Microstructure and mechanical properties investigation of Ni35A–TiC composite coating deposited on AISI 1045 steel by laser cladding

Hao Zhang 1 · Guofu Lian 2 · Qiang Cao 2 · Yingjun Pan 1 · Yang Zhang 3

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Abstract
In this research, the TiC–Ni35A composite coating was fabricated on the AISI 1045 steel substrate by laser cladding process. The cross-sectional morphology, microstructure, microhardness, and wear resistance of coatings obtained under different laser energy densities (E) and TiC powder ratios (PR) were analyzed. According to the results, all the coating had a reliable metallurgical bonding with the AISI 1045 steel substrate. The X-ray diffraction (XRD) analysis revealed that the coating phases were Ni and TiC. The average microhardness of the Ni35A-80wt.% TiC coating reached up to 75.1 HRC. The minimum coefficient of friction of the composite coating was only about 30% of the AISI 1045 steel substrate. The wear form was mainly adhesive wear when altering the TiC powder ratios, while the wear form also contained abrasion wear under different energy densities. The ability of decomposition and re-nucleation of TiC was significantly improved with the increase of laser energy densities and the decrease of TiC powder ratios. The microhardness, wear resistance, and coefficient of friction of the composite coating were improved because of the TiC strengthening phase particles. Compared with the AISI 1045 steel substrate, the microhardness and wear resistance of the composite coating were increased by 5.3 times and 6.3 times, respectively.

Keywords Laser cladding · Composite coating · Microstructure · Microhardness · Wear resistance

1 Introduction
Surface treatment has been a focus, receiving extensive study as a key technology for the repair and remanufacturing of industrial parts. The surface treatment can reduce material waste effectively and prepare components according to the performance requirements of special parts. There are various types of surface treatment techniques, such as physical vapor deposition (PVD), chemical vapor deposition (CVD), thermal spraying, and laser surface treatment [1]. As one of the advanced laser surface treatment technologies, laser cladding utilizes a high-energy-density laser beam as the energy source to melt the alloy powder and part of the substrate at the same time [2, 3]. The alloy powder is delivered into the molten pool by either synchronous feeding or presenting to form a reliable metallurgical bonding between the substrate and coating. Because of the simple process, superior processing efficiency, rapid heating and rapid cooling \(10^5–10^8\) K/s, low coating dilution rate, and small deformation, laser cladding uses the shortest cycle to achieve the purpose of surface modification and repair [4–8]. At present, it has been widely utilized in the repair and remanufacturing of high-value parts or parts with distinctive shapes [9, 10].

Since the properties of the cladding layer are mainly determined by the coating material, a considerable amount of scholars utilized different materials to obtain cladding layers, and the most typical of which is self-fluxing alloys. According to its core elemental content, it is classified as iron-based, nickel-based, cobalt-based, and other self-fluxing alloys [11, 12]. Since nickel-based alloys have good wettability, corrosion resistance, oxidation resistance, fatigue resistance, impact resistance, and other remarkable properties in high-
temperature environments, they have been widely applied in cold metalwork parts, crushing rollers, shafts, and other mechanical parts manufacturing [13–15]. However, its low wear resistance and poor hardness of nickel-based alloys lead to a shortened service life and a limitation in the application range [16]. In order to improve the hardness and wear resistance of the nickel-based alloy, the typical method is to add ceramic/hard phase particles to the nickel-based alloy [17, 18]. Metal matrix composites coatings (MMCs) are widely used in surface protection due to their extreme hardness, high fatigue strength, and superior wear resistance. As a typical reinforcement material, TiC was often selected as a “second phase” reinforcement particle added to the metal material due to its high melting point (~3000°C), high hardness (2800–3200 HV), low friction coefficient, high elastic modulus, and low density (~4.93 g/cm³). Also, the ductility of titanium carbide can be increased with nickel to prepare high-performance coatings because of the good wettability between Ni and TiC [19–22]. Hu et al. [23] obtained NiCrCoMo/TiC composite coatings by plasma sprayed using NiCrCoMo alloy powders and TiC powders. According to their results, with the increase of TiC powder content, the average porosity and hardness of the coating increased, and the wear volume decreased significantly. Saroj et al. [24] analyzed TiC-Inconel825 composite coating deposited on AISI 304 steel by tungsten inert gas (TIG) process; the microhardness increased with the increase of TiC content and the decrease of the current, and the wear resistance was enhanced 7 times after coating compared with the substrate. Saeedi et al. [25] investigated the hardness and mass loss of the NiCr–TiC composite clad. They found that the hardness increased and mass loss decreased with adding reinforcement particles; the mass loss for NiCr–TiC was almost three times less than that of the stainless steel substrate without cladding. Gu et al. [26] investigated densification, microstructure, and mechanical properties of nano-TiC reinforced Inconel 718 composites processed by selective laser melting (SLM) with the variation of laser energy linear density (E). A high nano-hardness, low friction coefficient, and low wear rate can be obtained when the E was 300 J/m, showing a significantly improved mechanical performance compared to the SLM-processed unreinforced nickel-based alloys. Many researchers have conducted sufficient research on additional effects of nickel-based alloys–TiC composite coatings [27–31].

