

Review Article

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Improving the microstructure and mechanical properties of laser cladded Ni-based alloy coatings by changing their composition: A review

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Abstract: Ni-based alloy coatings prepared by laser cladding has high bonding strength, excellent wear resistance and corrosion resistance. The mechanical properties of coatings can be further improved by changing the composition of alloy powders. This paper reviewed the improved microstructure and mechanical properties of Ni-based composite coatings by hard particles, single element and rare earth elements. The problems that need to be solved for the particle-reinforced nickel-based alloy coatings are pointed out. The prospects of the research are also discussed.

Keywords: laser cladding, Ni-based alloy, microstructure, mechanical properties

1 Introduction

The commonly used Ni-based alloy powders mainly consist of two series: Ni-B-Si and Ni-Cr-B-Si. The main phases exist in Ni-B-Si alloy coatings are Ni-Si solid solution (γ phase), borides (γ' phase) and γ - γ' eutectic phase. The coatings are easy to fabricate, which show high toughness, excellent wear resistance, corrosion resistance and high temperature resistance [1, 2]. The Ni-Cr-B-Si alloy is formed by adding an appropriate amount of Cr to the Ni-B-Si powder. The phase in Ni-Cr-B-Si alloy coatings is complex. Cr atoms can react with C atoms and B atoms to form carbides and borides, becoming the first strengthening phases of

the cladding layer, which can effectively improve the wear resistance of the metal surface. Cr atoms can also dissolve in Ni atoms and act as solid solution strengthening, which can significantly improve the hardness of coatings. Ni based alloy coatings have strong metallurgical bonding, good wear resistance and excellent corrosion resistance. It has broad application prospects in engineering [3, 4]. The commonly used methods of preparing Ni-based coatings include laser cladding, plasma spraying, TIG and so on.

Laser cladding, known as a promising method of surface engineering, has been widely applied in modification of surface properties. The high energy laser beam is used as the heat source and the alloy powder as the cladding material. The alloy powder and the matrix surface are melted quickly by the radiation of the high energy density laser. After the laser beam removes away, the molten metal solidified rapidly because of the heat conduction of the matrix, thus the cladding layer is completely metallurgic with the matrix, which aiming to improve the surface properties of matrix. At present, the commonly used laser cladding processes are preset powders method and simultaneous powder feeding method. In the preset powders method, the powder is pre-placed onto the substrate surface homogeneously. The laser spot melts the powders and surface of substrate along the set trajectory. After the laser left, the melt pool solidified into coating. The schematic diagram of the laser cladding with the preset powder method is shown in Figure 1. Simultaneous powder feeding method is to send powder to the molten pool while the laser is radiating. The schematic diagram of laser cladding with simultaneous powder feeding method is shown in Figure 2. The coatings obtained by laser cladding have smaller heat affected zone. The coatings have compact structure, good combination with substrate, low porosity and low content of inclusions [5].

The Ni-based coating prepared by laser cladding has a fine grain, dense microstructure, strong metallurgical bonding between the coating and the matrix, high hardness, excellent wear resistance and corrosion resistance. It has been widely used in aerospace, turbines, automo-

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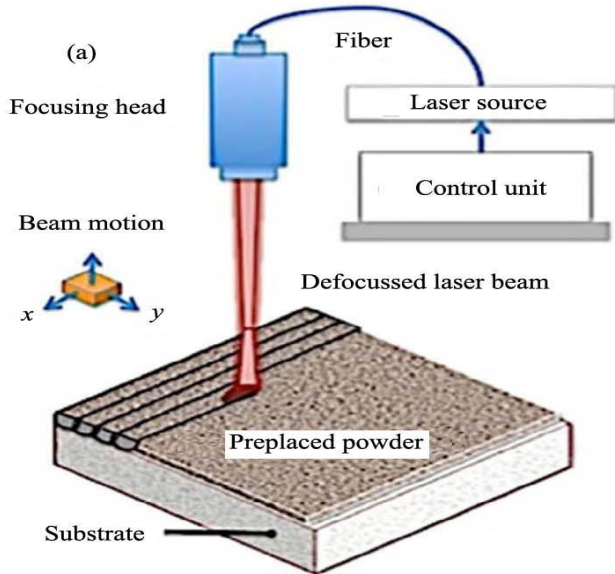


Figure 1: The schematic diagram of laser cladding with preset powder method [7]

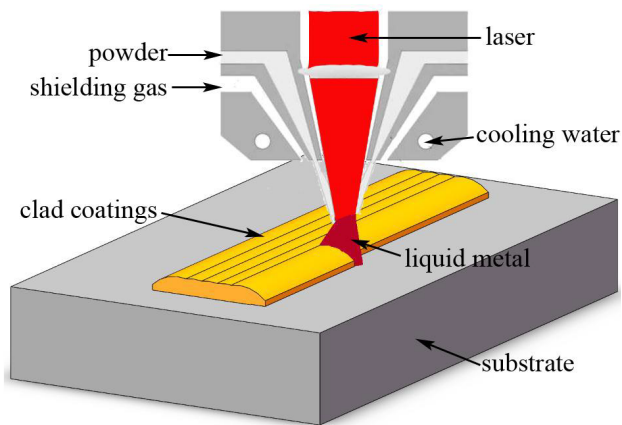


Figure 2: The schematic diagram of laser cladding with coaxial powder feeding

bile mold, piston rods, wearing plates and roller, but in different service environments and engineering components, wear is one of the three main reasons for the failure of engineering materials [6], laser cladding Ni-based coating can be used to repair the worn surface of components, which extends service life and improves mechanical properties. In addition, it is necessary to strengthen the surface, such as for steel, aluminum alloy, etc. However, in conventional NiCrBSi alloy coating, the amount of strengthening phase is less, and the surface properties need to be further improved. Ni-based alloy coatings reinforced by hard particles have high hardness, excellent wear resistance and corrosion resistance, and high temperature oxidation resis-

tance. In recent years, many researchers have done a lot of research on the use of strengthening phase particles to improve the performance of Ni based coatings, and explored the application of Ni based coatings in engineering. It is expected to provide theoretical and technical support in engineering applications.

2 Adding hard particles directly

The direct addition of hard particles is the mechanical mixing of reinforced particles with metal powders, and then the composite materials are prepared by solid state reaction or liquid casting. The advantage is that the phase selection is wide, the preparation is relatively simple, and the particle size is easy to control. The commonly used hard phase particles directly added include: WC, NbC, TiC, TaC and VC. For a more intuitive comparison of base alloy, cladding methods, hard particles and obtained mechanical properties, the hard particles, Table 1 listed the coatings reinforced by hard particles with direct addition method.

WC particles have the advantages of high melting point and moderate strength and toughness, good compatibility and high bonding strength with Ni-based coatings [8]. Ortiz *et al.* [9] used to prepare NiCrBSi coatings with different WC addition by laser cladding. It is found that the distribution of WC in the coating is not uniform, and the WC content at the bottom of the coating is higher (as shown in Figure 3). Ma *et al.* [10] prepared Ni60/WC composite coatings with wide-band laser and circular laser.

