Nano TiC particles modulate wear resistance and impact toughness of 40Cr alloy steel gradient-reinforced layer fabricated by laser melting deposition

Xi Wang, Weiguang Yang, Ti Zhou, Hai Zhou and He Liu

1 School of Mechanical Engineering, Yancheng Institute of Technology, No. 1 Hope Avenue Middle Road, Yancheng 224051, People’s Republic of China
2 Weihai Institute of Bionics, Jilin University, No. 5988 Renmin Street, Changchun 130025, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: ywg@ycit.edu.cn

Keywords: laser melting deposition, nano TiC, gradient-reinforced layer, wear resistance, impact toughness

Abstract

Alloy steel components can be subjected to serious damage from a variety of conditions during the industrial production procedures, such as wear and fracture failure. Therefore, the preparation of gradient-reinforced layers on the surface of the alloy steel was considered an effective technique to improve the performance. Along these lines, a 40Cr alloy steel, which was commonly used in industry, was systematically investigated in this work. The nano TiC ceramic material was selected in the hard phase. In this work, continuous-wave laser was used to fabricate gradient reinforced layers, which provided a technical reference for the development of protective reinforcement layers for alloy steels with excellent mechanical properties. A dense structure was formed inside the nano TiC gradient reinforced layer, which has a lower friction coefficient (0.25) and wear loss weight (23 mg). The height of the surface material loss under a heavy load wear environment (187 μm) was lower than that of a bare 40Cr alloy steel sample (1116 μm). The impact energy of the nano TiC gradient reinforced layer (75.27 J cm⁻²) was higher than that of a bare 40Cr alloy steel sample (15.25 J cm⁻²). Both the wear behavior and impact toughness strengthening mechanism of the nano TiC gradient reinforced layer were revealed.

1. Introduction

Gears are quite important mechanical components that transmit motion and power through continuous meshing. Various gears made from 40Cr alloy steel are used within the gearbox of a vehicle. Two types of serious gear failures usually occur during the operation of gears [1, 2]. The first type of failure is the wear of the gear surface. Under the application of relatively high loads, the gear surface undergoes material loss under the impact of wear. The second type of failure is the fracture of the gear itself. Improper gear changes and sharp braking while the car is in motion can cause huge overload loads on the gears. This instantaneous overload shock can impose gears breakage, posing hence a serious danger to a moving car. The manifestation of such types of phenomena can induce excessive wear and impact fracture [3, 4], which could seriously jeopardize the normal operation of gears. Consequently, gear strengthening methods are required to improve both the wear performance and impact toughness of the gears.

Under this direction, the preparation of high-performance reinforcement layers on gear surfaces is regarded as an effective enhancement method to improve the wear and impact resistance of the gears. Laser melting deposition (LMD) is a forward-looking technology for the rapid manufacture [5]. Compared with traditional fabrication, LMD has several advantages, such as excellent mechanical properties, fine microstructures, and smaller diffusion of solutes [6]. As an advanced technology, LMD has been used in various materials, such as titanium alloys [7, 8], steels [9, 10] and aluminum [11, 12]. Previous studies in the literature have shown that a
variety of composite materials can be used as reinforcement layers. Wilson et al [13] fabricated Inconel690/TiC composites by LMD and found that the addition of TiC increased the hardness and wear resistance. AlMangour et al [14] developed TiB2/316 L composites, which exhibited higher yield strength and ductility than pure iron.

Currently, a series of studies on the preparation of reinforced layers by using additive manufacturing-based techniques have focused on improving the performance of a single material [15–17]. Nemati et al [18] prepared micron and nano-sized TiC/Al-based composites and compared their hardness and wear resistance properties. In another interesting work, Li et al [19] employed titanium powder and carbon nanotubes of different contents to synthesize TiC-based composite metal–ceramic coatings on pure titanium substrates by applying an in situ using laser technology. The authors tested the high-temperature wear performance of the coatings with different carbon nanotubes contents. Compared with other hard particle reinforcements, TiC has higher wettability to 12CrNi2 alloy steel [20], and the solute drag effect of TiC particles can provide more nucleation sites during solidification. It can effectively improve the microhardness and wear resistance of the material [21]. Due to the mismatch between the thermal physical properties of the TiC reinforced phase and the 12CrNi2 alloy steel, thermal stress will be generated during the preparation process and cracks are likely to occur [22, 23], so this study developed a nano-TiC gradient reinforced layer. In previous studies of functional enhancement layers, researchers focused on improving single material properties [24, 25], while gears needed to improve wear resistance and impact toughness. In order to further understand the strengthening mechanism of the gradient reinforced layer, the nano-TiC gradient reinforced layer was developed in this study, and the wear resistance and impact toughness tests were carried out, which provided a reference for the development of the gradient reinforced layer with both wear resistance and impact toughness.

