Laser cladding of Ni60 + 17-4PH composite for a cracking-free and corrosion resistive coating

Zhaohui Chen[1], Ruifeng Li[1,*], Jiayang Gu[2], Zhongyu Zhang[2], Yanwu Tao[2], Yingtao Tian[3]

1 School of Materials Science and Engineering, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, 212003, P. R. China

2. Marine Equipment and Technology Institute, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, 212003, P. R. China

3. Department of Engineering, Lancaster University, Bailrigg, Lancaster LA1 4YW, UK

Abstract: In order to obtain a laser-cladded coating with no cracking and good corrosion resistance, this paper investigated laser cladding of a mixture of 17-4PH stainless steel and Ni60 powders on ASTM 1045 steel substrate. The surface cracking, mechanical properties and corrosion resistance of the coatings were assessed by various characterisation methods. The experimental results demonstrated that a crack-free coating can be obtained by adding 30% (or above) 17-4PH stainless steel into Ni60 alloy. The mechanical properties of the coatings were compromised by adding 17-4PH but stabilised at about 79% of pure Ni60 alloy, which is acceptable considering the benefit of elimination of surface cracking. Decrease in the mechanical properties were caused by the dilution of the strengthening elements and reduction of population of hard phases. Composite coating having 30% of 17-4PH also exhibited the smallest corrosion current, lowest corrosion potential and slowest corrosion rate and therefore the best corrosion resistance.

Keywords: Laser cladding, Ni60, 17-4PH, Surface cracking, Micro-hardness, Corrosion resistance

1 Introduction

Laser cladding is a surface modification technique that uses laser beam to melt powder materials creating a strong metallurgical bond between the coating and substrate. Coatings with different characteristics can be obtained by using various types of powder offering significant improvement in terms of wear resistance, corrosion resistance, high temperature resistance, oxidation resistance and electrical properties etc. [1], [2]. Laser cladding has gradually become an important surface engineering technology and been widely used in surface modification, re-manufacturing and repairing in various industrial applications such as aerospace, oil and gas, power generation and metal processing which often require high performance of components in harsh environments. For example, steel parts coated with laser cladded nickel based alloy often have very high hardness, excellent wear and corrosion resistance, and also high toughness which can significantly prolong service life and reduce the cost of production, but these benefits are difficult to be achieved by optimising the metallurgy of steel in the traditional way [3], [4].

Ni60 is a Ni-Cr-Fe based alloy offering high hardness, excellent corrosion, wear and heat resistance, which is usually used in thermal spraying process. When it is applied to laser cladding process, the rapid heating and cooling cycle will induce rigorous metallurgical reaction and result in less-favorable microstructures. The γ-Ni supersaturated solid solution can be easily formed and precipitated during multi-pass laser cladding process. The crystal lattice distortion can induce high level of internal stress in the coating and lead to cracking or pre-matured failure during service [5], [6]. In theory, cracks can occur when the internal stress exceeds the yield strength or the local plasticity is insufficient to accommodate the induced plastic deformation, which is often observed in laser cladding of nickel chromium based alloys [7]. Moreover, the presence of large amount but non-uniformly distributed Cr-rich hard phases can also increase the susceptibility of cracking and lead to high brittleness [8]–[10]. To remedy the negative influence of hard phases on mechanical properties, Pi et al. [11] utilized a modified composition of the powder and manipulated the solidification process which successfully reduced the tensile residual stress and risk of cracking in laser cladded coatings. In another study, Leunda et al. [12] effectively refined the hard phases and the dendrites in the coating by adding In_2O_3 to Ni60 powder resulted in reduced tendency of cracking.

17-4PH is a precipitation hardening martensitic stainless steel that offers an outstanding combination of high tensile/impact strength and high fracture toughness. It is also able to withstand relatively high temperature up to around 300 °C without much degradation of overall mechanical properties. Type 17-4PH powder has been widely used for laser cladding and recently in additive manufacturing for nuclear engery, aerospace, marine and chemical processing applications [13]–[15]. Although 17-4PH offers good corrosion resistance in mild acids, it is still far from satisfactory in corrosive demanding environment comparing with Ni60 alloy.