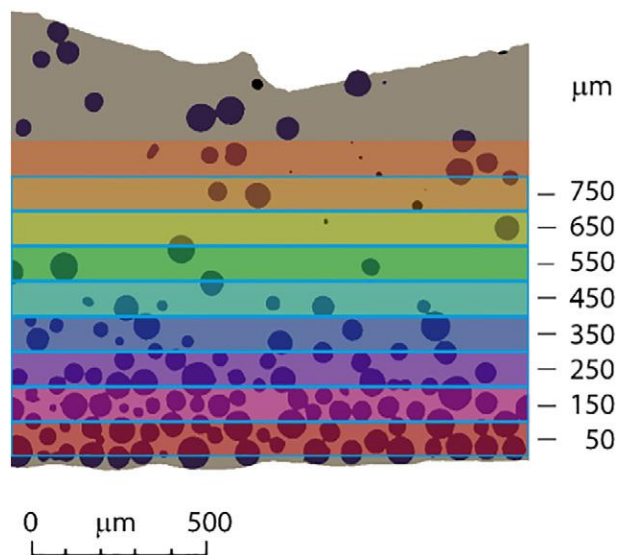
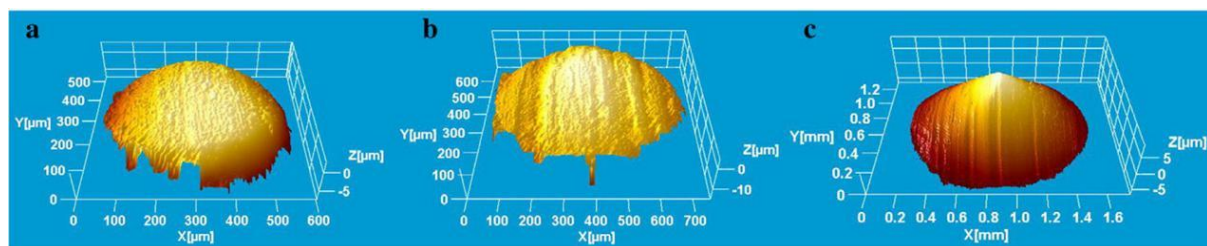


Figure 3: The distribution of WC particles in Ni based coatings [9]

Table 1: The coatings reinforced by hard particles with direct addition method

Researcher	cladding methods	Substrate	Hard particles	Base alloy	Mechanical properties
Ortiz <i>et al.</i> [9], Tobar <i>et al.</i> [11], Li <i>et al.</i> [14]	Different content of WC	C45E, AISI 304, H13	WC	Metco 12C, METCO 16C, Ni60A	The hardness of coatings was improved
Ma <i>et al.</i> [10]	Wide-band laser and circular laser	Q550 steel	WC	Ni60	The hardness and wear resistance of wide-band laser coatings was higher than circular laser coating
Guo <i>et al.</i> [12]	Preheated the substrate	1Cr18Ni 9Ti	WC	NiCrBSi	The hardness of coatings was about 5 times than substrate, and the wear resistance increased with the increase of WC.
Zhou <i>et al.</i> [13]	Laser induction hybrid cladding (LIHC), laser cladding (LC)	A medium carbon steel plate	WC	Ni-based alloy powder	The microhardness and wear resistance of multi-track LIHC coating were lower than multi-track LC coating
Da <i>et al.</i> [19], Zhang and Lei [20]	Different content of Cr ₃ C ₂	Martensitic stainless steel	Cr ₃ C ₂	Ni-based alloy	The hardness, wear resistance and ECW resistance of coatings were improved
Zhang and Zhang [21]	Ni + 50% Cr ₃ C ₂ , Ni+50%WC	Martensitic stainless steel	WC, Cr ₃ C ₂	Ni-based alloy	The ECW rate of both coatings decreased about 30% and 60% than substrate
Wilson and Shin [22], Xu <i>et al.</i> [25]	Different content of TiC	AISI 1018 steel, AISI 316L	TiC	Inconel 690 alloy, Inconel 625	The hardness, wear resistance and corrosion resistances of coatings were increased
Jiang <i>et al.</i> [23]	nano-TiCp	C45 mild steel plates	TiC	Inconel 625 powder	The hardness and modulus of coatings were higher than Inconel 625 substrate
Meng <i>et al.</i> [27]	Different content of B ₄ C	Ti-6Al-4V	B ₄ C	NiCrBSi	The hardness of coatings was three times higher than substrate

**Figure 4:** 3D non-contact mapping of worn surface: (a): NiCrBSi coating; (b): NiCrBSi/5%WC-Ni coating; (c): NiCrBSi/50%WC-Ni coating [12]

The wear loss of coatings was measured at different sliding distance with a load of 10 kg, and they found the coatings with hard carbides (WC and $M_{23}C_6$) and uniform distributed cored eutectic structure improved the hardness and wear resistance. Tobar *et al.* [11] studied the effect of WC volume fraction on the formation and properties of coatings, dense and crack-free coatings were obtained

with less than 50 wt.% WC, the hardness of coatings were dependent on WC content, which ranged between 600 Hv and 1000 Hv. Guo *et al.* [12] studied the wear resistance of NiCrBSi and NiCrBSi/WC-Ni coatings with the normal load of 5 N, the 3D non-contact surface mapping of the wear scars is shown in Figure 4, they found the hard WC particles is an effective method to improve the wear resis-

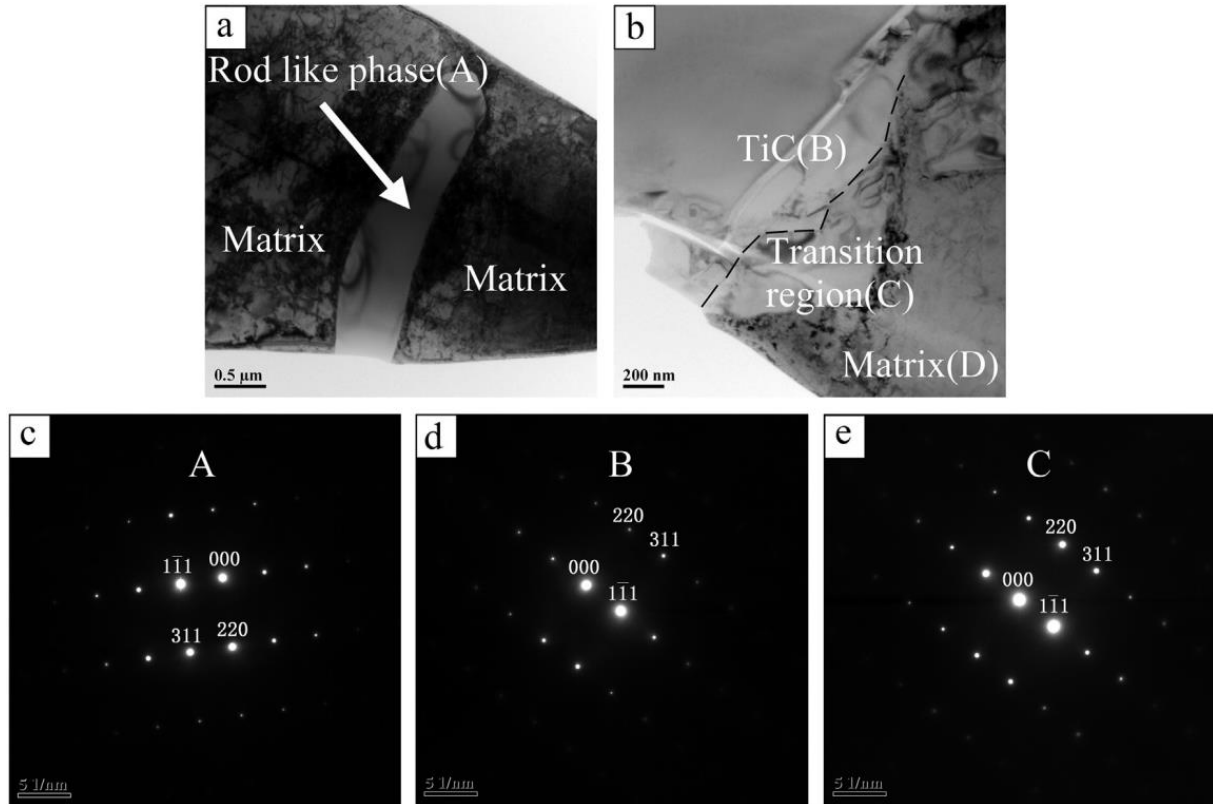


Figure 5: Fine structure of TiC (a): TEM images of rod like phase; (b): TiC, transition region and matrix of composites; (c): SAED patterns of rod like phase; (d): TiC; (e): transition region using zone axis [24]