More specifically, Fe-based 40Cr gradient reinforced layers consisting of nano TiC particles were prepared by continuous-wave laser melting deposition. The microstructure and microhardness of the gradient reinforced layer were also systematically analyzed. In addition, the impact toughness and wear performance were tested.

2. Experimental procedures

2.1. Materials preparation
The substrate that was used to prepare the experimental reinforcement layer was 40Cr alloy steel (sample size: 75 mm × 10 mm × 10 mm). The composition of the 40Cr alloy steel substrate (wt%) was the following: C 0.39, Si 0.21, Mn 0.57, Ni 0.24, Cr 1.17 and Fe remainder. After sanding the cut marks and oxide layer on the surface of the substrate, ultrasonically clean it with acetone. The powders that were used in the experiments were 12CrNi2 alloy steel powder (purity ≥ 99.5%, 50 mm) and nano TiC (purity ≥ 99.5%). The composition (wt%) of the 12CrNi2 was the following: C 0.12, Si 0.21, Mn 0.37, Ni 1.65, Cr 0.85 and Fe remainder. Micrographs of the original employed powders are shown in figure 1.

In this work, a nano TiC gradient reinforced layer was prepared. The gradient layer consisted of three layers of powder with composition parameters as in table 1. Furthermore, the powder mixture was weighed and placed in a horizontal ball mill and mixed at 100 RPM for 8 h. The ball milling parameters were optimized from our previous experiments [26].

2.2. Laser melting deposition process
In this experiment, the fiber laser (Model- A2000D fiber laser; Make- Raycus RFL, China) was used for laser melting deposition processing, equipped with a real-time control coaxial powder feeding system, and the

![Figure 1. Micrographs of powders: (a) 12CrNi2 powder; (b) nano TiC powder.](image-url)
motion execution was performed by a robot (Model: XB16 six-axis robot; Make: ROKAE, China). Figure 2 shows a schematic diagram of gradient reinforced layer processing. In the LMD process, the laser power was 2000W, the spot diameter was 1 mm, the scanning speed was 1 mm s$^{-1}$, and argon gas protection was used with a flow rate of 20 l min$^{-1}$.

### 2.3. Microstructure and microhardness

In order to further characterize the microstructure of the reinforcement layer, the cross-section of the sample was ground and polished. Subsequently, after polishing, the samples were etched for 3 min by using an etching agent (alcohol: 96%; HNO$_3$: 4%). The microstructure of the reinforced layer was analyzed by using an optical microscope (Model: AXIO; Make: Carl Zeiss, Germany), a scanning electron microscope (SEM) (Model: Evo 18; Make: Carl Zeiss, Germany) and energy dispersive spectroscopy (EDS) (Model: X-MaxN20; Make: Oxford, UK). The phase composition of the reinforced layer was analyzed by using an x-ray diffractometer (Model: D/Max 2500PC; Make: Rigaku, Japan). Peak matching was performed using X’pert HighScore Plus software, which has been used in several related studies [27]. As far as the microhardness of the reinforced layers is concerned, it was measured by using a microhardness tester (Model: MHBD-3000P; Make: Jujing, China) with a test load of 200 g and a dwell time of 15 s (referring to ASTM E384-2006).

### 2.4. Abrasion resistance

The abrasion resistance of the reinforced layer was tested by using a ring block abrasion tester (Model: MM-200; Make: Kehua, China). Schematic diagram shown in figure 3. Before executing the wear test, the surface roughness of the samples was polished to below 0.15 $\mu$m. The grinding disc material was GCr15, with a size of

![Figure 2. Schematic diagram of gradient reinforced layer processing.](image-url)
Φ50 mm * 10 mm, hardness of 59-63 HRC and a surface roughness value of 0.8 μm. On top of that, wear tests were carried out by using a grinding sub at 400 r min\(^{-1}\) under a load of 300 N (referring to ASTM G77-2005).