This study attempts to obtain a high strength, high toughness, crack-free and highly corrosion resistive composite coating by combining the advantages of both Ni60 and 17-4PH alloys. In this paper, mixtures of pre-alloyed Ni60 and 17-4PH powders in various proportion will be used as feedstock for laser cladding on a ASTM 1045 steel substrate. The benefits of adding 17-4PH stainless steel into Ni60 powder will be investigated in terms of surface cracking, changes on microstructure, micro-hardness and corrosion resistance etc. The composite powders developed in this study will be promising to solve the cracking problems in conventional Ni60 laser cladding process.

2 Materials and Experiments

2.1 Materials

The substrate for laser cladding is an ASTM 1045 steel plate in the dimension of 100 mm × 100 mm × 10mm. The cladding materials are mixtures of 17-4PH stainless steel and Ni60 nickel-based alloy powders, with diameter ranging between 140-325 μm. The chemical compositions of the powders are shown in Table 1 and Table 2, respectively.

Table 1 Chemical compositions of 17-4PH stainless steel powder (wt. %)

Ni	C	Cr	Si	Mn	P	S	Cu	Nb	Fe
3~5	0.07	15~17.5	1.00	1.00	0.04	0.03	3~5	0.15~0.45	Bal

Table 2 Chemical compositions of Ni60 nickel based alloy powder (wt%)

C	Cr	Si	W	Fe	B	Ni
0.80	15.5	4.00	3.00	15.00	3.50	Bal

2.2 Experiments

Four types of powder mixture (Ni60 + 10% 17-4PH, Ni60 + 20% 17-4PH, Ni60 + 30% 17-4PH and Ni60 + 40% 17-4PH) were obtained by using a QM-3SP2 planetary ball mill. Before laser cladding, the powders was heated to 150 °C and kept for 30 minutes in a drying chamber to eliminate the moisture. After drying, the powders were put into a DPSF-2 type coaxial powder feeder for laser cladding experiments.

Laser cladding experiments were conducted by using an IPG high power fiber laser (YLS-6000) at 1600 W output power and a scanning speed of 4 mm/s with a laser spot size of 5 mm. The powder feeding rate was 4.44 g/min assisted by a feeding argon gas flow rate of 12 L/min. The overlap ratio was kept as 30% for all of the experiments. Once the laser cladding was completed, the surface cracks of the cladding layer were characterized by dye penetration tests. The microstructure was observed by using a Zeiss

Merlin Compact scanning electron microscope (SEM). The phase in the cladding layer was analyzed by a Shimadzu XRD-6000X X-ray diffraction (XRD) system and the micro-hardness was tested by a fully automated FM-ARS900 Vickers microhardness tester at 0.2 kg load. Finally, the corrosion resistance was tested by a Coster CS2350 electrochemical workstation.

3 Results and Discussion

3.1 Crack characterization

Figure 1 shows the macrographs of the laser cladded Ni60 coatings with different contents of 17-4PH stainless steel after dye penetration tests. Large surface cracks were observed in pure Ni60 or in the mixture coatings where the content of 17-4PH was 10% and 20%. With the increase in the proportion of 17-4PH in the mixtures, those long surface cracks disappeared and only small number of spots were visible after dye penetration, as illustrated in Figure 1(d) and (e).