tance of Ni-based coatings. Zhou *et al.* [13] studied the effect of laser spots on the performance of WC-NiCrMo coating. It found that the microstructure and mechanical properties of the coatings prepared by circular spots and oval spots were different. The wear resistance of coatings made by multi-track LIHC was lower than multi-track LC under the same laser processing parameters, but the wear resistance improved 1.4 times as the laser scanning speed increase to 1500 mm/min. Li *et al.* [14] studied the effect of different WC addition on the microstructure of Ni60A/WC laser cladding layer. It is found that when the addition of WC is 20 wt.%, the main phases of the coating include γ - (Fe, Ni) dendrites and carbides with intergranular W rich. When the addition of WC is 33 wt.%, a lot of floc eutectic structure is distributed in the coating. When the addition of WC reaches 50 wt.%, the coating is mainly composed of M_6C , $M_{23}C_6$ and $Cr_4Ni_{15}W$. Zang *et al.* [15] used laser cladding technology to prepare Ni60/WC coatings on 20Cr steel substrate to improve the hardness and wear resistance of the surface. The phase of Ni60/WC coating is mainly composed of Fe-Ni, Cr_7C_3 and WC. The hard phase WC and Cr_7C_3 can improve the hardness and wear resistance of the coating. The hardness of the Ni60-WC coating

is 761Hv (The hardness Ni60A is 607Hv), and the wear resistance is 33% higher than that of the Ni60A coating.

Cr_3C_2 is one of the most widely used hard particles to reinforce metal-based coatings. Cr_3C_2 reinforced Ni-based coating has high hardness and excellent wear resistance, making it very suitable for the preparation of wear-resistant coatings [16, 17]. Yu *et al.* [18] prepared Ni- Cr_3C_2 composite coatings on the surface of Q235 steel by laser cladding. The grain size of the coating was fine, the microstructure was uniform and dense. The average hardness of the coating reached 1000-1200 Hv, the friction coefficient of the coating was about 0.44, and the friction performance was stable. The combination of Cr_3C_2 hard particles and metal matrix can effectively improve the bearing capacity of the cladding layer, which makes the coating have excellent wear resistance. Ni- Cr_3C_2 coatings were prepared by Da *et al.* [19] to improve the surface properties of stainless steel. The Cr_3C_2 decomposed into Cr and C atoms in the molten pool, and Cr_7C_3 and $Cr_{23}C_6$ were formed by the combination of Cr and C atoms. The hardness of the Ni- Cr_3C_2 coating reached 1000-1200 Hv, the hardness of the coating was about 400Hv higher than that of the Ni coating, and the wear resistance increased 1.7 times at the load

of 60 N. In addition, Zhang and Lei [20] found that the maximum hardness of Ni+Cr₃C₂ coating has arrived to 480 HV, and the corrosion resistance of Ni+50% Cr₃C₂ coating was about 50% higher than the substrate. Zhang and Zhang [21] also compared the mechanical properties of Ni-Cr₃C₂ and Ni-WC coatings. The hardness of the Ni-Cr₃C₂ coating is about 300 Hv lower than that of the Ni-WC coating, while the corrosion resistance of Ni-Cr₃C₂ coating is better than that of the Ni-WC coating.

The TiC reinforced metal matrix coating is studied mostly, because TiC presents high melting point, a high stability and hardness. Wilson and Shin [22] prepared the Inconel 690 coating enhanced by TiC particles by laser direct deposition. The hardness and wear resistance were improved with the TiC addition, the volume loss rate decreased 42% with the content of 40 vol.% TiC at the load of 2.269 kg. Jiang *et al.* [23] deposited 5 wt.% nanoscale TiC/Inconel 625 coating by laser assisted laser manufacturing. It found that the hardness and modulus of elasticity of the coating increased by 10.33% and 12.39%, respectively. Shen *et al.* [24] used TiC particles to enhance the Inconel 625 coating. The TEM images are shown in Figure 5, the coating was mainly composed of (Ni-Cr) solid solution matrix, TiC, and in-situ formed MC (M=Nb, Ti, Mo). Besides, a transition zone with a width of 3-5 μm existed between the γ matrix and the TiC particles. Xu *et al.* [25] used pure TiC particles to enhance Inconel 625 coatings to improve the surface properties of 316L stainless steel. The results showed that the distribution of TiC in the coating is very uniform. The hardness of the coating strengthened by TiC was 330 Hv (220 Hv without TiC), and the tensile strength was 824 MPa, which is much better than that of the coating without TiC addition. Besides, the corrosion resistance of the coating also increased with TiC addition. In addition, some researchers added Al₂O₃ [26], B₄C [27], SiO₂ [28] to Ni matrix powder to improve hardness, wear resistance and corrosion resistance of the coating.

3 In-situ synthesis of hard phase particles

The in-situ synthesis method is to add elements, then the elements react to form reinforced phase in the process of laser cladding, aiming to enhance the performance of the coating. This provides enough time to match the interface between the phase and the matrix metal, so the bonding strength and compatibility between the reinforced phase and matrix were significantly improved, and the interface was pure. Thus, the mechanical properties of materials

have also been correspondingly improved. In addition, the distribution characteristics of the reinforced phase can also be effectively controlled, such as size, morphology and distribution uniformity. Because of these advantages, in situ synthesis is widely used in laser cladding. The carbides and boride reinforcing phases in the coating are mostly prepared by this method [29].

Du *et al.* [30] used (Nb+C)/Ni60 powder to prepare NbC particle reinforced Ni60 alloy composite coating by laser cladding on the surface of 45 steel. There were no cracks, pores and other defects in the coating. The main phases in the coatings consist of γ -Ni, M₂₃C₆, NbC and CrB. NbC was generated by in-situ reaction during laser cladding. The morphology of NbC mainly consisted of fine granular, irregular block and petal-shaped. The microhardness of the Ni60 alloy coating reinforced by NbC particles reached 1000 Hv_{0.2}, which is about 38% higher than that of pure Ni60 coating. Niu *et al.* [31] used (Ni60+Nb₂O₅+C) mixed powder as the cladding material. The Ni-based composite coatings reinforced by NbC were prepared on the surface of A3 steel. The main phases of the Ni60/NbC coating include: γ -(Ni,Fe), carbides and NbC particles. The average hardness of the Ni60/NbC coating reached about 1200 HV, and the wear resistance is 1.5 times higher than that of the Ni60 coating at the load of 300 N.