2.5. Impact test
For the impact test, a standard Charpy V-notch impact specimen with dimensions of 55 mm * 10 mm * 10 mm was considered (referring to ASTM E23-2018). The impact test equipment is actually a pendulum impact tester (Model: PIT452D-4; Make: Kehua, China). The impact test parameters are the following: voltage 380 V, impact energy 450 J, power 37 KW.

3. Results and discussion
3.1. Phase composition of the reinforced layer
Figure 4 shows the extracted XRD phase analysis curves of nano TiC gradient reinforced layer. The gradient reinforced layer mainly contains carbides (TiC, Ni\(_3\)C, Cr\(_7\)C\(_3\), SiC) and intermetallic compounds (Ni\(_3\)Fe), while they consist of 12CrNi2 and TiC. During the laser deposition process, the maximum temperature of the molten
pool is 2800 K, which is lower than the melting point of nano TiC (3433 K). So nano TiC is not decomposed. During the preparation of the gradient reinforced layers, it can be seen that the pre-powder is first melted and then solidified with a very fast cooling rate [28]. During this process, the TiC particles will also migrate to the interior of the reinforced layer. The distribution of these intermetallic compounds and various cemented carbide phases had a direct effect on the hardness.

3.2. Reinforced layer microstructure

Figure 5 shows the microstructure of the nano TiC gradient reinforced layer. The thickness of the gradient reinforced layer was measured by the image measurement tool in the microscope: the total thickness of the gradient reinforced layer was 694 μm, and the thickness of each layer was nearly equal, about 230 μm. The dilution rate of the substrate in this study was 22.8%. The dilution rate refers to the degree to which the alloy composition is changed by the melting of the substrate during the laser melting deposition process. If the dilution rate is too low, the bonding between the reinforced layer and the substrate will be poor. If the dilution rate is too high, the performance of the reinforced layer will be reduced, and crack and deformation will easily occur. Generally, it is better to control the dilution rate within the range of 15% to 25% [29].

From figures 5(a)–(d), it can be seen that the uniformly dispersed TiC and agglomerated TiC within the reinforced layer [30]. The pores [31] appeared in the micrographs were not those produced during the laser melting deposition process, but rather a small number of defects after the use of the etching agent. The agglomeration of TiC particles in the pre-powder that enter the reinforced layer through LMD usually occurs as a result of the development of van der Waals forces between the ceramic particles. The microstructure produced by the agglomeration will vary depending on the TiC content. Under this perspective, when the TiC particle content is low, a small amount of TiC can be found. On the other hand, when the TiC particle content is high, TiC will form aggregates inside the reinforced layer, improving this substantially the performance of the reinforced layer. As far as the gradient reinforced layer is concerned, the metallurgical bonding between the alloy steel and the TiC particles is good, while the dense TiC structure also significantly increases the microhardness of the reinforced layer.

Figure 6 shows the Energy dispersive spectrum of the gradient reinforced layer. The EDS map selection area corresponds to figure 5. From the element distribution, it is found that the Ti element is uniformly dispersed...
the interface and the first layer, and the second layer and the third layer show agglomeration. This is also consistent with the TiC distribution in the SEM micrographs. The energy dispersive x-ray spectroscopy analysis results of the gradient reinforced layer are shown in table 2. Since 40Cr substrate and 12CrNi2 powder do not contain Ti element, the content of Ti in the table represents the content of TiC. It can be found that the content of Ti is basically consistent with the content of TiC in the gradient reinforced layer. It shows that almost all of the TiC enters the reinforced layer and forms a good metallurgical bond.

3.3. Microhardness

The microhardness characteristics of the nano TiC gradient reinforced layer along with the depth direction are shown in figure 7. Each microhardness value in the graph is calculated as the average of five different microhardness values obtained from internal indentations of the same depth [32]. The data shows that the microhardness tends to initially increase and then gradually decrease. Because the outermost layer is in direct contact with the external environment and the lower surface is in direct contact with the substrate during the preparation of the reinforced layer, the internal supercooling effect is higher than the supercooling of the outermost layer [33]. Consequently, the microhardness of the surface of the reinforced layer is higher than that of the outermost layer due to the relatively high degree of supercooling.