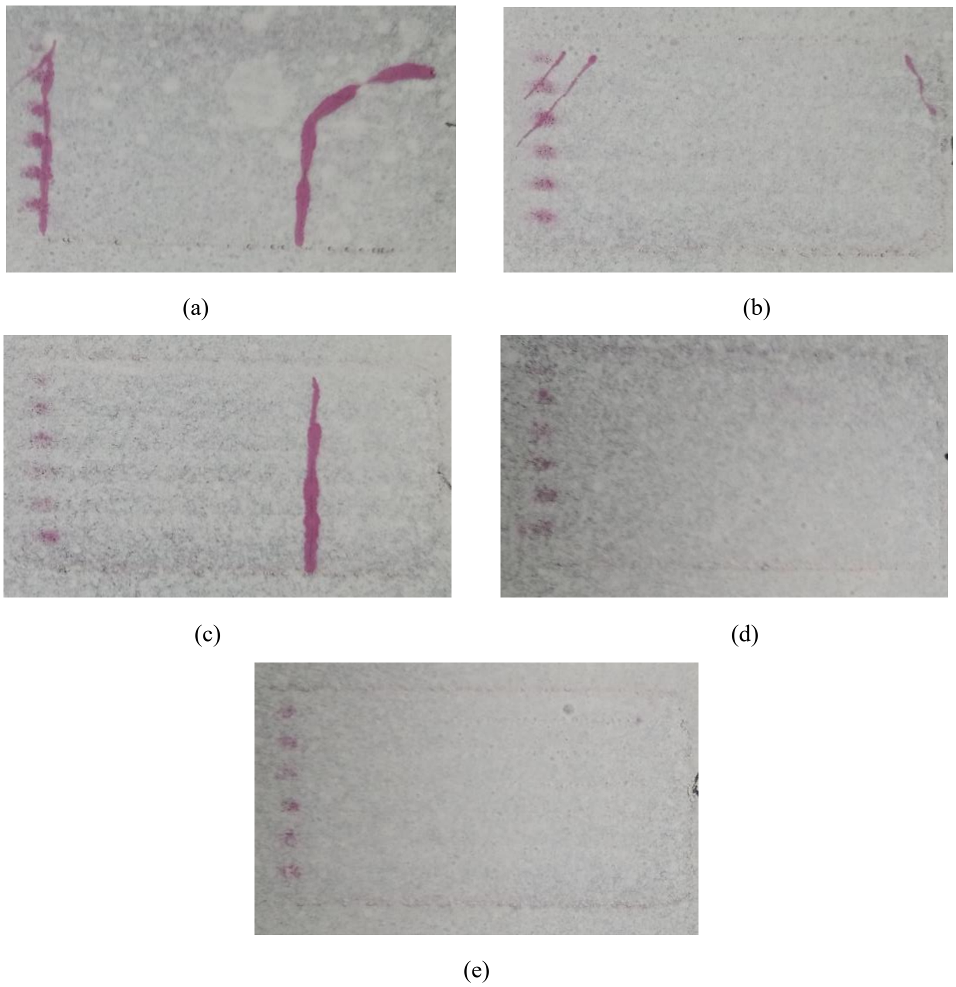


Figure 1 Ni60 contains different content of h7-4PH laser cladding coating coloring penetration test results (a)0%,(b)10%, (c)20%, (d)30% and (e)40%.

In order to quantitatively study the influences of different contents of 17-4PH on the length of surface cracks in the cladding coatings, the length of surface cracks were measured and illustrated in Figure 2. In the situation where no 17-4PH was added in, the total length of the surface crack was about 47.6 mm. As the 17-4PH powder was blended at a percentage of 10% and 20%, the surface crack length dropped to 23.4 mm and 18.5 mm, respectively. When the contents of 17-4PH increased to over 30%, the surface crack was hardly visible, so the crack length dropped to virtually zero. Therefore, the dye penetration tests proved that the addition of 30% or more 17-4PH in Ni60 powders can effectively inhibit the surface cracks formation during laser cladding. It should be noted that dye penetration has limited resolution and may only be able to reveal the surface cracks at macro-scale. For cracks in micrometer scale, one may need to use more precise measuring technique, such as high-resolution X-ray tomography.