However, there are few reports on composite coatings that fully consider the combined effect of laser cladding process parameters. Moreover, the type and content of different strengthening phases have different energy requirements and which have an important influence on the forming quality of the coating. Therefore, in the presented work, laser cladding was used to obtain TiC reinforced Ni35A composite coating on the AISI 1045 steel substrate to improve the mechanical properties (e.g., microhardness, wear resistance) and forming quality. The effect of laser energy density and TiC powder ratio on the cross-sectional morphology, microstructure, microhardness, and wear resistance of the coating has been extensively investigated. The results can guide the improvement of mechanical properties and forming quality in the composite material surface coating process.

### 2 Material and methods

At first, the AISI 1045 steel was selected as the substrate with a size of 40 mm × 20 mm × 5 mm. The laser beam diameter was adjusted to 4 mm. Cladding powder was made from Ni35A and TiC powder (Chengdu HUAYIN Powder Technology Co., Ltd., Chengdu, China) with a particle size ranging from 48 to 106 μm. The elemental composition of Ni35A and TiC powder is shown in Table 1. Figure 1 shows the scanning electron microscopy (SEM) image of the Ni35A powder, TiC powder, and TiC/Ni35A powder after ball milling.

Figure 2 shows the laser cladding system and laser cladding process. The laser cladding system includes a laser system (YLS-3000, IPG, Burbach, Germany), laser cladding nozzle with 300-mm focal length (FDH0273, Lasermech, Novi, MI, USA), industrial robot (M-710iC/50, FANUC, Yamanashi, Japan), water cooling system (TFLW-4000WDR-01-3385, Sanhe Tongfai, Sanhe, China), powder feeding system (CR-PGF-D-2, Songxing, Fuzhou, Changhua County, China), control system (PLC, Mitsubishi, Japan), and laser pulse control system (SX14-012PULSE, IPG, Burbach, Germany). Argon gas was used as the carrier and protective gas during the laser cladding process.

Before cladding, the AISI 1045 steel substrate surface was cleaned with ethanol. The Ni35A and TiC powder were mixed in a MITR-YXQM-2L ball mill machine (MITR, Changsha, China) for 30 min at a speed of 300 rpm and then placed in a vacuum dryer for an additional 30 min at a temperature of 120°C. After completion of the laser cladding, the sample was processed by cutting, setting, grinding, and polishing. Then the sample was immersed in 4% nitric acid and alcohol mixture for 3 s. An MVA-402TS microhardness tester (HDNS, Shanghai, China) was utilized to measure the microhardness with a 500 gram-force applied for a 30-s duration. In

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### Table 1 Elemental composition (wt.%) of Ni35A and TiC powder

| Powder | Element (wt.%) |
|--------|---------------|
|        | C  | Si  | O  | Fe | Cr | B  | T.C | F.C | N  | Ni  |
| Ni35A  | 0.32 | 3.35 | <0.05 | 2.75 | 7.75 | 1.65 | -   | -   | Rest|
| TiC    | -   | 0.02 | 0.5 | 0.08 | -   | >18.8 | <0.5 | 0.5 | -   |