More specifically, the average microhardness of the first layer is 681 HV, while the average microhardness of the second layer is 804 HV and the average microhardness of the third layer is 1009HV. The microstructure analysis shows that during the preparation of the reinforced layer, the entire TiC in the pre-powder enters the inner layer, and the increased TiC content promoted distribution of TiC in the reinforced layer. Since the first reinforced layer contains only a small amount of TiC, the microhardness of the first reinforced layer is relatively

![Figure 6](image.png)

*Figure 6. Energy dispersive spectrum of the reinforced layer: (a) the interface between the reinforced layer and substrate; (b) the first layer; (c) the second layer; (d) the third layer.*
3.4. Wear resistance and wear surface analysis

Figure 8(a) depicts the friction coefficients of a bare 40Cr alloy steel sample, the nano TiC gradient reinforced layer under the implementation of heavy load wear conditions. The coefficient of friction of the nano TiC gradient reinforced layer remained at the value of 0.25 for a fixed load of 300 N under heavy load wear conditions. This result indicates that the nano TiC gradient-reinforced layer has the lightest wear behavior on the surface. The bare 40Cr alloy steel sample control specimens had a friction coefficient of up to the value of 0.66, whereas a violent friction effect takes place on the 40Cr alloy steel substrate surface without the protection of the reinforcement layer.

Table 2. Results of the energy dispersive spectrum analysis (wt%).

| Element | C    | Ti   | Cr   | Fe   | Ni   |
|---------|------|------|------|------|------|
| a       | 16.56| 3.80 | 11.47| 53.01| 15.16|
| b       | 15.17| 9.15 | 9.81 | 48.90| 16.97|
| c       | 13.87| 26.96| 7.91 | 40.91| 10.35|
| d       | 12.97| 42.46| 5.53 | 30.44| 8.60 |
Figure 8(b) shows the wear weight loss of a bare 40Cr alloy steel sample, the nano TiC gradient reinforced layer under the application of a heavy load wear environment. The bare 40Cr alloy steel sample lost the most weight (151 mg) at a load of 300 N, indicating that it had the poorest wear resistance, whereas a dramatic material loss took place on the 40Cr substrate surface. The wear loss weight of the bare 40Cr alloy steel sample (151 mg) under the enforcement of heavy load friction conditions was significantly higher than that of the nano TiC gradient reinforced layer.
TiC gradient reinforced layer (23 mg). Also from the graph, it can be observed that a positive correlation between the friction coefficient and the weight of wear loss exists. When the friction coefficient of the reinforced layer becomes larger, the wear process becomes more intense and thus more weight is lost. Therefore, the coefficient of friction was proportional to the total wear weight loss. As the coefficient of friction increased, the friction between the counter-wear and the reinforced layer becomes more intense and the wear marks on the surface of the reinforced layer become deeper.

Figure 9 shows the wear surfaces of a bare 40Cr alloy steel sample and the nano TiC gradient reinforced layer under the application of heavy load wear conditions. Both the effects of plastic deformation and severe adhesive wear were observed on the surface of the bare 40Cr alloy steel sample. On top of that, the transfer of metallic material in the adhesive wear took place from the bare 40Cr alloy steel sample to the counterpart surface. The formation of grooves and a small amount of spalling surface can be also observed on the wear surface of the bare 40Cr alloy steel sample, which could lead to the production of wear debris and abrasive particles during the wear process. Hence, the surface of the bare 40Cr alloy steel sample is grooved by the counter-abrasive under the application of a relatively heavy load during the wear test. The above phenomenon proves that the wear mechanism of the bare 40Cr alloy steel sample is mainly adhesive wear.

The nano TiC gradient reinforced layer exhibits a slight spalling phenomenon under the application of high load wear, as the hard phase within the nano TiC gradient reinforced layer is evenly distributed and the reinforced layer is strengthened overall. The hard phase TiC in the reinforced layer improves the resistance to the applied compressive stresses. In addition, the TiC in the reinforced layer reduces the impact of the micro-cutting effect on the grinding substrate. Due to the formation of a relatively dense TiC structure within the nano TiC gradient reinforced layer, which has good resistance to micro-cutting action, the wear mark width is smaller than the bare 40Cr alloy steel sample.

