Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

A REVIEW OF THE CERAMIC REINFORCED Ni-BASED SUPERALLOYS

Abdalla Elmaghraby* and AMM Nazmul Ahsan†

*Department of Mechanical Engineering, The University of Texas Rio Grande Valley, Edinburg, TX, 78539
†Department of Manufacturing and Industrial Engineering, The University of Texas Rio Grande Valley, Edinburg, TX, 78539

Abstract

Superalloys based on nickel are an intriguing class of materials that exhibit exceptional performance in a variety of challenging environments, including corrosive media, elevated temperatures, and high pressure. This group of alloys is one of the promising options for the petrochemical, aerospace, and aviation industries and the defense sector. However, in certain situations, the industry's needs are greater than the progress made in alloys and superalloys, necessitating further research into alternative methods of improving material properties. Recently, ceramics have been used to fabricate metal matrix composites (MMCs) by adding them as reinforcements to the metal/alloy matrix fusing the properties of both alloys and ceramics. Given that the properties obtained from the alloy MMCs are significantly enhanced, a new chapter in nickel-based superalloys is emerging. This review article provides a comprehensive understanding of the research findings on ceramic-reinforced nickel-based superalloy MMCs, as well as future research trends.

Introduction

Strong, hard, ductile, and having a high melting point, nickel is a metal that is widely distributed in the Earth's crust. It also functions well at elevated temperatures, even near its melting point [1],[2]. The alloy created, when nickel is combined with other metals has improved qualities which make it one of the key components for producing mechanical parts for high-temperature applications, including gas turbines, aero-engines, nuclear reactors, furnaces, and aerospace components, is nickel-based superalloy [3],[4]. The strengthening mechanisms of precipitation, dispersion, and solid solution hardening are responsible for the mechanical properties and microstructure evolution of those superalloys [5],[6]. These wonderful qualities proved insufficient for many applications of the modern era; more improved properties are required, and some issues with Ni-superalloys must be taken into consideration. The hardness and strength of Ni-based superalloys make them difficult to machine, and their high melting temperatures make their fabrication energy-intensive [7],[8],[9]. These two Ni-based superalloy problems indicate that these materials require modification to improve their refinement and overcome their shortcomings. Because of this necessity, researchers began to consider more than just enhancing a material's qualities by adding other metals. They also considered combining ceramics with metals and alloys to obtain advantageous properties, which led to the development of the idea of metal matrix composites (MMCs) [10]. The idea behind it is straightforward: to give the Ni-based superalloys—the matrix material in this case—more strength, ductility, and resistance to wear and corrosion, simple ceramics are added [11]. Using ceramics as reinforcement to the newly created

MMCs, scientists realized that the properties of those materials can be tailored to use for specific applications [12],[13].

Microstructure and Properties of Ni-based Superalloys

Ni-based superalloys' superior thermomechanical qualities, such as creep resistance, combined with their high mechanical strength, good weldability, low thermal conductivity, work hardening tendencies, fatigue, oxidation, corrosion, excellent weldability, and high thermal stability, are some of the reasons they dominate many critical industries, including the automotive, aerospace, energy, chemical, and defense sectors [14],[15],[16],[17],[18]. The distinct microstructure of those superalloys, which usually consists of an intricate arrangement of phases and precipitates, is the cause of all those qualities and traits. There are two main phases– γ & γ' [19]. The γ phase is a solid solution based on nickel with a face-centered cubic crystal structure and the precipitation of $Ni_3(Al, Ti)$ within the matrix is identified as the other phase γ' [20]. Additionally, it was observed that the microstructure contained other phases, such as δ phase and some cohort of L12 precipitates, as well as extra phases of carbides, or MC carbides, at the grain boundaries [21],[22]. All these phases and precipitates contribute to the amazing properties and structural integrity. Shaping the microstructure and stabilizing it can be controlled through many ways such as the presence of nickel, aluminum, ruthenium, rhenium, and cobalt or some impurities like sulfur [23],[24],[25]. Another way is through thermomechanical processes such as hot forging [26] and heat treatment techniques [27].

Reinforcement Materials for Ni-based Superalloy MMCs

Numerous ceramic reinforcement groups exist, including nitrides, oxides, carbides, and borides [28], [29]. Every one of these groups serves to improve a specific set of properties; occasionally, the matrix is reinforced with more than one ceramic reinforcement which is known as a hybrid reinforced MMC [30]. It is not just ceramics either; certain metals, such as boron, are occasionally employed as reinforcement [31]. Ceramics are used less frequently than metals, primarily as reinforcement for metal matrix composites, cutting tools, catalysts, and insulators [32]. Ceramics are preferred for use as reinforcement materials due to their strength, chemical stability, low coefficient of expansion, and hardness [33],[34]. Ceramics do have certain disadvantages as well, such as poor ductility and fracture toughness [35].

Oxides are used to improve the MMC's hardness, wear and corrosion resistance, oxidation prevention, and thermal stability [36],[37]. In certain instances, oxide like Al_2O_3 is used to stop SiC from diffusing into the nickel matrix [38]. When it comes to reinforced nickel-chromium alloys, Al_2O_3 and TiO_2 are used to improve their wear resistance, thermal conductivity, and significantly lower their coefficient of thermal expansion as shown in Figures 1(a-b) [39]. An additional noteworthy instance involved the reinforcement of nickel and nickel-cobalt alloys using zirconia (ZrO_2). Microhardness, corrosion resistance, and wear resistance of the resulting composites were improved as observed in Figure 1(c) [40]. The ductility and strength of the composites were found to have significantly improved in another instance where the same reinforcement was used in conjunction with nickel [41].

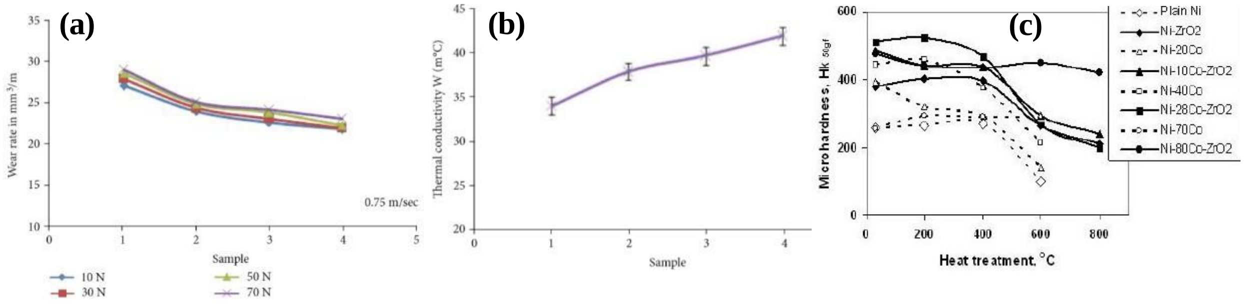

Figure 1. (a) Improved wear rate under different forces and (b) enhancement of thermal conductivity when reinforcing the nickel-chromium alloy with Al_2O_3 and TiO_2 [39]. (c) Improvement of micro hardness when reinforcing the nickel-cobalt alloy with zirconia [40].

Nitrides have a lubricating mechanism that increases surface slipperiness and improves anti-friction qualities, which helps lessen composite wear. Additionally, it improves the mechanical characteristics, such as oxidation kinetics and creep resistance, which help the MMCs function well at elevated temperatures [42],[43],[44]. When nickel-copper is reinforced with cubic boron nitride (c-BN), the resulting composite demonstrates enhanced magnetic and hardness characteristics as Figures 2(a-b) illustrate, decreased density, and increased electrical resistivity [45]. In a different instance, the composite that was produced after Inconel 718 was reinforced with hexagonal boron nitride (h-BN) demonstrated a decrease in hardness and compressive strength while lowering the coefficient of friction as Figures 2(c-d) show, as a result of the sliding lubricating effects based upon the exfoliating effect of boron nitride. This increased the composite's wear resistance [46].