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addition, repetitive measurements of microhardness at three different regions were measured at room temperature and then averaged. The microstructure and morphology were observed using a scanning electron microscope (SEM) TM3030Plus (HITACHI 550I, Tokyo, Japan) in a vacuum chamber. In addition, element analysis was performed using an energy-dispersive X-ray spectroscopy (EDS) system (A550I, IXRF, Austin, TX, USA) equipped on the SEM under the same testing condition. The wear resistance was examined with a UMT-2 high load scratch tester (Bruker, Billerica, MA, USA). The X-ray diffraction (XRD) analysis was conducted with Ultima IV XRD systems (Rigaku Corporation, Tokyo, Japan) at a scanning speed of 4°/min and a scanning angle range from 20° to 80°. 3D morphology of the abrasion surface was obtained using white light interferometry. In addition, a vernier caliper with an accuracy of 0.01 mm was used to measure the wear height loss of the coating after the scratch test, and the average value was calculated for 3 measurements at different wear regions. Conditions for the wear test are shown below in Table 2. The average value of the friction coefficient was calculated under the stable region along the wear time.

The laser cladding processing parameter variables were exhibited in Table 3. The influence of TiC powder ratio (PR) on the forming quality and performance of composite coating were investigated by preparing five different types of samples with different TiC powder ratios on the AISI 1045 steel substrate.
Table 2 Scratch testing parameters

| Parameters      | Unit         | Specifications            |
|-----------------|--------------|---------------------------|
| Friction pair   | -            | Cemented carbide—Φ 6 mm   |
| Force           | N            | 35                        |
| Speed           | mm.s⁻¹       | 10                        |
| Distance        | mm           | 4                         |
| Duration        | min          | 60                        |
| Mode            | -            | Reciprocating             |
| Temperature     | °C           | Room temperature          |

Note that during the laser cladding process, the forming quality and performance of coating were influenced by laser power, scanning speed, laser beam diameter, and so on. Therefore, this paper also investigated the specific energy density (E) supplied to the molten pool, which was calculated using Eq. 1 [32, 33]:

\[
E = \left(\frac{P}{(\pi r^2)}\right)(2r/v) \tag{1}
\]

where \(P\) is the laser power (w), \(r\) is the laser spot radius (mm), \(v\) is the laser scanning speed (mm.s⁻¹), and \(2r/v\) is the laser-material interaction time.

Based on the properties of TiC and the analysis of the coating at different TiC powder ratios, although a higher TiC powder ratio can improve the microhardness and wear resistance of the coating, cracks were easily generated in the coating due to the brittleness of TiC, which can further promote the peeling off phenomenon of the coating (see Fig. 3e). Besides, the decomposition and re-nucleation of TiC were best when the TiC powder ratio was 40wt.%. In addition, the deposited coating exhibited a reliable bonding with the substrate according to the results of the coating morphology and microstructure. Therefore, 40wt.% TiC powder ratio was selected to further the investigation by altering the energy density. The energy density (E) during the laser cladding process was varied from 52 to 104 J.mm⁻² (another four samples in Table 3).

Table 3 Experimental design for composite coating

| Sample | Laser power (w) | Scanning speed (mm.s⁻¹) | Gas flow (L.h⁻¹) | TiC powder ratio (wt.%) | Energy density (J.mm⁻²) |
|--------|-----------------|-------------------------|------------------|------------------------|-----------------------|
| 1      | 1300            | 6                       | 1200             | 0                      | 69                    |
| 2      | 1300            | 6                       | 1200             | 20                     | 69                    |
| 3      | 1300            | 6                       | 1200             | 40                     | 69                    |
| 4      | 1300            | 6                       | 1200             | 60                     | 69                    |
| 5      | 1300            | 6                       | 1200             | 80                     | 69                    |
| 6      | 1300            | 8                       | 1200             | 40                     | 52                    |
| 7      | 1100            | 6                       | 1200             | 40                     | 58                    |
| 8      | 1500            | 6                       | 1200             | 40                     | 80                    |
| 9      | 1300            | 4                       | 1200             | 40                     | 104                   |

3 Results and discussion

The concentration in this study focuses on the influence of energy density and powder ratio on the forming quality during laser cladding since the forming quality can significantly impact the serving life of the coated substrate. Therefore, investigation in several aspects for the deposited coating is essential to discuss in detail in the following sections: coating morphology by SEM, material structure with XRD, microstructure with SEM-EDS, microhardness, wear resistance, and coefficient of friction.