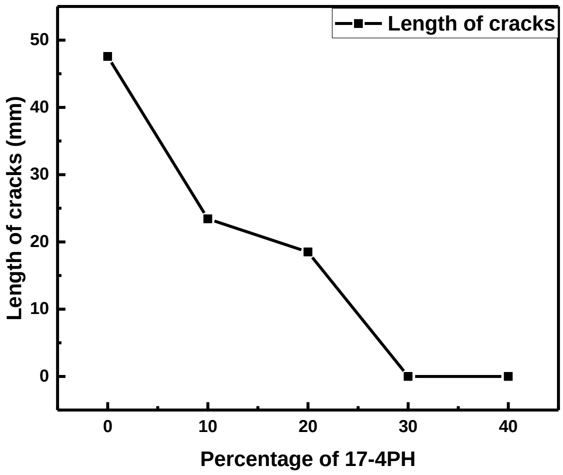
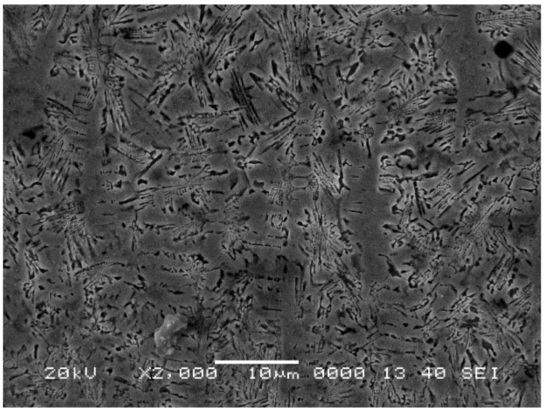


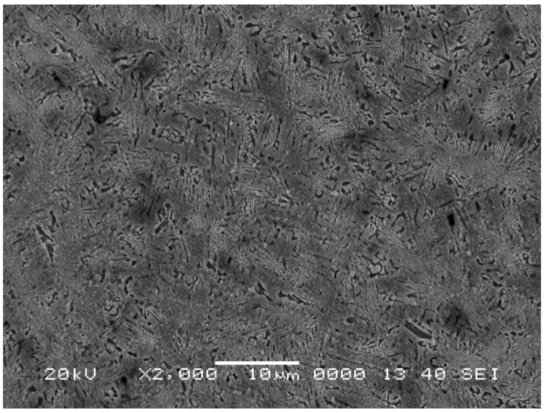
Figure 2 Total crack length of coatings with different 17-4PH content

3.2 Microstructure and phase analysis

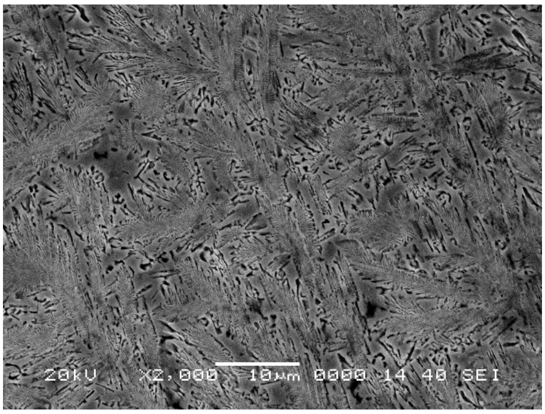
The microstructure of laser cladded coatings of various mixtures were observed by using SEM as shown in Figure 3. The microstructure of pure Ni60 coating has a typical hypoeutectic morphology, which is mainly composed of γ-Ni solid solution dendrites and Cr_7C_3, Ni_5Si_3 and Fe_2B particles among the dendrites [16]. During solidification, the hard phases Cr_7C_3 and Ni_5Si_3 nucleate between the dendrite arms and therefore hinder the coherence of the matrix. The liquid film between the dendrites and hard phases virtually has no ability to sustain any strain induced by the shrinkage resulting in micro-cracks and porosities. As shown in Figure 3(a), pure Ni60 alloy has a large number of micro-cracks within the eutectic phase that can act as a seed for further cracking. After adding 17-4PH in Ni60, the microstructure of the cladded coatings changed significantly. Due to the addition of 17-4PH powder, the content of C, Si and B elements was diluted which reduces the driving force for the diffusion-controlled formation of the abovementioned hard phases. During the laser cladding solidification process, the primary hard phase such as Cr_7C_3 is first precipitated from the melted alloy. When the tip of the γ-Ni dendrite reaches the hard particles, the growth is then interrupted so that the continuity of the matrix is deteriorated [17]. Therefore, with the increase of 17-4PH in the mixture, the reduced population of the hard particles lead to an improved coherence of the γ-Ni matrix which can potentially improve the toughness. As illustrated in Figure 3(b), (c) and (d), when the content of 17-4PH increased from 10% to 30%, the population of micro-cracks gradually reduced. Although no macro-scale surface crack was observed in the case of 30% 17-4PH, as shown in Figure 2, cracks in micrometer scale can still be spotted under high magnification of SEM (Figure 3(d)). When the content of 17-4PH increased to 40%, the population of the hard phases were significantly reduced and the γ-Ni solid solution and eutectic substrate became more coherent and almost crack-free, as shown in Figure 3(e).