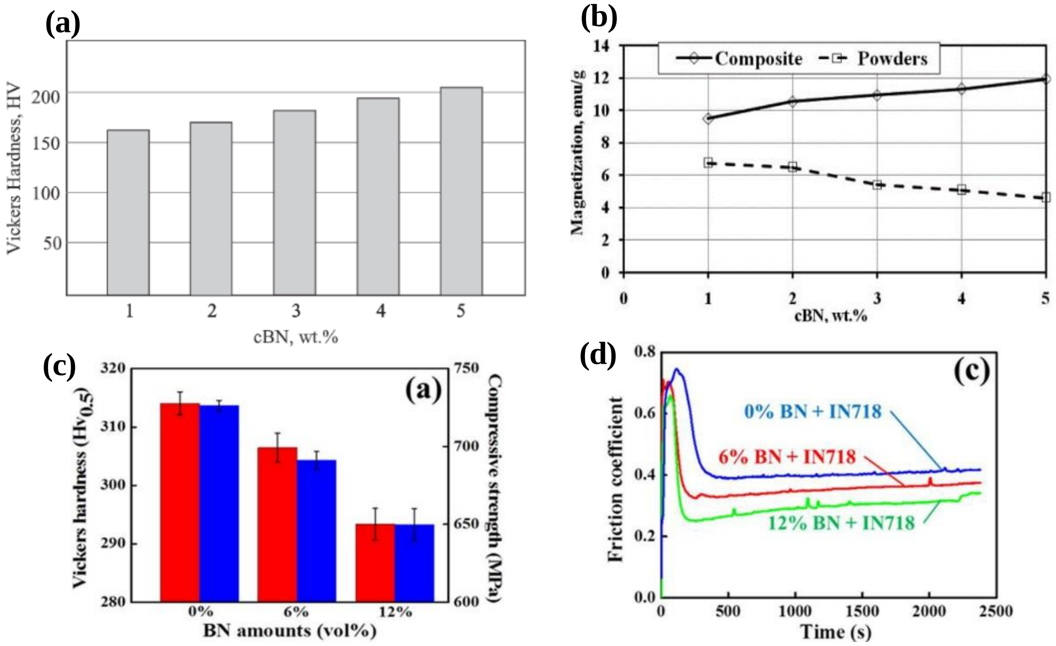

Figure 2. (a) Increase in hardness associated with the increase in c-BN content in nickel-copper alloy and (b) improvement of the magnetization of the composite with the increase in the c-BN content in nickel-copper alloy [45]. When reinforcing Inconel 718 with h-BN, hardness and compressive strength decrease (c) while lowering the coefficient of friction (d) [46].

Carbides are one of the most popular and well-developed type of reinforcement. Hardness, ductility, strength, creep resistance, corrosion resistance, wear resistance, and fatigue resistance are all improved by adding carbides to the MMCs [47], [48], [49]. The interesting example of using TiC to reinforce GTD222 revealed that while the elongation decreased by 5%, the composite characteristics showed significant improvements in strength [50] as observed in Figure 3(a). In an additional instance of using WC to reinforce a nickel-based matrix, it was observed that the resulting composites exhibited improved hardness, tensile strength, and wear resistance as shown in Figures 3(b-c) because the stiff carbide particles improved the composite's ability to share loads [51][52][53].

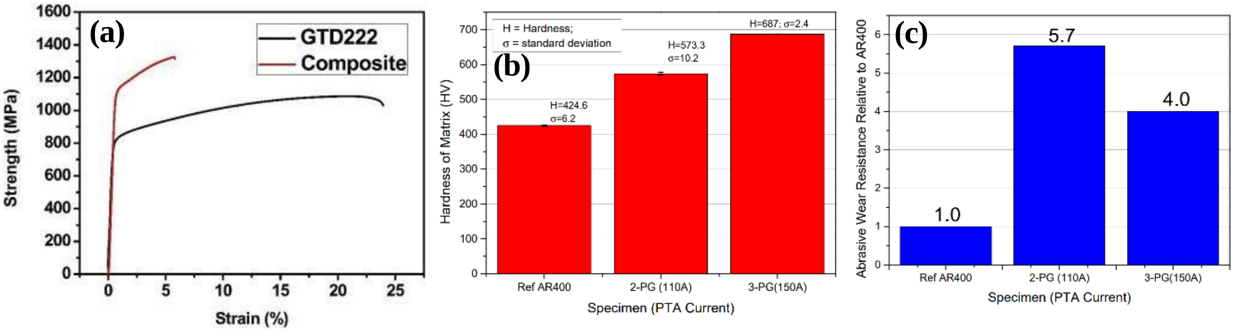

Figure 3. (a) Strength increases while ductility decreases in GTD222-TiC composite compared to the pure alloy [50]. (b) Hardness as well as (c) wear resistance increases after adding WC to nickel based composites [51][52][53].

Borides ceramic group is one of the least studied reinforcement groups. Along with having a lower density, improving performance at elevated temperatures, and increasing strength and hardness, this group tends to improve the mechanical properties of MMCs in the same way as most ceramic groups do [54], [55], [56], [57]. The use of borides to reinforce MMC is rare; one example is ZrB_2 reinforced Inconel 718. In comparison to the original alloy, the resulting high-temperature performance was improved, achieving 10% elongation, and the yield strength was increased by 10% to 15% as shown in Figure 4(a). The reduction in grain size can explain these improvements [58]. In a different instance, the hardness of fabricated composite increased by 50%–28% at the yield strength sacrificing the ductility as shown in Figure 4(b-c) when TiB_2 was used to reinforce Hastelloy X. Additionally, the inclusion of TiB_2 aids in the reduction of microcracks, improving performance at elevated temperatures [59].

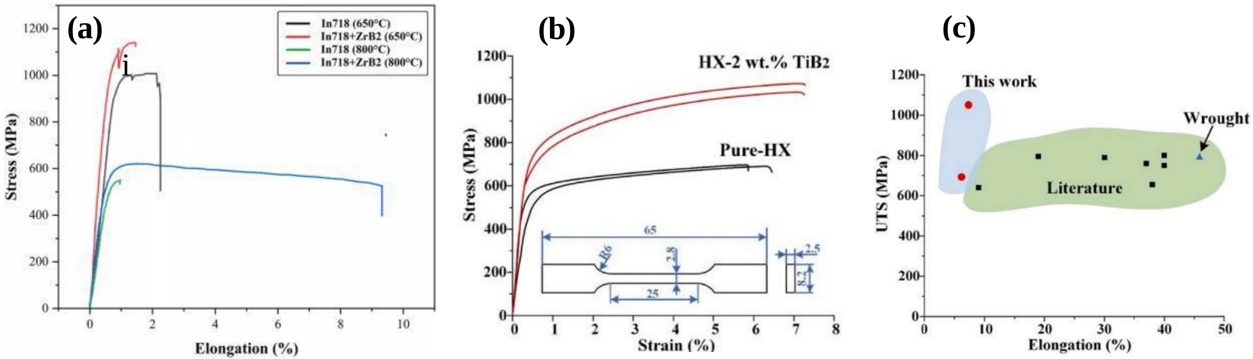

Figure 4. (a) Enhancement of high temperature performance of Inconel 718 reinforced with ZrB_2 [58] and (b & c) reinforcing hastelloy with TiB_2 increses strength and reduces ductility [59].

Fabrication Techniques for Ni-based Superalloy MMCs

There are many different MMC fabrication methods [60], so it is important to pick one carefully. There are no suggested methods for creating MMCs, as traditional techniques, such as stir casting, are economic and quick [61], [62] but challenging when it comes to the quality of the MMC because of many reasons such as porosity and agglomeration [63]. While laser powder bed fusion and other additive manufacturing techniques are precise when it comes to complex geometries [64], [65], their fabrication takes a long time and require post process treatment to achieve the desired properties [66], [67]. For a variety of reasons, including the rate of cooling and solidification among the others, the fabrication processes also modify the properties of composites [68], [69], [70]. For this reason, great care must be taken when selecting a fabrication technique. The fabrication methods can be classified as either liquid-state fabrication or solid-state fabrication.

Solid-state fabrication methods of MMCs:

Powder metallurgy can be used to produce a range of metal and composite materials. It is a manufacturing technique that uses metal powders either by themselves or in conjunction with non-metallic powders [71]. The mixing, pressing, sintering, shaping, and oil immersion processes combine to create the final product as shown in Figure 5 [72]. Because it provides a uniform microstructure for the composites and allows for control over process variables like temperature and reinforcement distribution [73], [74], this method is frequently used to create MMCs. Several examples of the application of powder metallurgy include the investigation of the mechanical characteristics of composites, such as nickel-graphene, and the impact of temperature changes during sintering [75]. Additionally, solid lubricants have been used as a second phase to develop self-lubricating nickel composites [76].