Figure 10 shows the wear morphology of a bare 40Cr alloy steel sample, the nano TiC gradient reinforced layer under a heavy load friction environment. More specifically, figure 10(a) illustrates the wear surface profile of a bare 40Cr alloy steel sample. The maximum wear depth of the bare 40Cr alloy steel sample is up to the value of 1116 μm. It can be seen that the surface of the bare 40Cr alloy steel sample is very rough and the substrate is very heavily cut under the action of the counter-abrasion substrate. As a result, significant material loss and deep gouges are imposed within the substrate. The rough surface leads to the formation of a high coefficient of friction and frictional forces, and in this case, the wear of bare 40Cr alloy steel sample becomes progressively more severe. The maximum wear depth of the nano-TiC gradient reinforced layer in figure 10(b) is 187 μm. The nano-TiC gradient reinforced layer has also a large amount of particulate hard phase TiC inside the layer, while

![Figure 9. Micrographs of wear surfaces](image-url)
these hard phases substantially increase the microhardness and the wear properties. The material loss shows that the addition of TiC can effectively improve the wear performance of the reinforced layer.

The employed wear model for the nano TiC gradient reinforced layer is shown in figure 11. Stage ①-② is the stage where the abrasive particles slide on the substrate when subjected to external load, and a deep and long plough furrow is produced as it is not hindered by the hard phase. During stages ②-③, the abrasive particles move from the substrate to the unit body, where are hindered by the hard unit body and either stop advancing or follow a rolling mode to continue advancing. Stages ③-④ are the stages where the abrasive particles move from the hard cell to the relatively soft substrate. We have to underline that the substrate specimen without a unitary body is always worn in stages ①-② and therefore deep and long furrows are produced. The increase in microhardness leads to a growth of the resistance to plastic deformation and a reduction of the depth of the furrow during wear, which significantly contributes to the increase in wear resistance [34].
3.5. Impact toughness and fracture surfaces

Figure 12 illustrates the impact fracture morphology of a bare 40Cr alloy steel sample and the nano TiC gradient reinforced layer. As can be observed from figure 12, the impact fracture surface of a bare 40Cr alloy steel sample is distributed with a large number of tough nests, which is a ductile fracture. The impact strength of a bare 40Cr alloy steel sample was 15.25 J cm^{-2}. The impact strength of nano TiC gradient reinforced layer was 75.27 J cm^{-2}. Due to the fast solidification nature of the LMD process, the internal grain boundaries and phase interfaces will increase, which could impede the movement of dislocations. On the other hand, due to the fine-grained strengthening effect of TiC [35], the grain growth can be effectively prevented, hindering thus the movement of dislocations and increasing the difficulty of crack extension [36]. Consequently, the impact resistance of the alloy steel is effectively improved. Hence, the impact strength of the nano-TiC gradient reinforced layer will have a greater increase.

4. Conclusion

In this work, nano TiC ceramic material was selected as the hard and reinforcing phase for the gradient reinforcement layer, which was fabricated on the surface of 40Cr alloy steel by using continuous-wave laser melting deposition process. The microstructure, microhardness, wear properties and impact toughness of the nano TiC gradient reinforced layer were thoroughly investigated and mechanismically explained.

1. Within the nano TiC gradient strengthening layer, TiC inside the strengthening layer was found to form a dense structure. The microhardness was gradually decreased from the surface of the reinforced layer to the matrix.

2. During the application of heavy load wear of 300 N, the coefficient of friction of the nano TiC gradient reinforced layer remained at the value of 0.25, the wear loss weight was 23 mg, the height of material loss on the surface was 187 μm. The high hardness and high coverage area of the nano TiC contributed to the manifestation of less plastic deformation and less wear.

3. The impact strength of the nano TiC gradient reinforced layer (75.27 J cm^{-2}) is significantly higher than that of a bare 40Cr alloy steel sample (15.25 J cm^{-2}). The distribution of TiC particles within the nano TiC gradient reinforced layer contributed also to a higher degree of crack deflection, which consumed more energy for the crack extension, resulting in higher impact toughness.
Acknowledgments

This work was supported by Yancheng Institute of Technology Research Startup Fund and Postgraduate Practice Innovation Program of Yancheng Institute of Technology (SJCX22_XY027).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

The authors declare that they have no conflicts of interest to report regarding the present study.