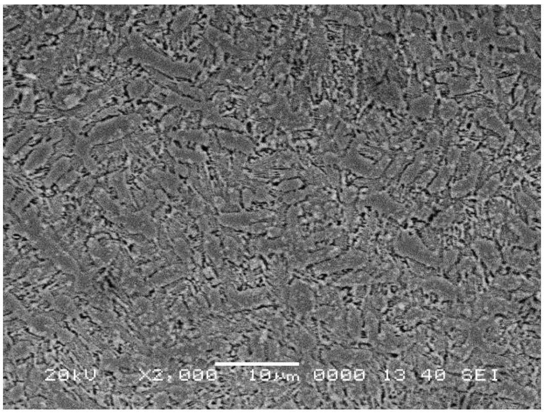
(a)



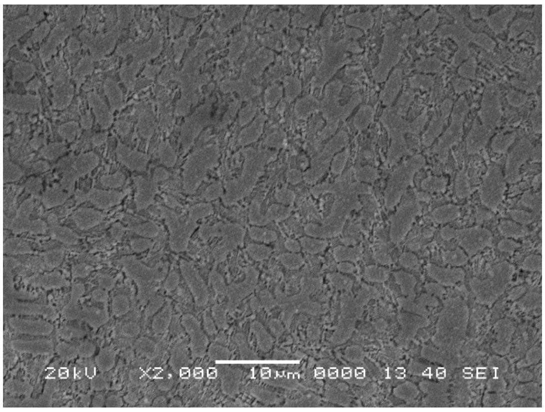
(b)



(c)



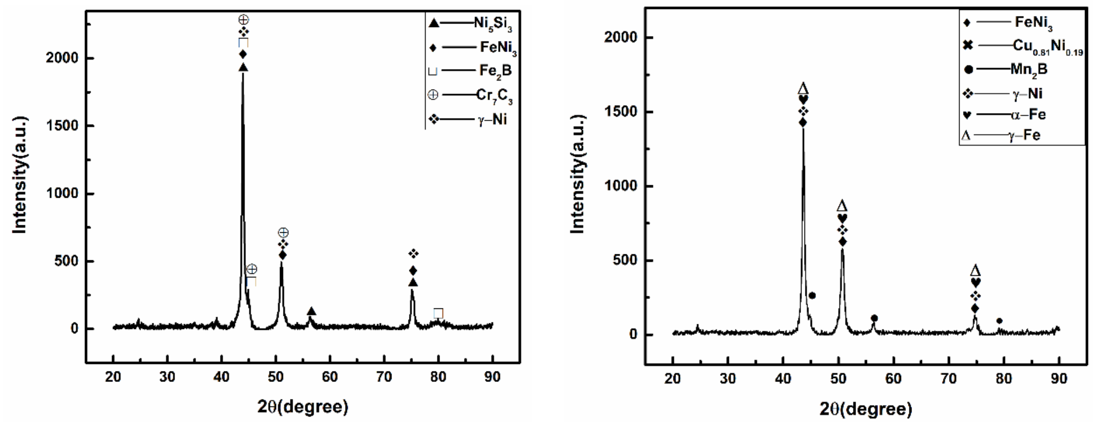
(d)



(e)

Figure 3 Microstructure of different 17-4PH cladding layer added to Ni60 (a)0%, (b) 10%, (c) 20%, (d) 30% ,(e) 40%