Cao *et al.* [32] studied the mechanism of the influence of the morphology of NbC with different Nb addition. The results showed that the morphology of NbC changed from granular to petaloid with the increase of Nb addition. The alloy powder will melt under the action of laser radiation. At higher temperatures, Nb and C combine to form NbC particles. As the temperature decreases, the molten pool begins to solidify, and a large number of NbC particles are engulfed by the liquid-solid interface. Due to the low diffusion rate of Nb and C atoms in the solid phase, the growth rate of NbC in the subsequent cooling process is significantly reduced, resulting in a smaller size (hundreds of nanometers), so most of NbC in the coating is granular. NbC particles not engulfed by the interface remain in the liquid phase and grow rapidly until the end of solidification. Due to the longer growth period of these NbC particles, the particles reached a larger size and eventually distributed in the matrix as petals (5 μm) or polyhedrons (2 μm).

Figure 6 shows the formation sketches of two typical NbC petals. NbC has a face-centered cubic structure. Due to the lower interfacial energy of the {100} crystal plane family, the growth rate of NbC in the <100> crystal direction is larger. Therefore, NbC particles can more easily obtain an octahedral structure, as shown in Figure 6a and 6b. The cooling rate of octahedral corners is large, and the

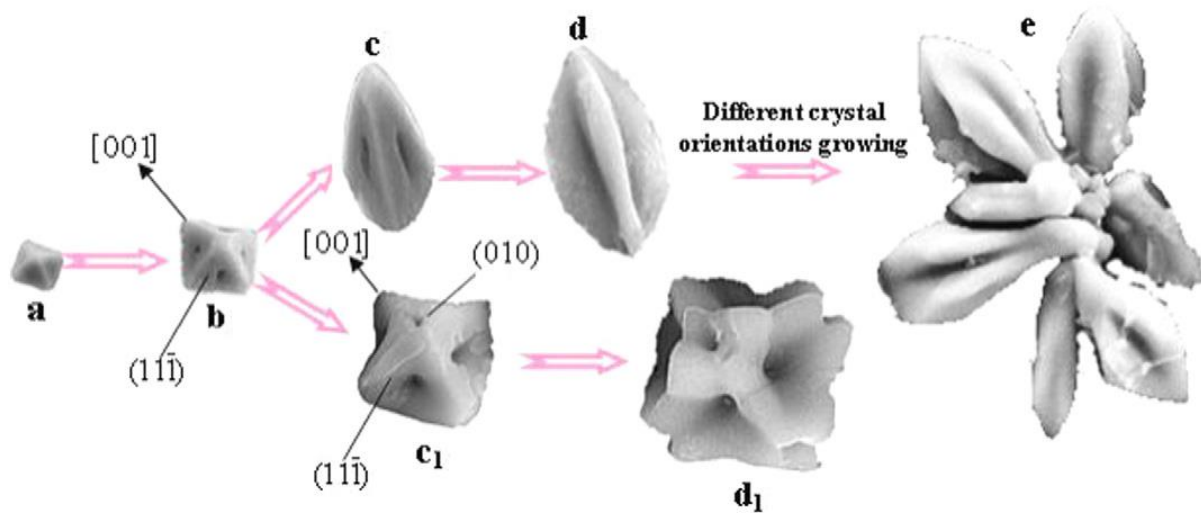


Figure 6: The mechanism of NbC growth [32]

growth rate of NbC in these regions is greater than the growth rate of the surface. As a result, pits appeared in the center of the surface. As NbC grows further in the $\langle 100 \rangle$ crystal direction, these pits are “stretched” (Figure 6c), which makes the cross-section of a single petal form a cross shape, as shown in Figure 6d. If NbC is grown in different crystal directions, the final morphology will be similar to that shown in Figure 6e. For several NbC grains, the growth rate at the corners of the octahedron is large, so that the $\{010\}$ crystal plane is perpendicular to the $\langle 100 \rangle$ direction of the crystal. Also, as shown in Figure 6c₁, the slower growth rate of NbC on these planes causes pits to appear in the center of the planes.

Wu [33] used pure Ti and pure graphite to in-situ synthesize TiC to enhance the Ni-based coating. The average microhardness of the coating reached 1250 Hv_{0.2} and the wear resistance has also been greatly improved at the load of 0.91 kg. Chao [34] used Ta₂O₅ and graphite to synthesize TaC particles in composite coatings to improve the surface properties of the coating. In addition, some researchers produced in-situ TiB [35], VC [36], TiB₂ [37] and TiN [38] particles to improve the performance of coating.

4 Adding a single element to improve the performance of coating

Nb can refine the grains of coatings significantly, and can also reduce the defects such as holes and cracks. The NbC particles can be generated by in-situ reaction with the

carbon atoms in the molten pool in the process of laser cladding. NbC presents a high melting point (3600°C), high free energy of formation (140.7 kJ/mol), high chemical stability, high stability and hardness. NbC possess a similar density (7.79 g/cm³ [39]) as that of Ni-based coatings, which is beneficial to the distribution uniformity of carbide particles in coatings. Wu *et al.* [40] produced Ni60A coatings with different Nb addition. Nb and C reacted to form NbC particles to refine the carbide particles and improve the wear resistance of the coatings. When the addition of Nb was 6 wt.%, the NbC phase was found in the coating. Compared with Nb-free coatings, the average hardness decreased by about 300 Hv_{0.2}, while the wear resistance increased by nearly 4 times. Cheng *et al.* [41] prepared Ni-Nb composite alloy coatings by laser cladding on 42CrMo substrate by adding Nb elements with different mass fractions in Ni-based coatings. When the amount of niobium added is 10 wt.%, The microstructure of the coating is significantly refined and denser, and the hardness of the coating reaches the highest, which is twice that of the nickel-based alloy coating without niobium.

Hu *et al.* [42] investigated the effect of Ti addition on crack and hardness of Inconel 625 coating. With the addition of Ti, the tendency to cracks becomes smaller. The addition of Ti promoted the formation of the (γ + Laves) eutectic phase, and caused the Laves phase to change from a point or short rod morphology to a layered and reticulated shape. When the amount of Ti added is 5 wt.%, The microhardness of the coating is increased by 100 Hv compared with that without Ti. Ma [43] added different mass fraction of Ti to the Ni60/WC composite coating to explore the effect of Ti on the microstructure and mechan-