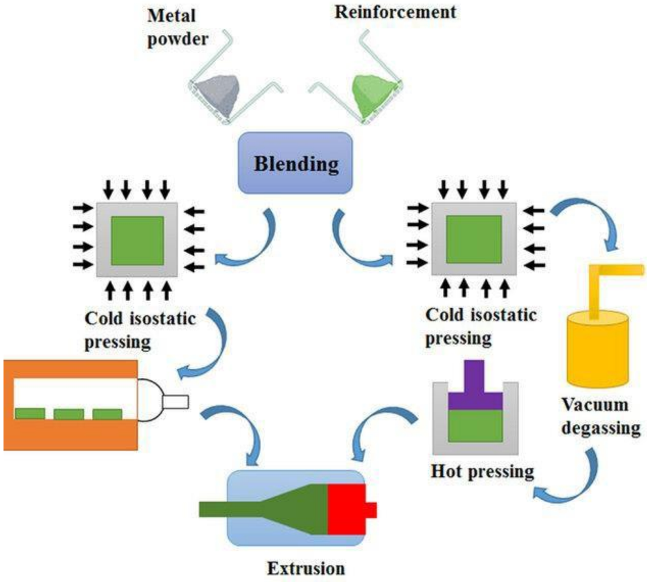

Figure 5. Powder metallurgy process of MMCs [77].

Laser powder bed fusion (LPBF) is an innovative additive manufacturing technique to fabricate 3D parts and structures. It relies on the selective laser melting of a thin layer of powder that has been spread out to take on the required shape on a building platform as shown in Figure 6. Another layer of powder is applied after the melted layer has solidified. Until the intended 3D shape is obtained, these steps are repeated [78], [79]. This process has numerous industrial applications in a variety of industries, including aerospace, defense, medical, and automotive [80]. The advantages of LPBF include its ability to fabricate intricate shapes with high-quality surfaces [81], low waste of row material due to the reusable nature of the powder after sieving [82], degree of customization [83], [84], and robust bonding between layers [82]. LPBF is used to fabricate advanced composites. For example, a study of LPBF of Ni-Ti coated diamond/N6 was conducted to examine the outcome of Ni-Ti incorporation with diamond and the microstructure behavior of the resulting composite material [85]. Another study of Haynes 230 reinforced with carbon nanotube (CNT) was conducted to examine the mechanical properties change with varying percentages of CNT (2.5% & 5%) [86].

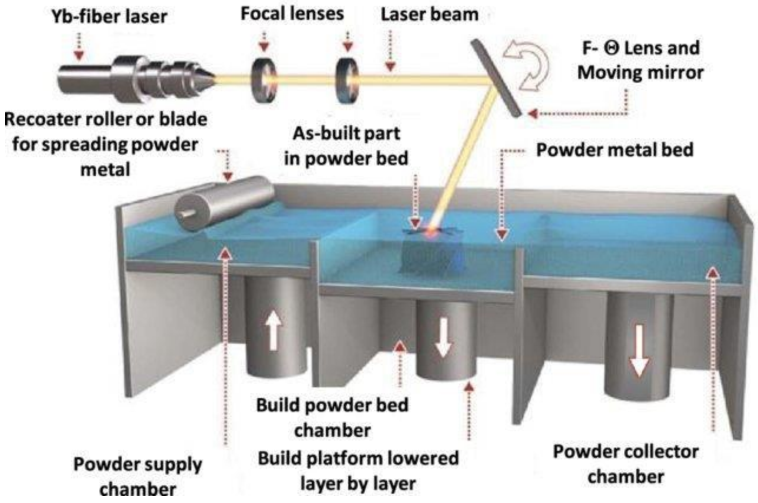

Figure 6. Laser powder bed fusion (LPBF) process [87]

Liquid state fabrication methods of MMCs:

Stir casting, which involves adding the reinforcement phase to the molten metal and mechanically stirring the mixture using the set up as shown in Figure 7(a), is one of the most popular methods for creating MMCs [88], [89], [90]. Stir casting is used in many industries, including the research and development of materials, the automotive, aerospace, and defense sectors [91], [92], [93]. Stir casting has many benefits, including mass production due to its scalability and efficiency, near-net shape products that require less machining, a simple method that requires few complications, decent bonding between the reinforcement and matrix for enhanced properties, a faster manufacturing rate than solid-state fabrication methods, and cost-effectiveness, which accounts for its widespread adoption [94], [95], [96], [97], [98]. A few intriguing cases have been reported involving the stir casting of MMCs. One such case involves examining how chills impact the mechanical properties and microstructure of an ASTM A 494 M grade nickel alloy reinforced with SiO_2 MMC. The goal of this study is to find out if nickel based MMC can be produced using a traditional electric induction furnace and how adding chills to the mixture affects both the mechanical and microstructure properties [99]. Another study examined the use of TiO_2 for Ni-Cu alloy reinforcement to investigate the impact of this material on the microstructure, thermal conductivity, and coefficient of thermal expansion [100].

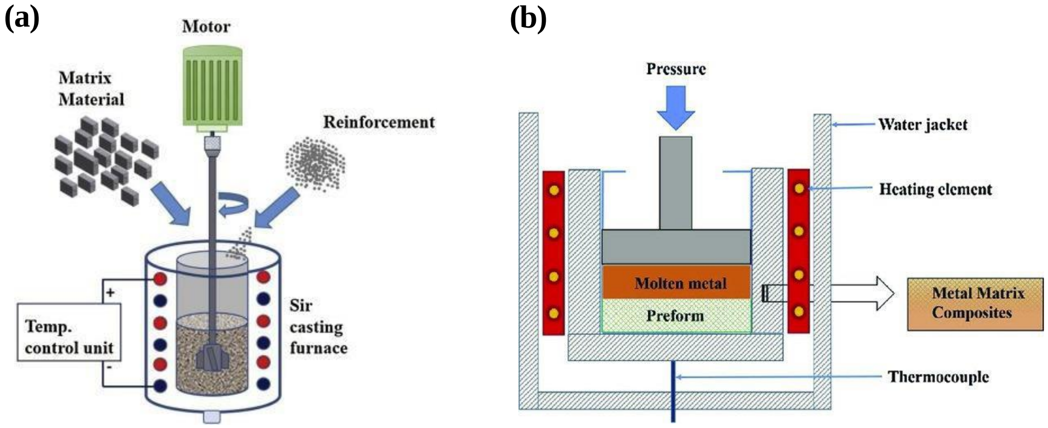

Figure 7. shows the (a) stir casting setup, (b) squeeze casting setup [101]

Squeeze casting is an MMC manufacturing technique that applies the concepts of gravity and pressurized casting by pouring melted metal into a preheated die as shown in Figure 7(b). Once the proper mixture volume is reached, pressure is gradually increased using a ram, and it is kept there until the mixture solidifies in a closed die. Pressure reduces shrinkage and micro-shrinkage porosity while facilitating the metal flow throughout the solidifying casting [102], [103], [104]. This type of casting has many advantages, including the ability to cast complex shapes and, similar to other casting techniques, the cost-effectiveness, high density, and quality of the products, as well as the vital role that pressure plays in enhancing the microstructure and producing good mechanical properties. It is also well-suited for mass production [105], [106], [107], [108], [109]. Many industries use squeeze casting such as automotive, defense, aerospace industries, and research and development [93], [105], [110], [111], [112]. Several intriguing studies have been conducted on squeeze casting, including one that tested the viability of creating Ni-Cr composite reinforced with Al_2O_3 by high temperature squeeze casting (HTSC), as well as the impact of the increase in temperature on the mechanical properties and microstructure [113]. Another instance involved the same materials but to study the creep behavior of the interpenetrated Ni-Cr/Alumina composites [114].

Applications

The improved properties of nickel-based metal matrix composites made it possible for the nickel MMC to compete with the well-known nickel-based superalloys as a response to the continuous need for more advanced materials with superior properties. Because of their high thermal strength and creep resistance, nickel MMCs are used in most parts found in industrial gas turbine engines, aviation, aerospace, and naval ships that are subjected to extreme heat [115], [116], [117], [118]. Due to their ability to withstand wear and their self-lubricating mechanisms resulting from the addition of reinforcement to the matrix material, bearings made of these materials are also frequently used in other industries [115], [119], [120], [121]. Additionally, nickel MMCs are perfect for use in pumps, pipe coatings, cutting tools, valves, automotive, electric, petrochemical, and electronic industries due to their high strength, toughness, resistance to corrosion, and high thermal and electrical conductivity [122], [123], [124].