Figure 4 compares the X-ray diffraction patterns of pure Ni60 laser cladded coatings and with 30% of 17-4PH. As discussed above, solidification during laser cladding process is highly non-equilibrium and intrinsically lead to supersaturation in the matrix and lattice distortion. The XRD pattern shown in Figure 4(a) confirms that the pure Ni60 alloy coating mainly consists of γ-Ni solid solution and hard phases such as Cr_7C_3, Ni_5Si_3 and Fe_2B. With 30% of additional 17-4PH, these hard phases disappear, instead, the composite coating mainly consists of γ-Ni, α-Fe and γ-Fe, as shown in Figure 4(b). This is because the dilution of C, Si and B elements reduces the nucleation rate of the hard particles and part of the Cr-rich γ-Fe solid solution transforms into α-Fe and Fe-Cr compounds [18].



(a) (b)

Figure 4 X-ray diffraction pattern of different 17-4PH content cladding layer: (a) 0% and (b) 30%.

3.3 Microhardness measurement

Vickers's microhardness measurement on laser cladded coatings with different compositions were carried out by using a FM-ARS900 tester with 0.2 kg load lasting for 10 s. Figure 5 plots the microhardness on top surface/center/bottom of the coatings, heat affected zones and substrates. An averaged microhardness of 575 $HV_{0.2}$ was obtained in pure Ni60 coating and the microhardness distribution was almost identical when only 10% of 17-4PH powder was added. When 20% 17-4PH was blended in, the averaged microhardness of the cladded coating slightly decreased, i.e. to about 550 $HV_{0.2}$. Microhardness demonstrates a dramatic decrease with the addition of 30% and 40% 17-4PH, to only about 450 $HV_{0.2}$ which is approximate 21% less than pure Ni60. But, the difference between the microhardness of coatings having 30% and 40% of 17-4PH was trivial. The heat affected zone (HAZ) was actually part of the substrate before laser cladding, due to the rapid heating and cooling during laser cladding process, the HAZ region undergoes an equivalent heat treatment and therefore exhibits a microhardness higher than the original substrate. In all cases, the microhardness of HAZ was about 100 $HV_{0.2}$ higher than that of the substrate.

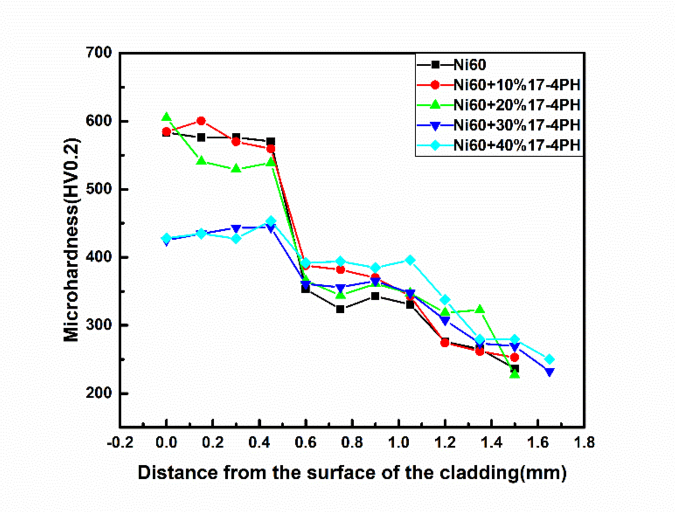


Figure 5 Hardness distribution of different 17-4PH content cladding layers

It is known that C, B and Si in the nickel based alloy can provide solid solution strengthening and also form hard compounds with Cr, Ni and Fe [19]. Because 17-4PH has relatively lower content of C and Si and does not contain B, mixing large proportion of 17-4PH with Ni60 results in dilution of these elements and therefore weakens both the strengthening effects. This explains why generally the microhardness of the cladding layer tends to decrease as more 17-4PH powders was added in Ni60. In addition, the hard phases not only reinforce the matrix, but can also hinder the movement of dislocations during deformation [20]. In general, when precipitation strengthening dominates, the strength of the material is proportional to amount of hard precipitates. This is why the microhardness decreases when the content of 17-4PH increases from 10% to 20%. When the content of 17-4PH exceeded 30%, as suggested by the XRD pattern, the hard phases disappeared and the effect of precipitation hardening is less significant than solid solution strengthening so that the microhardness remains at similar level and becomes less sensitive to the increase of volume fraction of 17-4PH.