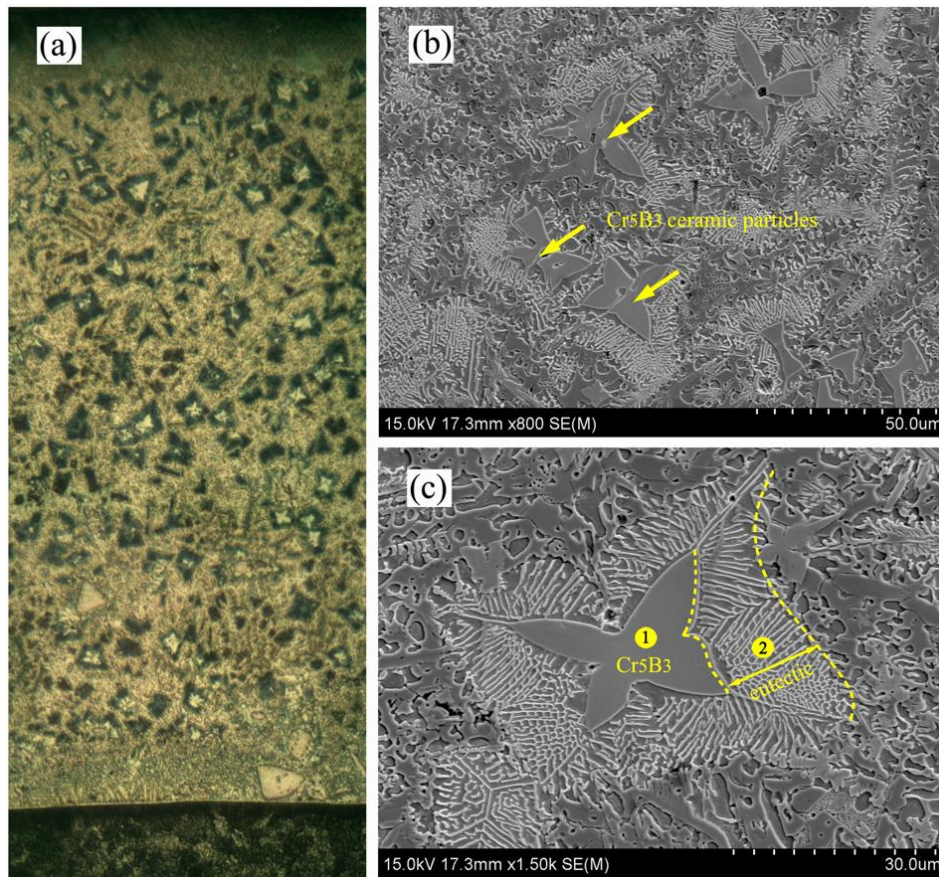


Figure 7: Microstructure of in-situ synthesized ceramic particles in Ni60-20WC coating (a): cross-section; (b): magnified SEM; (c): high magnification microstructure [43]

ical properties of the Ni60/WC coating, and analyzed the hard phase particles synthesized in situ. The microstructure of Ni60-20WC composite coating and Ni60-20WC-2Ti coating is shown in Figure 7 and 8. The results showed that the main ceramic particles in the Ni60/WC composite coating were Cr_5B_3 and M_{23}C_6 (M is Cr and W). After Ti addition, a large number of netted TiC appeared in the coating. Besides, the distribution of bulk Cr_5B_3 particles became more homogeneous, and the morphology changed from star shape to uniform square shape. Figure 9 shows the hardness distribution map of Ni60-20WC coating and Ni60-20WC-2Ti coating. It is found that the hardness distribution of coatings was more uniform with Ti addition, and the wear resistance increased by 2.6 times at the load of 100 N.

Yang *et al.* [44] prepared Al+ (Ti+B4C) composite coatings on the surface of AZ91D magnesium alloy, and the effects of Al on the microstructure and mechanical properties of the coatings were studied. In the process of laser cladding, Al_3Mg_2 , $\text{Al}_{12}\text{Mg}_{17}$, Al_3Ti and TiC particles were

produced by in-situ synthesis. The schematic diagram of compounds is shown in Figure 10. The hardness of the coating reached 348 Hv, which is about 5-6 times higher than that of AZ91D. After adding Al, the friction coefficient of the coating decreased, while the wear resistance and corrosion resistance of the coating increased.

Ta is a strong carbide forming element, which is easily reacted with C to form tantalum carbide (TaC). TaC has high hardness, high melting point (about 3880°C) and high chemical stability, and has excellent chemical resistance, thermal shock resistance and corrosion resistance [45]. Yu *et al.* [46] added Ta element to NiCrBSi powder, and used in-situ TaC particles to improve the mechanical properties of NiCrBSi coating. The results showed that the formation of TaC particles inhibits the formation of M_7C_3 and M_{23}C_6 , the amount of coarse carbide (M_7C_3 and M_{23}C_6) decreased, and the grain size is reduced. When the addition of Ta is 5 wt.%, the microhardness of the coating increased by 18%, and the wear resistance also improved. In addi-

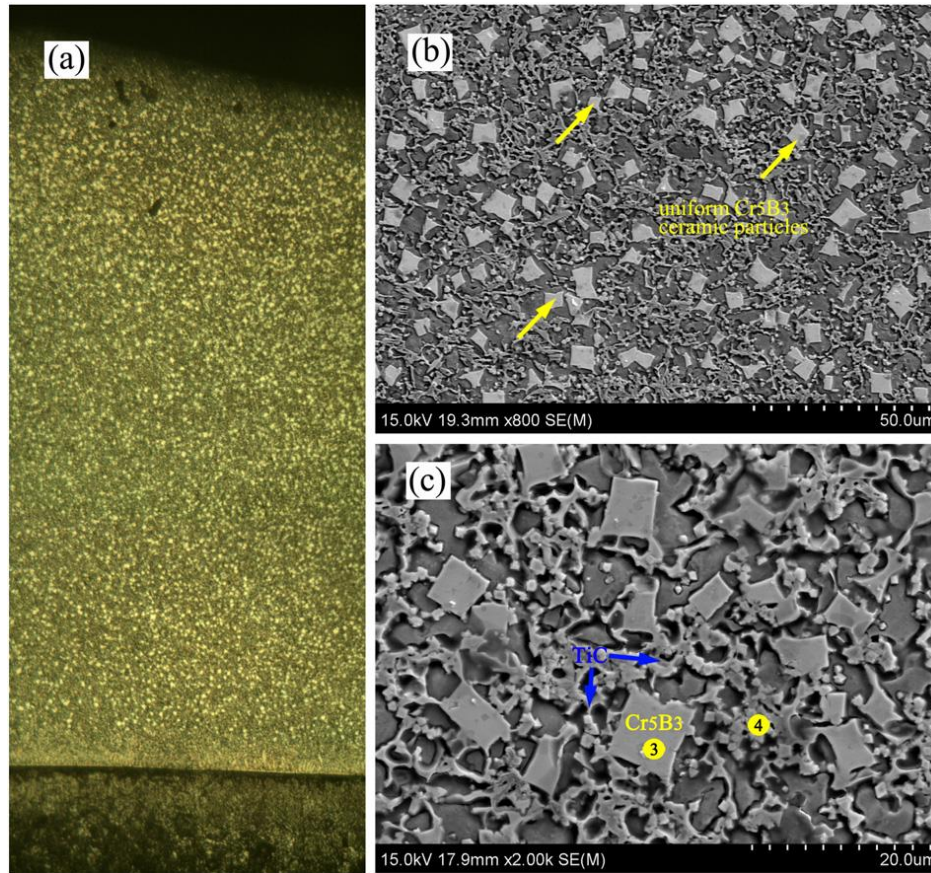


Figure 8: Microstructure of in-situ synthesized ceramic particles in Ni60-20WC-2Ti coating (a): cross-section; (b): magnified SEM; (c): high magnification microstructure [43]