Future Trends

Nickel-based metal matrix composites present many opportunities to improve mechanical, tribological, and corrosion-resistant characteristics in many industrial applications. Adding various reinforcements, like carbon nanotubes, graphene nanosheets, and titanium carbide, has improved the overall performance of nickel-based composites in a promising way. Because of their special blend of metallic and ceramic qualities, these materials are being investigated and found to be useful in a variety of industries, including aerospace, automotive, electronics, and defense. Further novel approaches to improving the characteristics of metal matrix composites based on nickel are being investigated by research and development in this field, opening new possibilities for materials science and engineering. A multidisciplinary strategy that incorporates materials science, chemistry, physics, engineering, and artificial intelligence will define the future directions in nickel-based metal matrix composites research. A dynamic and inventive environment is indicated in the field by the continuous investigation of novel materials, improved composite coatings, sustainable methods, and advanced composite materials like nickel-graphene nanocomposites. The development of high-performance materials for various industrial applications is expected to witness notable progress due to these trends, which will also influence the direction of future research on nickel-based alloys and metal matrix composites.

Conclusion

This review article has thoroughly investigated the field of nickel-based superalloy MMCs reinforced with ceramics. It has brought attention to the drawbacks of conventional nickel-based superalloys and the ways in which MMCs can be used to overcome them. This paper has examined the microstructural characteristics and traits of these composites, highlighting the impact of different elements such as the kind of reinforcement, processing methods, and resulting material properties.

Key takeaways from this review include:

- Superalloys based on nickel have great strength, thermal stability, and resistance to creep and corrosion, making them extremely effective in harsh environments.
- Still, more developments in these materials are required to meet the demands of contemporary applications.
- Ceramic reinforcements added to nickel-based superalloy MMCs offer a path toward improved properties.
- The MMCs' mechanical properties, thermal stability, and microstructure are all impacted by the choice of processing methods and reinforcement materials.

The potential of nickel-based superalloy MMCs is acknowledged in the present article, with particular attention to industries that require high-performance materials for harsh environments. It highlights the necessity of additional study to completely realize these composites' potential, enhance their characteristics for particular uses, and develop new MMCs.

References

[1] S. P. Dwivedi *et al.*, “The Microstructure and Properties of Ni-Si-La2O3 Coatings Deposited on 304 Stainless Steel by Microwave Cladding,” *Materials*, vol. 16, no. 6, p. 2209, Mar. 2023, doi: 10.3390/ma16062209.

[2] G. Genchi, A. Carocci, G. Lauria, M. S. Sinicropi, and A. Catalano, “Nickel: Human Health and Environmental Toxicology,” *Int J Environ Res Public Health*, vol. 17, no. 3, p. 679, Jan. 2020, doi: 10.3390/ijerph17030679.

[3] Sh. Kh. Mukhtarov *et al.*, “Recrystallisation behaviour and mechanical properties of a novel Re-containing nickel-base superalloy,” *Materials Science and Technology*, vol. 35, no. 13, pp. 1605–1613, Sep. 2019, doi: 10.1080/02670836.2019.1633726.

[4] C. T. Sims, “A contemporary view of nickel-base superalloys,” *JOM*, vol. 18, no. 10, pp. 1119–1130, Oct. 1966, doi: 10.1007/BF03378505.

[5] A. Aherwar, A. Singh, and A. Patnaik, “Study on mechanical and wear characterization of novel Co30Cr4Mo biomedical alloy with added nickel under dry and wet sliding conditions using Taguchi approach,” *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 232, no. 7, pp. 535–554, Jul. 2018, doi: 10.1177/1464420716638112.

[6] B. Geddes, H. Leon, and X. Huang, *Superalloys*. ASM International, 2010. doi: 10.31399/asm.tb.sap.9781627083133.

[7] G. Lu, H. Wu, Q. Yan, B. Lu, P. Mao, and M. Liu, “Influence of laser remelting on surface topography and chemical component of K423A nickel-base superalloy,” 2015. doi: 10.2991/mebe-15.2015.59.

[8] O. Stanners, S. John, H. M. Davies, I. Watkins, and S. Marchisio, “The Effect of Processing Variables on Powder Interlayer Bonding in Nickel-Based Superalloys,” *Materials*, vol. 13, no. 3, p. 601, Jan. 2020, doi: 10.3390/ma13030601.

[9] G. K. Salwan, R. Subbarao, and S. Mondal, “Analysis on the Suitability of Powder Metallurgy Technique for Making Nickel Based Superalloys,” *IOP Conf Ser Mater Sci Eng*, vol. 1248, no. 1, p. 012036, Jul. 2022, doi: 10.1088/1757-899X/1248/1/012036.

[10] S. Antonov *et al.*, “Comparison of thermodynamic database models and APT data for strength modeling in high Nb content γ–γ′ Ni-base superalloys,” *Mater Des*, vol. 86, pp. 649–655, Dec. 2015, doi: 10.1016/j.matdes.2015.07.171.

[11] A. Sergi, R. H. U. Khan, S. Irukuvarghula, M. Meisnar, A. Makaya, and M. M. Attallah, “Development of Ni-base metal matrix composites by powder metallurgy hot isostatic pressing for space applications,” *Advanced Powder Technology*, vol. 33, no. 2, p. 103411, Feb. 2022, doi: 10.1016/j.apt.2021.103411.

[12] K. Jayappa, V. Kumar, and G. G. Purushotham, “Effect of Reinforcements on Mechanical Properties of Nickel Alloy Hybrid Metal Matrix Composites Processed by Sand Mold Technique,” *Applied Science and Engineering Progress*, vol. 14, no. 1, Nov. 2020, doi: 10.14416/j.asep.2020.11.001.

[13] G. Veerappan, M. Ravichandran, M. Meignanamoorthy, and V. Mohanavel, “Characterization and Properties of Silicon Carbide Reinforced Ni-10Co-5Cr (Superalloy) Matrix Composite Produced Via Powder Metallurgy Route,” *Silicon*, vol. 13, no. 4, pp. 973–984, Apr. 2021, doi: 10.1007/s12633-020-00455-9.

[14] R. Ma, L. Li, R. Zhai, X. Meng, and J. Zhao, “Hot Deformation Behavior and Processing Map of GH901 Superalloy,” *Metals (Basel)*, vol. 11, no. 11, p. 1808, Nov. 2021, doi: 10.3390/met11111808.

[15] X. Lu, Z. Jia, X. Wang, G. Li, and Z. Ren, “Three-dimensional dynamic cutting forces prediction model during micro-milling nickel-based superalloy,” *The International Journal of Advanced Manufacturing Technology*, vol. 81, no. 9–12, pp. 2067–2086, Dec. 2015, doi: 10.1007/s00170-015-7310-0.

[16] D. Dubey, R. Mukherjee, and M. K. Singh, “A review on tribological behavior of nickel-based Inconel superalloy,” *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 238, no. 6, pp. 706–732, Jun. 2024, doi: 10.1177/13506501241235724.

[17] H. ElRakayby and K. Kim, “Deformation and densification behaviours of nickel-based superalloy during hot isostatic pressing,” *Powder Metallurgy*, vol. 60, no. 4, pp. 293–300, Aug. 2017, doi: 10.1080/00325899.2017.1298875.

[18] S. Lv, C. Jia, X. He, Z. Wan, Z. Chen, and X. Qu, “Effect of Preannealing on Microstructural Evolution and Tensile Properties of a Novel Nickel-Based Superalloy,” *Adv Eng Mater*, vol. 22, no. 6, Jun. 2020, doi: 10.1002/adem.202000134.

[19] A. Epishin, T. Link, M. Nazmy, M. Staubli, H. Klingelh□ffer, and G. Nolze, “Microstructural Degradation of CMSX-4: Kinetics and Effect on Mechanical Properties,” in *Superalloys 2008 (Eleventh International Symposium)*, TMS, 2008, pp. 725–731. doi: 10.7449/2008/Superalloys_2008_725_731.

[20] B. Kościelniak, S. Roskosz, and J. Cwajna, “Evaluation of Carbides in Turbine Blade Made of IN713C Superalloy After Hot Isostatic Pressing,” *Archives of Metallurgy and Materials*, vol. 62, no. 1, pp. 247–252, Mar. 2017, doi: 10.1515/amm-2017-0037.