ORCID iDs

Xi Wang https://orcid.org/0000-0002-9199-5431
Weiguang Yang https://orcid.org/0000-0002-0533-4822
Ti Zhou https://orcid.org/0000-0003-3226-5081
Hai Zhou https://orcid.org/0000-0003-0871-6559

References

[1] Liu H L, Liu H J, Zhu C C and Tang J Y 2020 Study on gear contact fatigue failure competition mechanism considering tooth wear evolution Tribol. Int. 147 106277
[2] Ravivarman R, Palmiradla K and Sekar R P 2018 Evolution of balanced root stress and tribological properties in high contact ratio spur gear drive Mech. Mach. Theory 126 491–513
[3] Zhang P R and Liu Z Q 2016 Physical-mechanical and electrochemical corrosion behaviors of additively manufactured Cr-Ni-based stainless steel formed by laser cladding Mater. Des. 100 254–62
[4] Ju H, Xu P, Lin C and Sun D 2015 Test and temperature field of finite element simulation about the effect of scanning speed on 304 stainless layer’s properties by laser cladding Mater. Res. Innov. 19 58–9 58–13
[5] Li Y J, Dong S Y, Yan S X, Liu X T, He P and Xu B S 2018 Microstructure evolution during laser cladding Fe-Cr alloy coatings on ductile cast iron Opt. Laser Technol. 108 235–64
[6] Li X, Stampfl I and Prinz F 2000 Mechanical and thermal expansion behavior of laser deposited metal matrix composites of Invar and TiC Mater. Sci. Eng. A 282 86–90
[7] Qin L Y, Men J H, Zhang L S, Zhao S, Li C F, Yang G and Wang W 2019 Microstructure homogenizations of Ti-6Al-4V alloy manufactured by hybrid selective laser melting and laser deposition manufacturing Mater. Sci. Eng. A-STRUCTURAL Mater. Prop. Microstruct. Process. 759 404–14
[8] Zhan Z X 2019 Experiments and numerical simulations for the fatigue behavior of a novel TA2-TA15 titanium alloy fabricated by laser melting deposition Int. J. Fatigue 121 20–9
[9] Zhan M J, Sun G F, Wang Z D, Shen X T, Yan Y and Ni Z H 2019 Numerical and experimental investigation on laser metal deposition as repair technology for 316L stainless steel Opt. Laser Technol. 118 849–92
[10] Wu C L, Zhang S, Zhang C H, Zhang J B, Liu Y and Chen J 2019 Effects of SiC content on phase evolution and corrosion behavior of SiC-reinforced 316L stainless steel matrix composites by laser melting deposition Opt. Laser Technol. 115 134–9
[11] Lei Z L, Tian Z, Li P, Chen Y B, Zhang H Q, Gu J Y and Su X 2017 Effect of Si content on microstructure and thermo-physical properties of the joint of Si-p/6063Al composite by laser melting deposition Opt. Laser Technol. 97 116–23
[12] Cui C Y, Li X D, Fang C, Zhang W L, Yuan Z W, Cui X G, Liu J Z, Xia C D and Liu Y F 2018 Effects of Marangoni convection on the embedding dynamic behavior of SiC nano-particles into the Al molten pool during laser micro-melting Mater. Des. 143 256–67
[13] Wilson J M and Shin Y C 2012 Microstructure and wear properties of laser-deposited functionally graded Inconel 690 reinforced with TiC Surf. Coat. Technol. 207 517–22
[14] Al-Mangour B, Kim Y K, Grzesiak D and Lee K A 2019 Novel TiB2-reinforced 316L stainless steel nanocomposites with excellent room and high-temperature yield strength developed by additive manufacturing Compos. Part B-Engineering 156 51–63
[15] Nazari K A, Rashid R A R, Palamisamy S, Xia K and Dargusch M S 2018 A novel Ti-Fe composite coating deposited using laser cladding of low cost recycled nano-crystalline titanium powder Mater. Lett. 229 301–4
[16] Zhang H, Chong K, Zhao W and Sun Z 2018 Effects of pulse parameters on in situ Ti-V carbides size and properties of Fe-based laser cladding layers Surf. Coatings Technol. 344 163–9
[17] Janicki D 2018 Microstructure and sliding wear behaviour of in-situ TiC-reinforced composite surface layers fabricated on ductile cast iron by laser alloying Metals (Basel) 11 75
[18] Nemati N, Khosroshahi R, Emamy M and Zoljiasatein A 2011 Investigation of microstructure, hardness and wear properties of Al-4.5 wt% Cu-TiC nanocomposites produced by mechanical milling Mater. Des. 32 3718–29
[19] Li L, Wang J, Lin P and Liu H 2017 Microstructure and mechanical properties of functionally graded TiC/3Ti6Al4V composite fabricated by laser melting deposition Ceram. Int. 43 16638–51
[20] Kong D et al 2019 Effect of TiC content on the mechanical and corrosion properties of Inconel 718 alloy fabricated by a high-throughput dual-feed laser metal deposition system J. Alloys Compd. 803 635–7
[21] Zhang H M, Dongdong G, Xi L X, Zhang H, Xia M J and Ma C L 2019 Anisotropic corrosion resistance of TiC reinforced Ni-based composites fabricated by selective laser melting J. Mater. Sci. Technol. 35 1126–36
Zhao R, Li X J, Wan M, Han J Q, Meng B and Cai Z Y 2017 Fracture behavior of Inconel 718 sheet in thermal-aided deformation considering grain size effect and strain rate influence Mater. Des. 130 413–25