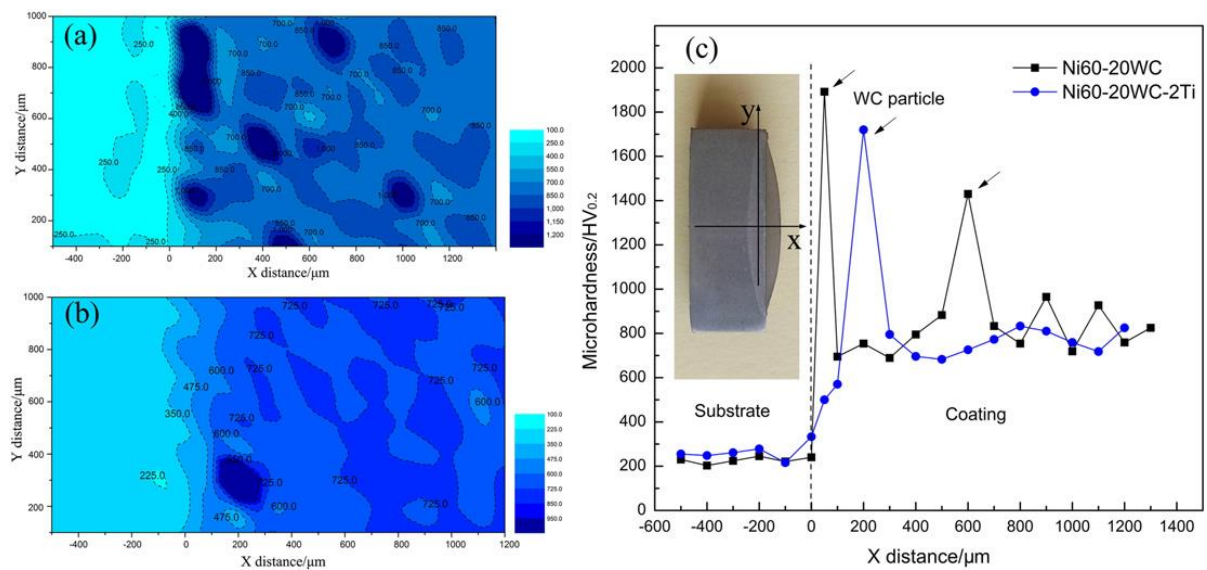


Figure 9: Microhardness test results (a): map distribution in Ni60-20WC coating; (b): map distribution in Ni60-20WC-Ti coating; (c): line profiles of two coatings [43]

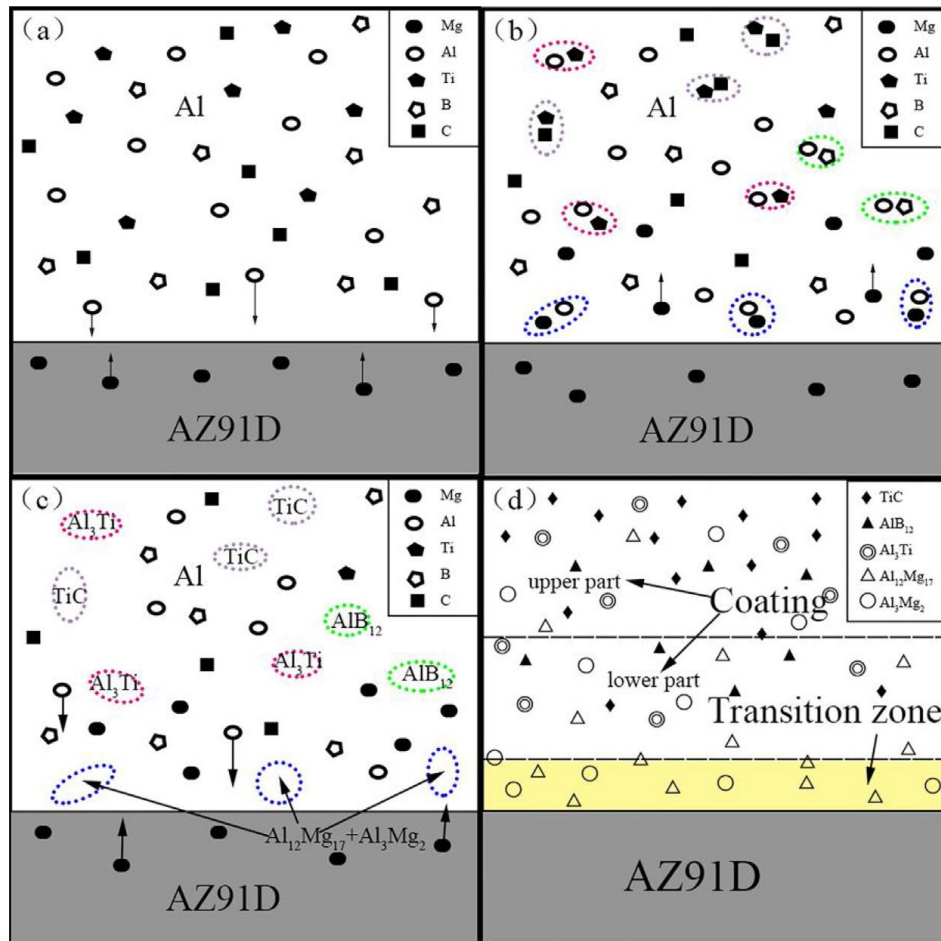


Figure 10: Schematic diagram of compounds [44]

tion, the addition of Ta reduced the crack sensitivity of Ni based composite coatings.

5 Adding rare earth elements

Rare earth elements are a general term for a class of elements and belong to the third group of elements. There are 17 kinds of lanthanide elements, such as lanthanum (La), cerium (Ce), and chemical elements similar to lanthanide. In the electron layer of the rare earth atom, the 4f electron layer is not filled by electrons. This results in a very active chemical property. The role of rare earth in metallurgy mainly includes: purifying the tissue, reducing the defect rate of the coatings, refining the microstructure, promoting the precipitation of the second phase, and forming the reinforced hard phase.

Zhao *et al.* [47] prepared Ni-based coatings with La_2O_3 addition on the surface of 30CrMnSiNi2A steel. It is found

that La tends to be distributed in dendrites, which limits the secondary growth of dendrites. The microstructure of the coating is more compact, and cracks and holes are not found in the coatings. The hardness of the coating reached 4 times that of the matrix. The friction coefficient was obviously lower than that of the matrix steel, and the wear resistance was nearly 9 times higher than matrix. Wang *et al.* [48] used laser cladding technology to prepare Ni60 alloy coating with La_2O_3 , Y_2O_3 and CeO_2 addition on 6063Al surface. The effects of rare earth elements on the microstructure and mechanical properties of Ni based coatings were studied. It has been found that the addition of rare earth elements results in the formation of stable rare earth compounds in the coating. The coatings with Y_2O_3 addition appeared Al_4La . The coatings with Y_2O_3 addition appear YAl_3 , AlNiY and Ni_{17}Y_2 . CeNi_5 and $\text{Ce}_3\text{Ni}_6\text{Si}_2$ appear in the coatings with CeO_2 addition. After adding rare earth, the microstructure of the coating was more compact and the hardness increased from 200

Hv to 350 Hv. The wear resistance was significantly improved at the load of 5N with the addition of La_2O_3 and CeO_2 .

6 Conclusion

The paper reviewed the research progress of improving the microstructure and mechanical properties of Ni-based composite coatings. The hardness, wear resistance and corrosion resistance of coatings can be effectively improved by many ways, such as in-situ synthesis of hard phase particles, adding hard particles directly, single element or rare earth elements, but there are still many problems that still need to be further studied.