[21] Y. Kim *et al.*, “Characterization of Hot Isostatically Pressed Ni-Based Superalloy IN 713C,” *Journal of Korean Powder Metallurgy Institute*, vol. 20, no. 4, pp. 264–268, Aug. 2013, doi: 10.4150/KPMI.2013.20.4.264.

[22] M. Detrois, R. C. Helmink, and S. Tin, “Microstructural Stability and Hot Deformation of γ–γ′–δ Ni-Base Superalloys,” *Metallurgical and Materials Transactions A*, vol. 45, no. 12, pp. 5332–5343, Nov. 2014, doi: 10.1007/s11661-014-2499-3.

[23] K. Kawagishi, H. Harada, A. Sato, A. Sato, and T. Kobayashi, “The oxidation properties of fourth generation single-crystal nickel-based superalloys,” *JOM*, vol. 58, no. 1, pp. 43–46, Jan. 2006, doi: 10.1007/s11837-006-0067-z.

[24] C. Liu *et al.*, “Research Progress of the Effects of Trace S Element on the Microstructure of Cast Nickel-base Superalloys,” *E3S Web of Conferences*, vol. 299, p. 02004, Aug. 2021, doi: 10.1051/e3sconf/202129902004.

[25] Z. Yu, X. Wang, F. Yang, Z. Yue, and J. C. M. Li, “Review of γ’ Rafting Behavior in Nickel-Based Superalloys: Crystal Plasticity and Phase-Field Simulation,” *Crystals (Basel)*, vol. 10, no. 12, p. 1095, Nov. 2020, doi: 10.3390/cryst10121095.

[26] T. Konkova, S. Rahimi, S. Mironov, and T. N. Baker, “Effect of strain level on the evolution of microstructure in a recently developed AD730 nickel based superalloy during hot forging,” *Mater Charact*, vol. 139, pp. 437–445, May 2018, doi: 10.1016/j.matchar.2018.03.027.

[27] X.-Y. Wang, M. Li, and Z.-X. Wen, “The Effect of the Cooling Rates on the Microstructure and High-Temperature Mechanical Properties of a Nickel-Based Single

Crystal Superalloy," *Materials*, vol. 13, no. 19, p. 4256, Sep. 2020, doi: 10.3390/ma13194256.

[28] V. Kumar, G. Yadav, and P. Gupta, "Structural and Mechanical Behavior of Copper-TiC-Graphite Hybrid Metal Matrix Composites Fabricated by Microwave Sintering Technique," *ECS Journal of Solid State Science and Technology*, vol. 12, no. 4, p. 047001, Apr. 2023, doi: 10.1149/2162-8777/acca48.

[29] J. Subramanian, S. Seetharaman, and M. Gupta, "Processing and Properties of Aluminum and Magnesium Based Composites Containing Amorphous Reinforcement: A Review," *Metals (Basel)*, vol. 5, no. 2, pp. 743–762, May 2015, doi: 10.3390/met5020743.

[30] V. Balasubramani, R. Pandiarajan, B. Stalin, and V. Kavimani, "Mechanical and metallurgical characterization of B $_4$ C and SiC reinforced stir casted AA6061 hybrid MMC," *Phys Scr*, vol. 98, no. 10, p. 105922, Oct. 2023, doi: 10.1088/1402-4896/acf1dd.

[31] P. K. Verma, S. Warghane, U. Nichul, P. Kumar, A. Dhole, and V. Hiwarkar, "Effect of boron addition on microstructure, hardness and wear performance of Ti-6Al-4 V alloy manufactured by laser powder bed fusion additive manufacturing," *Mater Charact*, vol. 172, p. 110848, Feb. 2021, doi: 10.1016/j.matchar.2020.110848.

[32] B. S. Vasile, A. C. Birca, V. A. Surdu, I. A. Neacsu, and A. I. Nicoară, "Ceramic Composite Materials Obtained by Electron-Beam Physical Vapor Deposition Used as Thermal Barriers in the Aerospace Industry," *Nanomaterials*, vol. 10, no. 2, p. 370, Feb. 2020, doi: 10.3390/nano10020370.

[33] L. Yuan, J. Han, J. Liu, and Z. Jiang, "Mechanical properties and tribological behavior of aluminum matrix composites reinforced with in-situ AlB2 particles," *Tribol Int*, vol. 98, pp. 41–47, Jun. 2016, doi: 10.1016/j.triboint.2016.01.046.

[34] S. Goswami, K. Ghosh, R. Ghosh, and N. Mandal, "Little amounts of carbon nanotubes as anti-wear reinforcement for alumina in dry sliding," *Int J Appl Ceram Technol*, vol. 20, no. 2, pp. 1278–1297, Mar. 2023, doi: 10.1111/ijac.14248.

[35] M. Saha and M. Saha, "3D Printing of Nanoceramics: Present Status and Future Perspectives," 2022, doi: 10.22541/au.166454835.58560007/v1.

[36] P. Márquez-Martínez *et al.*, "Processing and characterization of Inconel 718/Al2O3 nanocomposite powder fabricated by different techniques," *Powder Technol*, vol. 398, p. 117124, Jan. 2022, doi: 10.1016/j.powtec.2022.117124.

[37] D.-G. Cho, S.-K. Yang, J.-C. Yun, H.-S. Kim, J.-S. Lee, and C. S. Lee, "Effect of sintering profile on densification of nano-sized Ni/Al2O3 composite," *Compos B Eng*, vol. 45, no. 1, pp. 159–164, Feb. 2013, doi: 10.1016/j.compositesb.2012.07.054.

[38] L. Zhang, N. Shi, J. Gong, and C. Sun, "Preparation of SiC Fiber Reinforced Nickel Matrix Composite," *J Mater Sci Technol*, vol. 28, no. 3, pp. 234–240, Mar. 2012, doi: 10.1016/S1005-0302(12)60047-4.

[39] G. R. Devi, C. B. Priya, C. Dineshbabu, R. Karthick, K. Thanigavelmurugan, and P. Paramasivam, "Modelling and Deliberation of Multireinforcement Surface on Tribothermal Adsorption Performance of Nickel Alloy Matrix Hybrid Nanocomposite," *Adsorption Science & Technology*, vol. 2022, Jan. 2022, doi: 10.1155/2022/3697662.

[40] M. Srivastava, A. Srinivasan, and V. K. William Grips, "Influence of Zirconia Incorporation on the Mechanical and Chemical Properties of Ni-Co Alloys," *American Journal of Materials Science*, vol. 1, no. 2, pp. 113–122, Aug. 2012, doi: 10.5923/j.materials.20110102.19.

[41] K. F. Zhang, S. Ding, and G. F. Wang, “Different superplastic deformation behavior of nanocrystalline Ni and ZrO2/Ni nanocomposite,” *Mater Lett*, vol. 62, no. 4–5, pp. 719–722, Feb. 2008, doi: 10.1016/j.matlet.2007.06.048.

[42] A. Uz Zaman *et al.*, “Development and Characterization of Boron-Nitride Reinforced Nickel Matrix Composites,” *MATEC Web of Conferences*, vol. 381, p. 02009, Jun. 2023, doi: 10.1051/matecconf/202338102009.

[43] Yu-nan Tian, Z. Dou, L. Niu, and T. Zhang, “Effects of Titanium Nitride Particles on Copper Matrix-Graphite Composite Properties,” *Russian Journal of Non-Ferrous Metals*, vol. 61, no. 3, pp. 387–395, May 2020, doi: 10.3103/S1067821220030190.

[44] M. R. Abdul Karim, M. A. Khan, A. U. Zaman, and A. Hussain, “Hexagonal boron nitride-based composites: an overview of processing approaches and mechanical properties,” *Journal of the Korean Ceramic Society*, vol. 60, no. 1, pp. 1–23, Jan. 2023, doi: 10.1007/s43207-022-00251-8.

[45] A. El-Tantawy, W. M. Daoush, and A. E. El-Nikhaily, “Microstructure and properties of BN/Ni-Cu composites fabricated by powder technology,” *J Exp Nanosci*, vol. 13, no. 1, pp. 174–187, Jan. 2018, doi: 10.1080/17458080.2018.1467049.