3.1 Coating morphology

Figure 3 illustrates the cross-sectional SEM images of a typical single track coating by laser cladding process with 69 J.mm⁻² energy density for different TiC contents (0, 20, 40, 60, 80wt.%). Generally, all the coating had excellent bonded interfaces with the substrate. It can be observed that coating was composed of four zones: cladding zone (CZ), bonding zone (BZ), heated affected zone (HAZ), and substrate (SZ).

It can be noted that the coating of Fig. 3a had no dark phase, and the forming quality was greater than others. In addition, it was evident that Fig. 3b–e had an almost uniform composite coating without an obvious structural difference. However, it can be found that when the TiC content was 80wt.% (Fig. 3e), obvious cracks and peeling off phenomenon were observed in the coating. This was caused by the excessive TiC powder ratio, leading to the increase of the brittleness of the cladding layer and increasing the tendency to generate cracks. Due to the high melting point of TiC, when TiC powder content kept increased to 80wt.% in the powder mixture, the thermal energy of the laser was primarily absorbed by TiC. Consequently, the laser energy absorbed by the molten pool under this condition was lower than other samples with lower TiC percentages. As a result, with the increase of the solidification rate in the molten pool, the residual stress in the coating was unable to release and form cracks [34]. In addition, the
excessive TiC content in the powder mixture was not able to fully reach the decomposition and re-nucleation temperature [35, 36], which lead to the TiC only adhering to the surface of the cladding layer and accelerating its tendency to peel off from the coating.

Figure 4 and Fig. 3c illustrate the cross-sectional SEM images of TiC–Ni35A composite coating deposited by laser cladding process with 40wt.% TiC content at different energy densities (52, 58, 69, 80, 104 J.mm$^{-2}$). It can be seen that the coatings had no interfacial gap appeared between the cladding layer and substrate at different energy densities. Moreover, it can be found that large TiC particles existed in the cladding layer when laser energy density was 52 J.mm$^{-2}$, while small TiC particles were observed when laser energy density was 104 J.mm$^{-2}$. The lifetime of the molten pool was extended with the increase of laser energy density, which resulted in a significant increase in the convection effect of the molten pool [37]. Hence, the TiC powder in the cladding layer had more time to decompose and re-nucleate, resulting in fine TiC particles.

3.2 XRD analysis

Figure 5 shows the X-ray diffraction (XRD) patterns of TiC–Ni35A composite coating on the AISI 1045 steel with different TiC powder ratios (0, 20, 40, 60, 80wt.%) by laser cladding process. The analysis by XRD was performed in order to identify the type of component phase in the coating. It can be noted that the TiC–Ni35A composite coating layer was mainly composed of TiC and Ni, and it can be demonstrated that no new secondary phases were formed other than TiC and Ni during the laser cladding process, since the laser cladding process of the research was mainly a physical reaction, and chemical was negligible. No significant differences in the XRD patterns were observed when TiC was added to the sample, and there was merely a difference in the peak intensities due to the difference in TiC content percentage. Interestingly, it can be found that the relative intensity of the TiC peak reached a maximum of 80wt.% TiC (sample 5) at a 2θ position of 41.48°, and the relative intensity of Ni peak reached a maximum of 0wt.% TiC (sample 1) at a 2θ position of 43.98°.

Fig. 3 Cross-sectional SEM images of the coatings deposited with 69 J.mm$^{-2}$ energy density and different TiC powder ratios: a 0wt.% b 20wt.% c 40wt.% d 60wt.% and e 80wt.%
3.3 Microstructure

It is well known that the microstructure of any coating had a significant impact on its properties. Therefore, a detailed microstructural analysis study of produced coatings is indispensable to evaluate its mechanical performance (e.g., microhardness, wear resistance). In this study, the microstructure of the cladding layer was investigated to comprehend the effect of the TiC powder ratio and the energy density in the laser cladding process.

