there is the optimisation of the cost of the technologies that constitute additive manufacturing. However, another element that should be taken into consideration is the potential uses of AM-produced MMCs. When it comes to the economic aspect of the manufacturing of MMCs using AM, it is frequently the case that the usual way of fabrication is not the best option. This is because AM is one of the emerging technologies. Especially for the low volume production that is typically found in manufacturing in a centralised facility, recent study on the cost of additive manufacturing (AM) reveals that, from a financial point of view, AM delivers a reasonably decent value [402]. This is especially true for the low volume output that is typically found in AM. In contrast, the expansion of automation results in an increase in the possibility for cost-opportunities in distributed industrial production. This is a positive development. There are a variety of costs that are currently linked with additive manufacturing (AM) technology [402]. These costs include material prices, machine costs, build envelope utilisation, build time, energy usage, and human costs. A rough estimate of the costs associated with the materials is somewhere in the region of thirty percent to fifty percent, depending on the type of materials that are utilised and the quantity that is utilised. 403, 404: [403] The cost of machines ranges from around 10–20 percent, while the cost of energy is between 5 and 15 percent. Because of the problems that have been described above, the reduction of expenses that are related with AM technologies is not as simple and clear as it might be. Therefore, it is required to carry out cost and cost savings on a large scale across the entirety of the additive manufacturing process. The selection and optimisation of materials is one of the most expensive operations that is currently being performed [404].

There have been numerous potential application areas for AM-produced metal-metal composites in a variety of industrial sectors as a result of the advantages of additive manufacturing (AM) technologies, which include design freedom, material use, topology optimisation, rapid prototyping, customisation, and less assembly [39]. Additionally, the advantages of metal-metal composites (MMCs), which include strength, rigidity, weight reduction, wear resistance, corrosion resistance, thermal property, and an increase in fatigue life [1, 405], have led to the development of numerous potential application areas for AM-produced MMCs. Both additively manufactured composites (AMCs) and thermochemically manufactured composites (TMCs) have applications in the aerospace sector. Fuel nozzles and engine parts, for example, require lightweight structural frames in order to function properly. In addition, additive manufacturing can be used to manufacture space capsule interior structures and space suit accessories due to the high specific strength of these materials and their ability to be created in a personalised manner [68, 284].

TMCs that are created by AM have the potential to be employed in biomedical applications due to their high strength, compatibility, and the capacity to be shaped in intricate geometries. This is because AM is capable of producing TMCs because of these characteristics. An example of one of these applications is the production of surgical instruments, orthopaedic implants, and individualised orthodontic treatment [293]. In the chemical and petroleum industries, the AM-produced NMCs have been utilised in applications that demand them to function under extreme conditions. These applications include nuclear reactors, automobile exhaust and turbochargers, valves, pumps, and a variety of other applications [330, 338]. Because of the exceptional heat transmission, CRW, and ORW characteristics that they possess, this is the current situation. The demand for improving the performance and mass efficiency of developments in aerospace and automotive engineering is well established as a result of this. Additionally, the understanding of the potential application of MMCs in additive manufacturing (AM) is well documented. The process of producing female genital mutilations (also known as FGMs) has become much simpler as a result of technological advancements.

Such a reality that will further optimise the qualities of the material resources that are available. Enhancing the important physical properties of AM-produced MMCs through the development of new processes and expanding the applications of AM-produced MMCs in the field of personalised manufacture and repair are the primary objectives of this research. These objectives will be accomplished through the development of new procedures. The development of this sector calls for the cooperation of specialists from a wide range of fields, and the requirements for cost-effectiveness and the efficient utilisation of resources will be the primary focus of research in the years to come.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26jun2045

V. CONCLUSIONS

This article, which is a part of this collection, offers a summary of the most recent advancements in AM of MMCs. It is included in this collection. The advancements that incorporate these things include additive manufacturing (AM) technologies, feedstock, reinforcements, magnetic material composites, and strengthening mechanisms, among other things. MMCs have been put to use for a wide range of industrial applications for a substantial amount of time. This is primarily due to the excellent characteristics that they possess. On the other hand, the common processes that are utilised for the production of MMMC components are lengthy and costly. These techniques entail a number of processing phases. Consequently, as a result of this, it is becoming a new source of optimism in the sphere of MMC industrial production. It is still common practice to use powder-based additive manufacturing techniques for the production of metal-metal composites (MMCS), despite the fact that numerous types of additive manufacturing techniques have been developed over the course of the past few decades. Some examples of these techniques include powder bed fusion (PBF), deposition engineering (DED), and blasting technologies.

The behaviour of MMCs that are produced using additive manufacturing is discussed, along with the impact that feedstocks have on the performance of these materials. In-situ and ex-situ procedures are often used in conjunction with one another when it comes to the processing of feedstocks during the manufacturing process. The first technique entailed the production of a composite powder, in which the reinforcement and the metal matrix were distributed in a manner that was uniform throughout the resulting powder. The second approach required the manufacture of a combination powder, which included the metal matrix powder and additives blended together. This powder was then used in the second process. Regardless of the circumstances, it is of the utmost importance to achieve a constant distribution of reinforcement in order to create MMCs that have a high level of performance. It is necessary to make use of reinforcements that offer a high level of thermal stability, hardness, and compatibility with the metallic matrix. This should be the alternative that is favoured. Throughout the course of this review, it was demonstrated that oxides, carbides, and borides have been the primary materials that have been utilised in MMCs the majority of the time.

In the creation of high-performance metal-metal composites (MMCs), specifically those material combinations consisting of titanium, aluminium, iron, and nickel, additive manufacturing (AM) technologies have been shown to be effective. When it comes to MMCs, the integration of reinforcement results in a reduction in the grain size of the metal matrix in contrast to the grain size of the pure metal matrix. In turn, this results in superior mechanical qualities, which in turn results in the prevention of cracks from forming and spreading throughout the material. Furthermore, the quick cooling rate that is utilised in the AM process contributes to the enhancement of the microstructures of MMCs. MMCs are the final product of the additive manufacturing process, and they are able to take advantage of the advantages offered by both the technologies of additive manufacturing and the materials used for reinforcing. However, there are a significant number of challenges that have not yet been overcome in order to make a larger transition of the potential for full-scale commercialisation of AM-produced MMCs. This transformation is necessary in order to make a larger transition. When it comes to the design, processing, and optimisation techniques for these materials, having a full grasp of the processing – micro-structure – property of the AM-produced MMCs will prove to be advantageous. in point of fact, this understanding will prove to be beneficial.

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