[46] S. H. Kim *et al.*, “Thermo-mechanical improvement of Inconel 718 using ex situ boron nitride-reinforced composites processed by laser powder bed fusion,” *Sci Rep*, vol. 7, no. 1, p. 14359, Oct. 2017, doi: 10.1038/s41598-017-14713-1.

[47] T. Poloczek, A. Lont, and J. Górka, “The Structure and Properties of Laser-Cladded Inconel 625/TiC Composite Coatings,” *Materials*, vol. 16, no. 3, p. 1265, Feb. 2023, doi: 10.3390/ma16031265.

[48] T. Borkar *et al.*, “Laser-Deposited In Situ TiC-Reinforced Nickel Matrix Composites: 3D Microstructure and Tribological Properties,” *JOM*, vol. 66, no. 6, pp. 935–942, Jun. 2014, doi: 10.1007/s11837-014-0907-1.

[49] P. Berthod and E. Conrath, “Creep and oxidation kinetics at 1100°C of nickel-base alloys reinforced by hafnium carbides,” *Mater Des*, vol. 104, pp. 27–36, Aug. 2016, doi: 10.1016/j.matdes.2016.04.079.

[50] R. Wang *et al.*, “Nano-size carbide-reinforced Ni matrix composite prepared by selective laser melting,” *Nano Materials Science*, vol. 2, no. 4, pp. 316–322, Dec. 2020, doi: 10.1016/j.nanoms.2019.11.003.

[51] G. Munday, J. Hogan, and A. McDonald, “On the microstructure-dependency of mechanical properties and failure of low-pressure cold-sprayed tungsten carbide-nickel metal matrix composite coatings,” *Surf Coat Technol*, vol. 396, p. 125947, Aug. 2020, doi: 10.1016/j.surfcoat.2020.125947.

[52] A. N. S. Appiah, O. Bialas, A. Czupryński, and M. Adamiak, “Powder Plasma Transferred Arc Welding of Ni-Si-B+60 wt%WC and Ni-Cr-Si-B+45 wt%WC for Surface Cladding of Structural Steel,” *Materials*, vol. 15, no. 14, p. 4956, Jul. 2022, doi: 10.3390/ma15144956.

[53] J. Domitner *et al.*, “Microstructure Characterization of Nickel Matrix Composite Reinforced with Tungsten Carbide Particles and Produced by Laser Cladding,” *Adv Eng Mater*, vol. 24, no. 11, Nov. 2022, doi: 10.1002/adem.202200463.

[54] L. Yuan, J. Han, J. Liu, and Z. Jiang, “Mechanical properties and tribological behavior of aluminum matrix composites reinforced with in-situ AlB2 particles,” *Tribol Int*, vol. 98, pp. 41–47, Jun. 2016, doi: 10.1016/j.triboint.2016.01.046.

[55] B. ISE and S. MEGURO, “Content of ZrB<sub>2</sub> in the Ni-ZrB<sub>2</sub> Composite Layer Electrodeposited by Dispersion Plating,”

Denki Kagaku oyobi Kogyo Butsuri Kagaku, vol. 61, no. 2, pp. 212–217, Feb. 1993, doi: 10.5796/electrochemistry.61.212.

[56] P. Morampudi, V. S. N. V. Ramana, K. S. ram Vikas, R. Rahul, and C. Prasad, "Effect of nano ZrB2 particles on physical, mechanical and corrosion properties of Al6061 metal-matrix nano composites through stir casting route," *Engineering Research Express*, vol. 4, no. 2, p. 025010, Jun. 2022, doi: 10.1088/2631-8695/ac5f66.

[57] Y. Zheng *et al.*, "The microstructure evolution and precipitation behavior of TiB2/Inconel 718 composites manufactured by selective laser melting," *J Manuf Process*, vol. 79, pp. 510–519, Jul. 2022, doi: 10.1016/j.jmapro.2022.04.070.

[58] E. Tekoğlu *et al.*, "Metal matrix composite with superior ductility at 800 °C: 3D printed In718+ZrB2 by laser powder bed fusion," *Compos B Eng*, vol. 268, p. 111052, Jan. 2024, doi: 10.1016/j.compositesb.2023.111052.

[59] Z. Zhang, Q. Han, S. Yang, Y. Yin, J. Gao, and R. Setchi, "Laser powder bed fusion of advanced submicrometer TiB2 reinforced high-performance Ni-based composite," *Materials Science and Engineering: A*, vol. 817, p. 141416, Jun. 2021, doi: 10.1016/j.msea.2021.141416.

[60] J. Ruzic, M. Simić, N. Stoimenov, D. Božić, and J. Stašić, "Innovative processing routes in manufacturing of metal matrix composite materials," *Metallurgical and Materials Engineering*, vol. 27, no. 1, pp. 1–13, Mar. 2021, doi: 10.30544/629.

[61] T. B. YÜKSEL, U. AYBARÇ, and O. ERTUĞRUL, "Effects of Stirring Duration and Casting Temperature in Ultrasonic Assisted Stir Casting of Al A356 Matrix Composites," *Politeknik Dergisi*, vol. 23, no. 4, pp. 1265–1275, Dec. 2020, doi: 10.2339/politeknik.629473.

[62] P. Sharma, S. Sharma, and D. Khanduja, "A study on microstructure of aluminium matrix composites," *Journal of Asian Ceramic Societies*, vol. 3, no. 3, pp. 240–244, Sep. 2015, doi: 10.1016/j.jascer.2015.04.001.

[63] T. B. YÜKSEL, U. AYBARÇ, and O. ERTUĞRUL, "Effects of Stirring Duration and Casting Temperature in Ultrasonic Assisted Stir Casting of Al A356 Matrix Composites," *Politeknik Dergisi*, vol. 23, no. 4, pp. 1265–1275, Dec. 2020, doi: 10.2339/politeknik.629473.

[64] A. A. Martin *et al.*, "Dynamics of pore formation during laser powder bed fusion additive manufacturing," *Nat Commun*, vol. 10, no. 1, p. 1987, Apr. 2019, doi: 10.1038/s41467-019-10009-2.

[65] A. Aversa *et al.*, "Microstructural and Mechanical Characterization of Aluminum Matrix Composites Produced by Laser Powder Bed Fusion ," *Adv Eng Mater*, vol. 19, no. 11, Nov. 2017, doi: 10.1002/adem.201700180.

[66] M. Hofele, J. Schanz, A. Roth, D. K. Harrison, A. K. M. De Silva, and H. Riegel, "Process parameter dependencies of continuous and pulsed laser modes on surface polishing of additive manufactured aluminium AlSi10Mg parts," *Materwiss Werksttech*, vol. 52, no. 4, pp. 409–432, Apr. 2021, doi: 10.1002/mawe.202000335.

[67] Moshiri, Candeo, Carmignato, Mohanty, and Tosello, "Benchmarking of Laser Powder Bed Fusion Machines," *Journal of Manufacturing and Materials Processing*, vol. 3, no. 4, p. 85, Oct. 2019, doi: 10.3390/jmmp3040085.

[68] Q. Hui, D. Y. Shao, C. M. Li, J. J. Chen, X. Li, and N. P. Cheng, "Effects of Processing Parameters on Properties of SiCp/Al Composites," *MATEC Web of Conferences*, vol. 67, p. 06016, Jul. 2016, doi: 10.1051/matecconf/20166706016.

[69] “Property Enhancement of Aluminium Based MMCs with Various Reinforcements,” *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 2S2, pp. 539–546, Dec. 2019, doi: 10.35940/ijitee.B1076.1292S219.

[70] D. D. Gu, W. Meiners, K. Wissenbach, and R. Poprawe, “Laser additive manufacturing of metallic components: materials, processes and mechanisms,” *International Materials Reviews*, vol. 57, no. 3, pp. 133–164, May 2012, doi: 10.1179/1743280411Y.0000000014.

[71] N. Fatchurrohman, A. N. Binti Mamat, M. Yetrina, and R. Muhida, “Investigation of Metal Matrix Composites Aluminium Reinforced Graphite Particles Produced Using Powder Metallurgy,” *J Teknol*, Dec. 2022, doi: 10.35134/jitekin.v12i2.70.

[72] J. Idris and M. A. Kabir, “Powder Metallurgy Development For The Production Of Metal Matrix Composite,” in *Processing and Fabrication of Advanced Materials VIII*, WORLD SCIENTIFIC, 2001, pp. 921–931. doi: doi:10.1142/9789812811431_0108.