Figure 6 shows the microstructure approximately in the middle region in the cladding zone of the laser cladding processed composite coating with the variation of TiC powder ratio (0, 20, 40, 60, 80wt.%). It is clear to be found that SEM images (Fig. 6) show a significant difference with the increase of TiC content in the composite coating. The main factor of this phenomenon is that the melting temperature of TiC (~3000°C) is considerably higher than the Ni35A (~1050°C); a higher ratio of TiC powder requires more energy to accomplish the decomposition and re-nucleation process.

The EDS analysis in the whole area corresponding to Fig. 6 was performed, and the results were illustrated in Table 4. It can be found that in the row of Fig. 6a, the elemental composition was similar to the Ni35A powder in the coating prepared without any TiC powder. Interestingly, the C and Ti percentage in the cladding layer increased gradually with the increase of TiC powder ratio (Fig. 6b–e); it is evident that the total content of Ti and C was almost equal to the TiC powder ratio. In contrast, the percentage of Cr, Fe, and Ni decreased with the increase of the TiC powder ratio in the coating.

In general, the microstructure had no secondary dendrite arm in the SEM image as shown in Fig. 6a. Figure 6b–e displays the microstructure of TiC changed from the dendritic crystal structure to a larger TiC particle structure. This phenomenon was formed by the TiC content in these four different sets of TiC powder ratio (20, 40, 60, 80wt.%). Since the laser energy density was kept at 69 J.mm\(^{-2}\) for all the setpoint and the melting temperature of TiC is reasonably higher than the melting temperature of Ni35A, the melting of TiC powder became less incomplete when adding more TiC content. With the increased amount of TiC percentage from 20wt.% in Fig. 6b to 80wt.% in Fig. 6e, the trend of decomposition and re-nucleation of the dissolved TiC grow into the
dendritic crystal structure and became weak, resulting in a large TiC particle structure. Note that Fig. 6e shows that the corners and sharp edges of the TiC particles had a slight smoothness [36, 38], with respect to their original morphology as a reinforcing phase within a very fewer amounts of Ni35A in the coating.

In order to identify the differently shaded regions (dark and light) in the coating morphology, a high magnified SEM image and corresponding EDS analysis were performed for the coating produced with 40wt.% (Fig. 6c, marked 1, 2) as demonstrated in Fig. 7. Elemental analysis by EDS corresponding to the dark and light regions was tabulated in Table 5. It can be noticed that the dark region (marked as 1) was composed of high percentage of Ti and C. On the contrary, the light region (marked as 2) had a high elemental content of Cr, Fe, and Ni in combination with less amount of Ti and C. Considering the XRD analysis results, it can be determined that the dark region and light region were TiC and Ni-based alloy, respectively.

Figure 8 illustrates the SEM images of the composite coating produced with 40wt.% TiC at different laser energy densities (52, 58, 80, 104 J.mm\(^{-2}\)), where Fig. 6c shows the microstructure at the laser energy at 69 J.mm\(^{-2}\). It can be clearly seen from Fig. 8 and Fig. 6c that when the TiC powder ratio was fixed, the morphology of the TiC in the composite coating hardly changed with the increase of the laser energy density. However, the ability of decomposition and re-nucleation of TiC particles was significantly influenced by different energy densities. The TiC particles became smaller as the laser energy density increased. It can be concluded that the TiC particles can absorb more energy for decomposition and re-nucleation at the same time with the increase of laser energy density, obtaining a finer and uniform microstructure [39]. Besides, due to the TiC powder ratio in the composite coating fixed at this condition, the energy required for the decomposition

| Sample | Element (wt.%) |
|--------|---------------|
|        | C  | Ti | Cr | Fe | Ni  |
| Fig. 6a | 1.403 | 0.158 | 6.241 | 3.415 | 88.783 |
| Fig. 6b | 3.781 | 16.342 | 5.004 | 2.070 | 72.804 |
| Fig. 6c | 5.860 | 35.145 | - | 3.187 | 55.808 |
| Fig. 6d | 7.629 | 51.846 | - | 1.406 | 39.119 |
| Fig. 6e | 12.369 | 83.807 | - | 1.259 | 2.566 |
and re-nucleation of TiC was constant, so the excessive energy will no longer be used for decomposition and re-nucleation. When the laser energy density reached a certain limit, the size of TiC particles tended to be stabilized (see Fig. 8c, d).