Nguyen Q B, Zhu Z, Chua B W, Zhou W, Wei J and Nai S M L 2018 Development of WC-Inconel composites using selective laser melting Arch. Civ. Mech. Eng. 18 1410–20

Yang L Q, Li Z Y, Zhang Y Q, Wei S Z and Liu F Q 2018 Al-TiC in situ composite coating fabricated by low power pulsed laser cladding on AZ91D magnesium alloy Appl. Surf. Sci. 435 1187–98

Yang W, Wang X, Zhou H and Zhou T 2021 Effect of nano TiC on microstructure and microhardness of composite additive manufacturing 316L stainless steel Mater. Res. Express 8 126521

Zhang Z H, Wang X, Zhang Q Q, Liang Y H, Ren L Q and Li X J 2019 Fabrication of Fe-based composite coatings reinforced by TiC particles and its microstructure and wear resistance of 40Cr gear steel by low energy pulsed laser cladding Opt. Laser Technol. 119 105622

Mago J, Bansal S, Gupta D and Jain V 2020 Investigation of microwave processing parameters on development of Ni-40Cr(3)C(2) composite clad and their characterization Metall. Mater. Trans. A-Physical Metall. Mater. Sci. 51 4288–300

Masanta M, Sharif F M and Choudhury A R 2016 Microstructure and properties of TiB2-TiC-Al2O3 coating prepared by laser assisted SHS and subsequent cladding with micro-/nano-TiO2 as precursor constituent Mater. Des. 90 307–17

Bansal S, Mago J, Gupta D and Jain V 2021 Parametric optimization and analysis of cavitation erosion behavior of Ni-based +10WC microwave processed composite clad using Taguchi approach Surf. Topogr. Prop. 9 015011

Bansal S, Mago J, Gupta D and Jain V 2021 Microwave cladding of NiCrSiC-5Al2O3 on austenitic stainless steel to improve cavitation erosion resistance Surf. Topogr.: Metrol. Prop. 9 35036

Mago J, Bansal S, Gupta D and Jain V 2021 Cavitation erosion behavior of microwave-processed Ni-40Cr(3)C(2) composite clads: a parametric investigation using ultrasonic apparatus Proc. Inst. Mech. Eng. Part L-Journal Mater. Appl. 235 263–92

Mago J, Bansal S, Gupta D and Jain V 2021 Influence of microwave heating on metallurgical and mechanical properties of Ni-40Cr(3)C(2) composite clads in the context of cavitation erosion resistance characteristics Proc. Inst. Mech. Eng. Part C-Journal Mech. Eng. Sci. 235 1258–76

Schwendner K I, Banerjee R, Collins P C, Brice C A and Fraser H L 2001 Direct laser deposition of alloys from elemental powder blends Scr. Mater. 45 1123–9

Zhang X D, Godfrey A, Huang X X, Hansen N and Liu Q 2011 Microstructure and strengthening mechanisms in cold-drawn pearlitic steel wire Acta Mater. 59 3422–30

Ma Y, Wang H, Xiao Y, Fan X, Tong J, Guo L and Tian L 2016 Friction and wear behaviour of steel with bionic non-smooth surfaces during sliding Mater. Sci. Technol. 32 257–65

Sahoo B N and Panigrahi S K 2016 Synthesis, characterization and mechanical properties of in situ (TiC-TiB2) reinforced magnesium matrix composite Mater. Des. 109 300–13