- 1) The direct addition of hard particles can significantly improve mechanical properties of Ni-based coatings. WC, Cr_3C_2 and TiC can effectively improve the hardness and wear resistance of coatings, the corrosion resistance of Ni- Cr_3C_2 coatings is better than that of Ni-WC coatings. However, some researchers found that the particles sometimes are distributed non-uniformly, such as sank or floated in the coatings.
- 2) The size, morphology and distribution of in-situ NbC, TiC, TaC, TiB, VC, TiB_2 and TiN particles can be improved, resulted in the increase of hardness and wear resistance. In situ NbC consisted of fine granular, irregular block and petal-shaped, and the $\langle 100 \rangle$ crystal direction showed a higher growth rate. The wear resistance of Ni60/NbC coatings improved 1.5 times than that of Ni60 coatings.
- 3) The addition of Nb, Ti, Al, Ta elements has effect of refining grain and microstructure, hard particles can be in-situ synthesized by the single element and C element in the molten pool, which improved the wear resistance of coatings. However, the improvement results of single element on hardness were inconsistent, some researchers found the hardness of coatings decreased with the addition of Nb or Ti elements.
- 4) Rare earth La_2O_3 , Y_2O_3 and CeO_2 have the effect of reducing the defect rate, refining the microstructure, promoting the precipitation of the second phase and hard particles. La_2O_3 and CeO_2 are more effective to improve the hardness and wear resistance of coatings.
- 5) Laser cladding is a process of non-equilibrium crystallization. The thermodynamics, phase transition kinetics, interfacial behavior and diffusion behavior

involved in heating and solidification are needed to be explored. In addition, the relevant standards of laser cladding are not yet perfect, and this technology has not been widely applied in industrial production.

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References

- [1] Sharma, S. P., D. K. Dwivedi, and P. K. Jain. Effect of La_2O_3 addition on the microstructure, hardness and abrasive wear behavior of flame sprayed Ni based coatings. *Wear*, Vol. 267, No. 5-8, 2009, pp. 853–859.
- [2] Chaliampalias, D., G. Vourlias, E. Pavlidou, S. Skolianos, K. Christafis, and G. Stergioudis. Comparative examination of the microstructure and high temperature oxidation performance of NiCrBSi flame sprayed and pack cementation coatings. *Applied Surface Science*, Vol. 255, No. 6, 2009, pp. 3605–3612.
- [3] Zhang, J., Y. Hu, X. J. Tan, L. Guo, and Q. M. Zhang. Microstructure and high temperature tribological behavior of laser cladding Ni60A alloys coatings on 45 steel substrate. *Transactions of Non-ferrous Metals Society of China*, Vol. 25, No. 5, 2015, pp. 1525–1532.
- [4] Wang, P. Z., J. X. Qu, and H. S. Shao. Cemented carbide reinforced nickel-based alloy coating by laser cladding and the wear characteristics. *Materials & Design*, Vol. 17, No. 5-6, 1996, pp. 289–296.
- [5] Bansal, A., S. Zafar, and A. K. Sharma. Microstructure and abrasive wear performance of Ni-WC Composite Microwave Clad. *Journal of Materials Engineering and Performance*, Vol. 24, No. 10, 2015, pp. 1–9.
- [6] Wang, S. L., Z. Y. Zhang, Y. B. Gong, and G. M. Nie. Microstructures and corrosion resistance of Fe-based amorphous/nanocrystalline coating fabricated by laser cladding. *Journal of Alloys and Compounds*, Vol. 728, 2017, pp. 1116–1123.
- [7] Quazi, M. M., M. A. Fazal, A. S. M. A. Haseeb, F. Yusof, H. H. Masjuki, and A. Arslan, Effect of rare earth elements and their oxides on tribo-mechanical performance of laser claddings: A review. *Journal of Rare Earths*, Vol. 34, No. 6, 2016, pp. 550–564.
- [8] Paul, C. P., S. K. Mishra, P. Tiwari, and L. M. Kukreja. Solid-Particle Erosion Behaviour of WC/Ni Composite Clad layers with Different Contents of WC Particles. *Optics & Laser Technology*, Vol. 50, 2013, pp. 155–162.
- [9] Ortiz, A., A. García, M. Cadenas, M. R. Fernández, and J. M. Cueto. WC particles distribution model in the cross-section of laser clad NiCrBSi+WC coatings, for different wt% WC. *Surface and Coatings Technology*, Vol. 324, 2017, pp. 298–306.
- [10] Ma, Q. S., Y. J. Li, J. Wang, and K. Liu. Investigation on cored-eutectic structure in Ni60/WC composite coatings fabricated by wide-band laser cladding. *Journal of Alloys and Compounds*, Vol. 645, 2015, pp. 151–157.