Figure 9 illustrates the mapping EDS analysis of the cross-section of the coating produced with 58 J.mm⁻² energy density and 40wt.% TiC. It can be found that the dark phase in the coating was rich in C and Ti, while the light phase was composed of a large amount of Ni. It can be determined that the dark phase was TiC and the light phase was Ni, which was consistent with the results presented in Fig. 6, Fig. 7, Table 4, and XRD phase analysis. In addition, a small amount of Fe and Cr can be discovered in the coating. Under the action of a high-energy laser beam, the Fe and Cr elements in the AISI 1045 steel substrate entered into the coating under the convection in the molten pool during the cladding process.

### 3.4 Microhardness

To investigate the microhardness of the produced TiC–Ni35A composite coating and its variation with the position of the coating, microhardness was measured at the cross-section of the composite coating. Figures 10 and 11 represent the microhardness profile measured against the position of the composite coating from the top surface of the coating to the substrate for samples processed at different conditions.

Figure 10 shows the microhardness profile of the composite coating measured at multiple positions with different TiC powder ratios. It can be observed a sharp increase trend in the microhardness from the substrate toward the cladding surfaces. From the plot, the microhardness of the composite was enhanced with the increase of the TiC powder ratio. In terms of the coating zone, which refers to the first five red dots from the right side of the position axis, the average microhardness value ranged from 44.5 HRC in the pure Ni35A coating to an average value of 75.1 HRC of Ni35A-80wt.% TiC composite coating. The microhardness of the coating prepared by laser cladding was significantly higher than the AISI 1045 steel substrate, referring to the left side of the position axis. The highest microhardness of the coating reached nearly 5 times that of the AISI 1045 steel substrate.

The microhardness increased with the increase of the TiC powder ratio because TiC is well known to serve as a hardness reinforcement compound. When the TiC powder ratio was lower, the TiC concentration in the coating was relatively low, and the hard phase structure was correspondingly less, which was not conducive to improving the microhardness of the coating. On the contrary, the TiC powder ratio in the coating increased gradually, which can increase the microhardness of the coating effectively [35].

Similarly, in order to analyze the impact of different energy densities at the cross section of the composite coating, the microhardness value was measured for the composite coating produced when the TiC powder ratio was 40wt.%. Figure 11 shows the effect of energy density on the microhardness and its distribution of the composite coating. The microhardness value of composite coating was in the range of 50–65 HRC. All of the composite coatings had a higher average microhardness value than that of the AISI 1045 steel substrate.

From the plot, the microhardness of the composite coating increased with the increase of energy density. Based on Fig. 11, the influence of changing laser energy density did not imply an obvious change on the microhardness of the coating, and the microhardness change trend was relatively gentle. It is well known that the amount, size, and distribution of strengthening particles, as well as defects of pores and micro-cracks, are the main influencing factors on the microhardness [40, 41]. In addition, the laser power together with scanning speed determined the amount of energy density induced for all TiC particles decomposition and re-nucleation. Therefore, the increased energy density resulted in more energy during the laser cladding process, indicating that the ability of decomposition and re-nucleation increased effectively of TiC particles. Thus, the TiC particles had enough time to accomplish...
decomposition and re-nucleation to become smaller in their size with the increase of energy density. According to the Hall–Petch relationship, the smaller the strengthening particles, the larger the microhardness. In addition, the life of the molten pool was extended with the increase of laser energy density, which resulted in a decrease in the solidification rate.
of the molten pool, and TiC particles had sufficient time to decompose and re-nucleate. The prolonged lifespan of the molten pool was beneficial to the release of residual stress in the coating and increased the path of pores to escape from the coating and so on. Hence, it is possible to reduce the defects and increase the microhardness of the coating. Under the action of high energy density, the iron element in the AISI 1045 steel substrate entered into the coating through the strong convection of the molten pool to produce a solid solution strengthening effect, which resulted in the coating having a greater microhardness with higher energy density.