[73] A. I. Selmy, F. Shehata, A. Fathy, and E. Gewfiel, “FABRICATION AND CHARACTERIZATION OF ALUMINUM- GRAPHITE COMPOSITES,” *ERJ. Engineering Research Journal*, vol. 34, no. 2, pp. 181–187, Apr. 2011, doi: 10.21608/erjm.2011.67270.

[74] V. T. Pham *et al.*, “The effect of sintering temperature on the mechanical properties of a Cu/CNT nanocomposite prepared via a powder metallurgy method,” *Advances in Natural Sciences: Nanoscience and Nanotechnology*, vol. 2, no. 1, p. 015006, Mar. 2011, doi: 10.1088/2043-6262/2/1/015006.

[75] O. Kurapova, I. Smirnov, E. Solovyeva, I. Archakov, and V. Konakov, “The effect of reduced graphene oxide (rGO) and thermally exfoliated graphite (TEFG) on the mechanical properties of ‘nickel-graphene’ composites,” *Letters on Materials*, vol. 10, no. 2, pp. 164–169, 2020, doi: 10.22226/2410-3535-2020-2-164-169.

[76] M. L. Parucker, A. N. Klein, C. Binder, W. Ristow Junior, and R. Binder, “Development of self-lubricating composite materials of nickel with molybdenum disulfide, graphite and hexagonal boron nitride processed by powder metallurgy: preliminary study,” *Materials Research*, vol. 17, no. suppl 1, pp. 180–185, Nov. 2013, doi: 10.1590/S1516-14392013005000185.

[77] K. Zhang, H. Won Jang, and Q. Van Le, “Production methods of ceramic-reinforced Al-Li matrix composites: A review,” *Journal of Composites and Compounds*, vol. 2, no. 3, pp. 76–84, May 2020, doi: 10.29252/jcc.2.2.3.

[78] W. Ji, R. Zhou, P. Vivegananthan, M. See Wu, H. Gao, and K. Zhou, “Recent progress in gradient-structured metals and alloys,” *Prog Mater Sci*, vol. 140, p. 101194, Dec. 2023, doi: 10.1016/j.pmatsci.2023.101194.

[79] I. Yadroitsev, I. Yadroitsava, and A. Du Plessis, “Basics of laser powder bed fusion,” in *Fundamentals of Laser Powder Bed Fusion of Metals*, Elsevier, 2021, pp. 15–38. doi: 10.1016/B978-0-12-824090-8.00024-X.

[80] K. Ratanapongpien, A. Khantachawana, and K. Kondoh, “Effect of Laser Scanning Speed and Fine Shot Peening on Pore Characteristics, Hardness, and Residual Stress of Ti-6Al-4V Fabricated by Laser Powder Bed Fusion,” *Metals (Basel)*, vol. 14, no. 2, p. 250, Feb. 2024, doi: 10.3390/met14020250.

[81] S. C. Bodner *et al.*, “Inconel-steel multilayers by liquid dispersed metal powder bed fusion: Microstructure, residual stress and property gradients,” *Addit Manuf*, vol. 32, p. 101027, Mar. 2020, doi: 10.1016/j.addma.2019.101027.

[82] E. Santecchia, S. Spigarelli, and M. Cabibbo, "Material Reuse in Laser Powder Bed Fusion: Side Effects of the Laser—Metal Powder Interaction," *Metals (Basel)*, vol. 10, no. 3, p. 341, Mar. 2020, doi: 10.3390/met10030341.

[83] H. Zhang, J. Lu, G. Xu, K. Luo, I. Okulov, and W. Xue, "Island scan length effect on processability, microstructure, and mechanical property of laser powder bed fusion processed nickel matrix composites," *Materials Science and Engineering: A*, vol. 864, p. 144559, Feb. 2023, doi: 10.1016/j.msea.2022.144559.

[84] J. Albert, S. Purschke, and C. Fleck, "Effect of Process Variables on Microstructure, Flow, and Tensile Properties of Nickel-Based Superalloys with Designed Porous Structures Manufactured by Laser-Based Powder Bed Fusion," *Adv Eng Mater*, vol. 25, no. 13, Jul. 2023, doi: 10.1002/adem.202300006.

[85] S. Zhang, M. Ding, L. Wang, W. Ge, and W. Yan, "Laser powder bed fusion of diamond/N6 MMCs enabled by Ni-Ti coated diamond particles," *Mater Des*, vol. 217, p. 110635, May 2022, doi: 10.1016/j.matdes.2022.110635.

[86] L. Cao, R. L. Bradford-Vialva, R. M. Eckerle, F. Herman, C. Jones, and D. A. Klosterman, "Development of Carbon Nanotube-Reinforced Nickel-Based Nanocomposites Using Laser Powder Bed Fusion," *Adv Eng Mater*, vol. 25, no. 4, Feb. 2023, doi: 10.1002/adem.202201197.

[87] T. Özel, A. Altay, B. Kaftanoğlu, R. Leach, N. Senin, and A. Donmez, "Focus Variation Measurement and Prediction of Surface Texture Parameters Using Machine Learning in Laser Powder Bed Fusion," *J Manuf Sci Eng*, vol. 142, no. 1, Jan. 2020, doi: 10.1115/1.4045415.

[88] H. Dieringa, "Applications: magnesium-based metal matrix composites (MMCs)," in *Fundamentals of Magnesium Alloy Metallurgy*, Elsevier, 2013, pp. 317–341. doi: 10.1533/9780857097293.317.

[89] M. G. Akhil, K. M. N. S. Manu, T. P. D. Rajan, and B. C. Pai, "Liquid Phase Processing of Metal Matrix Composites," in *Encyclopedia of Materials: Composites*, Elsevier, 2021, pp. 160–172. doi: 10.1016/B978-0-12-819724-0.00095-1.

[90] R. Bauri and D. Yadav, "Introduction to Metal Matrix Composites," in *Metal Matrix Composites by Friction Stir Processing*, Elsevier, 2018, pp. 1–16. doi: 10.1016/B978-0-12-813729-1.00001-2.

[91] M. Kataria and S. K. Mangal, "Characterization of aluminium metal matrix composite fabricated by gas injection bottom pouring vacuum multi-stir casting process," *Metallic Materials*, vol. 56, no. 04, pp. 231–243, 2018, doi: 10.4149/km_2018_4_231.

[92] S. Srivastava, M. K. Bhatnagar, N. Verma, T. G. Mamatha, and M. Vishnoi, "Characterization of Aluminium Hybrid Metal Matrix Composites." 2021. doi: 10.21203/rs.3.rs-648677/v1.

[93] P. Pandiyaraj, A. Manivannan, C. K. A. Pandian, and B. V. Ramnath, "Mechanical &Amp;amp; Tribological Behaviour of Squeeze Casted Mg/SiC Composites for Defense Applications," 2023, doi: 10.21203/rs.3.rs-2725905/v1.

[94] R. Chebolu, R. Nallu, R. Chanamala, S. K. Sharma, and R. Rudrapati, "Influence of SiC/TiB2 Particles Addition on Corrosion Behavior of As-Cast Zn-Al-Cu Alloy Hybrid Composites," *Journal of Engineering*, vol. 2022, pp. 1–5, Aug. 2022, doi: 10.1155/2022/3669584.

[95] M. Ravikumar, H. N. Reddappa, R. Suresh, and M. Sreenivasa Reddy, "Experimental studies of different quenching media on mechanical and wear behavior of

Al7075/SiC/Al2O3 hybrid composites," *Frattura ed Integrità Strutturale*, vol. 15, no. 55, pp. 20–31, Dec. 2020, doi: 10.3221/IGF-ESIS.55.02.

[96] V. Bharath *et al.*, "Microstructural Evolution, Tensile Failure, Fatigue Behavior and Wear Properties of Al2O3 Reinforced Al2014 Alloy T6 Heat Treated Metal Composites," *Materials*, vol. 15, no. 12, p. 4244, Jun. 2022, doi: 10.3390/ma15124244.

[97] F. Shehata, N. ElMahallawy, M. Arab, and M. Agwa, "Equal Channel Angular Pressing of Al-SiC Composites Fabricated by Stir Casting," *Open J Met*, vol. 03, no. 02, pp. 26–33, 2013, doi: 10.4236/ojmetal.2013.32A1004.