- [11] Tobar, M. J., C. Álvarez, J. M. Amado, G. Rodríguez, and A. Yáñez. Morphology and characterization of laser clad composite NiCrBSi-WC coatings on stainless steel. *Surface and Coatings Technology*, Vol. 200, No. 22-23, 2006, pp. 6313–6317.
- [12] Guo, C., J. M. Chen, J. S. Zhou, J. R. Zhao, L. Q. Wang, Y. J. Yu, et al. Effects of WC-Ni content on microstructure and wear resistance of laser cladding Ni based alloys coating. *Surface and Coatings Technology*, Vol. 206, No. 8-9, 2012, pp. 2064–2071.
- [13] Zhou, S. F., J. B. Lei, X. Q. Dai, J. B. Guo, Z. J. Gu, and H. B. Pan. A comparative study of the structure and wear resistance of NiCrBSi/50 wt.% WC composite coatings by laser cladding and laser induction hybrid cladding. *International Journal of Refractory Metals and Hard Materials*, Vol. 60, 2016, pp. 17–27.
- [14] Li, F.Q., X. Y. Feng, Y. B. Chen. Effect of WC content on microstructure of WC/Ni60A laser cladding layer. *Chin. J. Las.*, Vol. 43, No. 1, 2016, pp. 0403009-1-0403009-7.
- [15] Zang, C. C., T. Z. Wang, Y. D. Zhang, J. H. Li, H. Zeng, and D. Q. Zhang. Microstructure and Tribological Properties of laser cladding Ni60 + 35WC-Ni coating. *Rare Metals*, Vol. 39, No. 5, 2019, pp. 385–391.
- [16] Matthews, S., B. James, and M. Hyland. High temperature erosion-oxidation of Cr_3C_2 -NiCr thermal spray coatings under simulated turbine conditions. *Surface and Coatings Technology*, Vol. 70, 2013, pp. 203–211.
- [17] Lou, D. Y., C. L. He, S. Shang, C. Liu, and Q. Cai. Microstructure and performances of graphite scattered Cr_3C_2 -NiCr composites prepared by laser processing. *Materials Letters*, Vol. 93, 2013, pp. 304–307.
- [18] Yu, J., L. Zhu, L. M. Luo, and J. Li. Antifriction properties of laser cladding Cr_3C_2 -Ni composite coating. *Hot Working Technology*, Vol. 39, No. 6, 2010, pp. 86–88.
- [19] Da, W. Z., T. C. Lei, and F. J. Li. Laser cladding of stainless steel with Ni- Cr_3C_2 for improved wear performance. *Wear*, Vol. 251, No. 1-12, 2001, pp. 1372–1376.
- [20] Zhang, D. W., and T. C. Lei. The microstructure and erosive–corrosive wear performance of laser-clad Ni– Cr_3C_2 composite coating. *Wear*, Vol. 255, No. 1-6, 2003, pp. 129–133.
- [21] Zhang, D. W., and X. P. Zhang. Laser cladding of stainless steel with Ni- Cr_3C_2 and Ni-WC for improving erosive-corrosive wear performance. *Surface and Coatings Technology*, Vol. 190, No. 2, 2005, pp. 212–217.
- [22] Wilson, J. M., and Y. C. Shin. Microstructure and wear properties of laser-deposited functionally graded Inconel 690 reinforced with TiC. *Surface and Coatings Technology*, Vol. 207, No. 9, 2017, pp. 517–522.
- [23] Jiang, D., C. Hong, M. Zhong, M. Alkhayat, A. Weisheit, A. Gasser, et al. Fabrication of nano-TiCp reinforced Inconel 625 composite coatings by partial dissolution of micro-TiCp through laser cladding energy input control. *Surface and Coatings Technology*, Vol. 249, No. 7, 2014, pp. 125–131.
- [24] Shen, M. Y., X. J. Tian, D. Liu, H. B. Tang, and X. Cheng. Microstructure and fracture behavior of TiC particles reinforced Inconel 625 composites prepared by laser additive manufacturing. *Journal of Alloys and Compounds*, Vol. 734, 2018, pp. 188–195.
- [25] Xu, X., G. Y. Mi, L. D. Xiong, P. Jiang, X. Y. Shao, and C. Wang. Morphologies, microstructures and properties of TiC particle reinforced Inconel 625 coatings obtained by laser cladding with wire. *Journal of Alloys and Compounds*, Vol. 740, 2018, pp. 16–27.
- [26] Ikeno, S., K. Furuta, and K. J. Matsuda. Effect of alumina particle size on aging in Al₂O₃/Al-Cu-Mg composite materials. *J. JPN. I. MET*, Vol. 45, No. 5, 1995, pp. 249–252.
- [27] Meng, Q. W., L. Geng, and B. Y. Zhang. Laser cladding of Ni-base composite coatings onto Ti-6Al-4V substrates with pre-placed $\text{B}_4\text{C}+\text{NiCrBSi}$ powders. *Surface and Coatings Technology*, Vol. 200, No. 16-17, 2006, pp. 4923–4928.
- [28] Rajab, F. H., Z. Liu, and L. Li. Production of stable superhydrophilic surfaces on 316L steel by simultaneous laser texturing and SiO_2 deposition. *Applied Surface Science*, Vol. 427, 2018, pp. 1135–1145.
- [29] Lu, W. J., D. Zhang, X. N. Zhang, R. J. Wu, T. Sakata, and H. Mori. Microstructure and tensile properties of in situ (TiB+TiC)/Ti (Tib:TiC=1:1) composites prepared by common casting technique. *Materials Science and Engineering A*, Vol. 311, No. 1-2, 2001, pp. 142–150.
- [30] Du, J. N., G. Dong, Q. L. Deng, and J. H. Yao. Microstructure and properties of laser clad NbC/Ni60 alloy composite coating. *Applied Laser*, No. 4, 2012, pp. 277–281.
- [31] Niu, X., M. J. Chao, W. L. Wang, B. Yuan, and E. J. Liang. In situ synthesized NbC particulate reinforced Ni-based composite coatings by laser cladding. *Chinese Journal of Lasers*, Vol. 33, No. 7, 2006, pp. 987–992.
- [32] Cao, Y. B., S. X. Zhi, Q. Gao, X. T. Tian, T. Geng, X. Guan, et al. Formation behavior of in-situ NbC in Fe-based laser cladding coatings. *Materials Characterization*, Vol. 119, 2016, pp. 159–165.
- [33] Wu, X. L. In situ formation by laser cladding of a TiC composite coating with a gradient distribution. *Surface and Coatings Technology*, Vol. 115, No. 2-3, 1999, pp. 111–115.
- [34] Chao, M. J., W. L. Wang, E. J. Liang, and D. Ouyang. Microstructure and wear resistance of TaC reinforced Ni-based coating by laser cladding. *Surface and Coatings Technology*, Vol. 202, No. 10, 2008, pp. 1918–1922.
- [35] Moghaddam, E. G., N. Karimzadeh, N. Varahram, and P. Davami. Impact-abrasion wear characteristics of in-situ VC-reinforced austenitic steel matrix composite. *Materials Science and Engineering A*, Vol. 585, No. 22, 2013, pp. 422–429.
- [36] Zhao, G. L., C. Z. Huang, H. L. Liu, B. Zou, H. T. Zhu, and J. Wang. Preparation of in-situ growth TaC whiskers toughening Al_2O_3 ceramic matrix composite. *International Journal of Refractory Metals & Hard Materials*, Vol. 36, 2013, pp. 122–125.
- [37] Wang, Z. T., X. H. Zhou, and G. G. Zhao. Microstructure and formation mechanism of in-situ TiC-TiB₂/Fe composite coating. *T. Nonferr. Metal. Soc.*, Vol. 18, No. 4, 2008, pp. 831–835.
- [38] Li, M., J. Huang, Y. Y. Zhu, and Z. G. Li. Effect of heat input on the microstructure of in-situ synthesized TiN-TiB/Ti based composite coating by laser cladding. *Surface and Coatings Technology*, Vol. 206, No. 19-20, 2012, pp. 4021–4026.
- [39] Liu, K., Y. J. Li, J. Wang, and Q. S. Ma. Effect of high dilution on the in situ synthesis of Ni-Zr/Zr-Si(B, C) reinforced composite coating on zirconium alloy substrate by laser cladding. *Materials & Design*, Vol. 87, 2015, pp. 66–74.
- [40] Wu, W. T., Y. Zhang, and B. H. Song. Effect of niobium on Microstructure and wear resistance of Ni60 laser cladding layer. *Journal of Shijiazhuang Tiedao University*, Vol. 30, No. 2, 2017, pp. 105–110.
- [41] Cheng, Y., G. Dong, and G. X. Chen. Effect of niobium on microstructure and microhardness of laser clad nickel based alloy. *Materials for Mechanical Engineering*, Vol. 38, No. 9, 2014, pp. 24–28.

- [42] Hu, Y. L., X. Lin, X. B. Yu, J. J. Xu, M. Lei, and W. D. Huang. Effect of Ti addition on cracking and microhardness of Inconel 625 during the laser solid forming processing. *Journal of Alloys and Compounds*, Vol. 711, 2017, pp. 267–277.
- [43] Ma, Q. S., Y. J. Li, and J. Wang. Effects of Ti addition on microstructure homogenization and wear resistance of wide-band laser clad Ni60/WC composite coatings. *International Journal of Refractory Metals & Hard Materials*, Vol. 64, 2017, pp. 225–233.
- [44] Yang, L. Q., Z. Y. Li, Y. Q. Zhang, S. Z. Wei, and F. Q. Liu. Al-TiC in situ composite coating fabricated by low power pulsed laser cladding on AZ91D magnesium alloy. *Applied Surface Science*, Vol. 435, 2018, pp. 1187–1198.
- [45] Xiang, H., Y. Xu, L. Zhang, and L. Cheng. Synthesis and microstructure of tantalum carbide and carbon composite by liquid precursor route. *Scripta Materialia*, Vol. 55, No. 4, 2006, pp. 339–342.
- [46] Yu, T., Q. L. Deng, G. Dong, and J. G. Yang. Effects of Ta on microstructure and microhardness of Ni based laser clad coating. *Applied Surface Science*, Vol. 257, No. 11, 2011, pp. 5098–5103.
- [47] Zhao, N., L. Tao, H. Guo, and M. Q. Zhang. Microstructure and wear resistance of laser clad Ni-based coatings with nanometer La_2O_3 addition. *Rare Metal Materials and Engineering*, Vol. 46, No. 8, 2017, pp. 2092–2096.
- [48] Wang, C. L., Y. Gao, Z. C. Zeng, and Y. K. Fu. Effect of rare-earth on friction and wear properties of laser cladding Ni-based coatings on 6063Al. *Journal of Alloys and Compounds*, Vol. 727, 2017, pp. 278–285.