### 3.5 Wear resistance

In order to analyze the wear resistance of the composite coating prepared by laser cladding, the UMT-2 high load scratch tester (Bruker, Billerica, MA, USA) was used to conduct the test of the composite coating with the friction and wear parameters shown in Table 2. The wear height loss measured under different TiC contents and different energy densities is shown in Fig. 12 and Fig. 13, respectively. It can be clearly seen from Fig. 12 that the wear height loss of the composite coating became less with the increase of the TiC powder ratio (ranging from 0 to 60wt.%). However, when the TiC powder ratio reached 80wt.%, the wear height loss of the composite coating had a slight increase. Owing to the coating had begun to appear the peeling off phenomenon when the TiC powder ratio reached 80wt.% (see Fig. 3). Meanwhile, Fig. 6e clearly shows a weak ability of decomposition and re-nucleation at 80wt.% TiC. As a result, under high-speed wear conditions, the hard phase particles were easily separated from the coating and formed wear debris. The wear debris staying on the worn surface accelerated the wear of the cladding layer, which led to the increase of the wear height loss of the coating. The minimum wear height loss of the composite coating was only 15.0% of the substrate. The results proved that the wear resistance of the coating obtained by laser cladding technology had been significantly improved compared with the uncoated AISI 1045 steel substrate.

Figure 13 shows that the 3D wear morphologies of coating at different TiC powder ratios. It is evident that the wear residual in Fig. 13a–d appeared less and less affected under the wear condition, which was contributed from the increasing TiC powder ratio from 0 to 60wt.%. When the TiC powder ratio further increased to 80wt.% (Fig. 13e), the worn surface of the coating became worse than that of 60wt.% TiC (Fig. 13d). The worn surface track width of the coating was the largest, and the worn depth was the deepest (Fig. 13a), and there was no accumulation of wear debris in the worn coating, indicating that the wear of the coating was more serious. When the TiC powder ratio was 20wt.% (Fig. 13b), the worn track in the coating...
became narrower compared with Fig. 13a, and a large amount of wear debris was found to accumulate. The type of wear debris was mostly formed by the composite coating peeling off under high-speed friction, and the wear form of the cladding layer was adhesive wear. Besides, the TiC hard phase particles acted as an anti-wear skeleton in the coating. However, due to the low TiC powder ratio in the cladding layer, the effect of the anti-wear skeleton decreased at this condition, which resulted in wear debris on the worn surface. Hence, the peeled-off hard phase particles continued to act as abrasive particles in the dry friction process until it disappeared on the worn surface, and the cladding layer had a wider and deeper worn track. With the TiC content increased to 40wt.%, and 60wt.%, the worn track became shallower and narrower. More reinforcement phases can prevent the coating from forming wear debris during the wear process to reduce wear. Interestingly, when the TiC powder was increased to 80wt.%, the worn surface track of the coating became deeper in the comparison with that of 60wt.% TiC. According to the analysis of the cross-sectional morphology in Fig. 3, it is shown that the TiC hard phase particles cannot be fully completed by the process of decomposition and re-nucleation under a certain energy density (69 J.mm$^{-2}$). Hence, a large amount of TiC hard particles were not able to dissolve into the Ni35A phase, which was adhered to the surface and had poor bonding with the coating. During the high-speed wear, these TiC particles were peeling off easily and led to a worse surface morphology in the worn track than that of 60wt.%. In summary, all analysis of worn surface morphology was consistent with the analysis trend of wear height loss, and the wear form of the Ni35A/TiC composite coating was primarily adhesive wear.

Figure 14 illustrates the different wear height loss under different energy densities with 40wt.% TiC powder ratio. Following the increase of the energy density, the wear height loss of the coating was decreased. But the decreasing values were on a relatively small scale, which indicated that the energy density had a nonsignificant effect on the wear height loss, and the trend was consistent with the plot of
microhardness change in Fig. 11. Combining with Fig. 6c and Fig. 8, it can be concluded that the higher the energy density promoted, the stronger the decomposition and re-nucleation of TiC particles, which resulted in the formation of fine TiC particles. The fine TiC particles were more stable during the wear process and difficult to form wear debris, so an effective reduction of wear height loss can be obtained.