[98] , Sathyaraj et al., Sathyaraj et al., "Fabrication of Aluminium 6061- SiC-Al2O3 MMC and HMMC by Stir Casting Technique and Comparing the Mechanical Properties," *International Journal of Mechanical and Production Engineering Research and Development*, vol. 8, no. 1, pp. 635–642, 2018, doi: 10.24247/ijmperdfeb201870.

[99] G. Purushotham and J. Hemanth, "Action of Chills on Microstructure, Mechanical Properties of Chilled ASTM A 494M Grade Nickel Alloy Reinforced with Fused SiO2 Metal Matrix Composite," *Procedia Materials Science*, vol. 5, pp. 426–433, 2014, doi: 10.1016/j.mspro.2014.07.285.

[100] J. Kumaraswamy *et al.*, "Thermal Analysis of Ni-Cu Alloy Nanocomposites Processed by Sand Mold Casting," *Advances in Materials Science and Engineering*, vol. 2022, pp. 1–11, Aug. 2022, doi: 10.1155/2022/2530707.

[101] A. Ramanathan, P. K. Krishnan, and R. Muraliraja, "A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities," *J Manuf Process*, vol. 42, pp. 213–245, Jun. 2019, doi: 10.1016/j.jmapro.2019.04.017.

[102] G. T. Kridli, P. A. Friedman, and J. M. Boileau, "Manufacturing processes for light alloys," in *Materials, Design and Manufacturing for Lightweight Vehicles*, Elsevier, 2010, pp. 235–274. doi: 10.1533/9781845697822.2.235.

[103] Ş. Bayraktar and A. P. Hekimoğlu, "Current technologies for aluminum castings and their machinability," in *Advanced Welding and Deforming*, Elsevier, 2021, pp. 585–614. doi: 10.1016/B978-0-12-822049-8.00019-0.

[104] A. A. Luo, A. K. Sachdev, and D. Apelian, "Alloy development and process innovations for light metals casting," *J Mater Process Technol*, vol. 306, p. 117606, Aug. 2022, doi: 10.1016/j.jmatprotec.2022.117606.

[105] Y. Choi, Z. Zu, K. Matsugi, K. Sugio, and G. Sasaki, "Microstructures of Al<sub>3</sub>Ni Particles Reinforced Composites by Infiltration and Reaction Method and Their Properties," *Mater Trans*, vol. 58, no. 8, pp. 1235–1237, 2017, doi: 10.2320/matertrans.M2017056.

[106] H. Hassanin and K. Jiang, "Fabrication of Near Net Shape Alumina Nickel Composite Micro Parts using Aqueous Suspension," in *2009 IEEE 22nd International Conference on Micro Electro Mechanical Systems*, IEEE, Jan. 2009, pp. 721–724. doi: 10.1109/MEMSYS.2009.4805484.

[107] Y. Sun, J. Sun, M. Liu, and Q. Chen, "Mechanical strength of carbon nanotube–nickel nanocomposites," *Nanotechnology*, vol. 18, no. 50, p. 505704, Dec. 2007, doi: 10.1088/0957-4484/18/50/505704.

[108] A. Dulęba, M. Cholewa, and D. Scelina, "The Influence of the Forced Movement of Components on the Structure in Fabricated AlSi/CrxCy Composite Castings," *Archives of Foundry Engineering*, vol. 12, no. 1, Jan. 2012, doi: 10.2478/v10266-012-0005-1.

[109] A. Mohandas and N. Radhika, “Studies on Mechanical Behaviour of Aluminium/Nickel Coated Silicon Carbide Reinforced Functionally Graded Composite,” *Tribology in Industry*, vol. 39, no. 2, pp. 145–151, Jun. 2017, doi: 10.24874/ti.2017.39.02.01.

[110] O. O. Edosa, F. K. Tekweme, and K. Gupta, “Squeeze casting for metal alloys and composites: An overview of influence of process parameters on mechanical properties and microstructure,” *China Foundry*, vol. 20, no. 2, pp. 148–158, Mar. 2023, doi: 10.1007/s41230-022-2030-1.

[111] K. K. SONI *et al.*, “Ion microprobe studies of reactions in squeeze-cast aluminium alloy matrix composites,” *J Microsc*, vol. 177, no. 3, pp. 414–423, Mar. 1995, doi: 10.1111/j.1365-2818.1995.tb03572.x.

[112] Y. P. Jeon and C. G. Kang, “Reheating process for thixoforging of metal matrix composites fabricated by induction heating and the mechanical stirring process,” *Proc Inst Mech Eng B J Eng Manuf*, vol. 217, no. 10, pp. 1383–1391, Oct. 2003, doi: 10.1243/095440503322617153.

[113] J. Edelbauer, D. Schuller, O. Lott, and A. Nagel, “High Temperature Squeeze Casting of Nickel Based Metal Matrix Composites with Interpenetrating Microstructure,” *Materials Science Forum*, vol. 825–826, pp. 93–100, Jul. 2015, doi: 10.4028/www.scientific.net/MSF.825-826.93.

[114] A. Haeger, K. G. Schell, A. Nagel, E. C. Bucharsky, R. Oberacker, and M. J. Hoffmann, “Fabrication and High Temperature Creep Behaviour of Interpenetrated Nickel–Chromium/Alumina Composites,” *Adv Eng Mater*, vol. 14, no. 9, pp. 795–801, Sep. 2012, doi: 10.1002/adem.201200055.

[115] J. Kumaraswamy, V. Kumar, and G. Purushotham, “A review on mechanical and wear properties of ASTM a 494 M grade nickel-based alloy metal matrix composites,” *Mater Today Proc*, vol. 37, pp. 2027–2032, 2021, doi: 10.1016/j.matpr.2020.07.499.

[116] Z. Wang *et al.*, “Research Progress of Laser Additive Manufacturing Nickel-Based Alloy Metal Matrix Composites,” *Metals (Basel)*, vol. 13, no. 1, p. 129, Jan. 2023, doi: 10.3390/met13010129.

[117] B. K. Anil Kumar, M. G. Ananthaprasad, and K. GopalaKrishna, “Action of Cryogenic chill on Mechanical properties of Nickel alloy Metal Matrix Composites,” *IOP Conf Ser Mater Sci Eng*, vol. 149, p. 012116, Sep. 2016, doi: 10.1088/1757-899X/149/1/012116.

[118] L. Cao, R. L. Bradford-Vialva, R. M. Eckerle, F. Herman, C. Jones, and D. A. Klosterman, “Development of Carbon Nanotube-Reinforced Nickel-Based Nanocomposites Using Laser Powder Bed Fusion,” *Adv Eng Mater*, vol. 25, no. 4, Feb. 2023, doi: 10.1002/adem.202201197.

[119] X. Dangsheng, “Lubrication behavior of Ni–Cr-based alloys containing MoS2 at high temperature,” *Wear*, vol. 251, no. 1, pp. 1094–1099, 2001, doi: https://doi.org/10.1016/S0043-1648(01)00803-1.

[120] J. Zhen *et al.*, “High-temperature tribological behavior of a nickel alloy matrix solid-lubricating composite under vacuum,” *Tribol Int*, vol. 110, pp. 52–56, Jun. 2017, doi: 10.1016/j.triboint.2017.02.011.

[121] F. Li, J. Cheng, S. Zhu, J. Hao, J. Yang, and W. Liu, “Microstructure and mechanical properties of Ni-based high temperature solid-lubricating composites,” *Materials Science and Engineering: A*, vol. 682, pp. 475–481, Jan. 2017, doi: 10.1016/j.msea.2016.11.069.

[122] G. Purushotham and J. Hemanth, “Influence of fused Silica and chills incorporation on Corrosion, Thermal and Chemical composition of ASTM A 494 M Grade Nickel alloy,”

IOP Conf Ser Mater Sci Eng, vol. 149, p. 012042, Sep. 2016, doi: 10.1088/1757-899X/149/1/012042.

[123] A. Graboś, P. Rutkowski, J. Huebner, P. Nieroda, D. Kata, and S. Hayashi, "Thermal properties of Inconel 625-NbC metal matrix composites (MMC)," *Mater Des*, vol. 224, p. 111399, Dec. 2022, doi: 10.1016/j.matdes.2022.111399.

[124] S. Tabrez *et al.*, "Nickel metal matrix composites reinforced with solid lubricants: A comprehensive review," *Mater Today Proc*, Jul. 2023, doi: 10.1016/j.matpr.2023.07.081.