Figure 15 shows the 3D wear morphologies of coating at different energy densities with 40wt% TiC. It can be found that the worn surface of the composite coating had spalling pits (Fig. 15a), which were caused by the large TiC hard phase particles peeling off due to incompletion on the decomposition and re-nucleation process under the low energy density (52 J.mm\(^{-2}\)). Meanwhile, the TiC hard phases produced micro-cracks and peeled off under the compressive stress and shear forces, which resulted in the coating generating spalling pits, and the wear form of the worn surface was abrasion wear. The worn surface appeared more wear debris with the increase of laser energy density (Fig. 15b, c), and the worn surface became shallower than that of Fig. 15a. Owing to the increase of the laser energy density, the ability of decomposition and re-nucleation of TiC hard phase particles was improved. The coating can obtain finer TiC hard phase particles at high energy densities (58 J.mm\(^{-2}\), 80 J.mm\(^{-2}\)) to improve the wear resistance of the coating, and the wear form of the coating was adhesive wear. When the energy density increased to 104 J.mm\(^{-2}\), the worn surface (Fig. 15d) became smoother and shallower than that of others. This phenomenon was accomplished by the dissolution of TiC particles into the Ni-based alloy structure, owing to the good wettability among the Ni-based alloy, TiC, and the AISI 1045 steel substrate.

3.6 Coefficient of friction

Figure 16 shows the average coefficient of friction (COF) of the AISI 1045 steel substrate and the coatings obtained under different conditions following the scratch test shown in Table 2. Under the same testing condition, the COF of the AISI 1045 steel substrate was 0.85, while the lowest COF of the coating was 0.25 (sample 4). It can be seen from the plot...
with different conditions that the COF of all coatings was significantly lower than the AISI 1045 steel substrate, indicating that the wear resistance of the coating was better than the substrate. Since the microhardness of the AISI 1045 steel substrate was lower than the cladding layer, wear debris was easily formed in the scratching test and adhered to each other, which led to the increase of substrate COF than the coatings. The TiC hard phase served as reinforcement particles that effectively improve the microhardness of the coatings. Along with the increase of energy density, better dissolution of TiC particles was achieved into the Ni-based alloy, which further decreased the COF of coatings.

4 Conclusions

Ni35A and Ni35A/TiC composite coatings with high hardness and favorable wear resistance on the AISI 1045 steel substrate were successfully coated by the laser cladding process. All the coating had a reliable metallurgical bonding with the AISI 1045 steel substrate.

The effect of laser energy density and TiC powder ratio on the cross-sectional morphology of the coating was analyzed. The TiC powder ratio had a significant effect on the cross-sectional morphology of the coating. The excessive TiC powder ratio was prone to cause peeling off and cracking in the coating.

The main phases of the coating were Ni and TiC. The decomposition and re-nucleation ability of the TiC were weakened with the increase of TiC powder ratio or the decrease of laser energy density, which led to the differences of the coating structure under different TiC powder ratios or different energy densities.

Compared with the AISI 1045 steel substrate, the microhardness and wear resistance of the prepared coating had been significantly improved. The coating enhanced the microhardness and wear resistance by 5.3 times and 6.3 times, respectively.

Due to the decomposition and re-nucleation effect, the TiC particles were dissolved into the Ni-based alloy structure, which improved the wear resistance and reduced the coefficient of friction effectively. The wear form was mainly adhesive wear when changing the TiC powder ratios in different levels. While the energy densities were adjusted, there was also abrasion wear involved.

Author contribution Hao Zhang: methodology, investigation, formal analysis, and writing—original draft. Guofu Lian: formal analysis, writing—original draft, writing—review and editing, and funding acquisition. Qiang Cao: investigation and formal analysis. Yingjun Pan: formal analysis, writing—original draft, writing—review and editing, and supervision. Yang Zhang: formal analysis, writing—original draft, and writing—review and editing.

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Data availability All related data and materials are available in the manuscript text.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

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