3.4 Corrosion resistance tests

The corrosion resistance of the composite coatings were evaluated by running a number of polarization curves in 3.5%NaCl solution. Figure 6 plots the polarization curves of laser cladded composites containing 20%, 30% and 40% of 17-4PH, respectively, which were obtained by sweeping the potential from -1.5 V to +0.75 V. When the potential increases, a dynamic passivation layer is formed until a so-called breakdown potential (E_b) is reached. Then, the passivation film begins to dissolve and a surge of current can be observed. It is inaccurate to assess the corrosion resistance on the basis of the breakdown potential because it can be affected by the self-corrosion potential. The corrosion current plays a more significant role and generally a smaller value is preferred [21].

The polarisation curves can be interpreted by using the C-View software and the corresponding corrosion current, breakdown potential and corrosion rate can be thereafter obtained, as listed in Table 3. It can been seen that the corrosion current I_{corr} is the smallest when the content of 17-4PH is 30% and the corrosion potential E_{corr} also moves closer to the neutral position. A corrosion rate of 0.33594 (mm/a) was also the smallest among the assessed three situations. The reason for a higher corrosion rate occurring in 40% of 17-4PH composite is probably due to the insufficient γ-Ni solid solution and the increased fraction of α-Fe [22]. In summary, laser cladded composite coating consisting of 30% 17-4PH exhibits the best corrosion resistance.

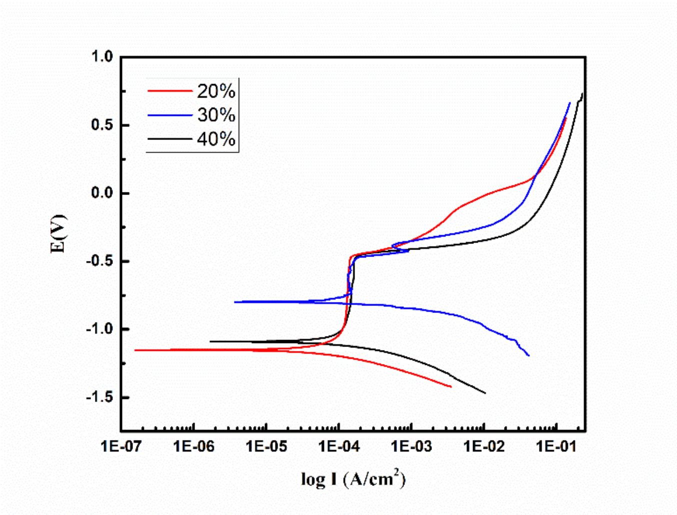


Figure 6 Electrochemical corrosion polarization curves of different 17-4PH content cladding layers

Table 3 Polarization curve parameters of different 17-4PH content cladding layers

Addition amount of 17-4PH	I_{corr} (A/cm^2)	E_{corr} (V)	Corrosion rate (mm/a)
20%	4.14E-05	-1.1529	0.97491
30%	1.43E-05	-0.7849	0.33594
40%	2.23E-05	-1.0806	0.52527

4 Conclusion

In this study, laser cladding of composite coatings by blending 17-4PH stainless steel into Ni60 powders were investigated and the following conclusions can be drawn based on the experimental results:

1. Adding 17-4PH stainless steel into Ni60 powder can effectively inhibit the formation of the coarse and brittle hard phase in the coating and suppress the surface cracks formation. A crack-free coating can be obtained when the content of 17-4PH reaches 30% or above.
2. The mechanical strength of the composite coatings decreases about 21% of pure Ni60 while the content of 17-4PH increase to over 30%. The drop in the mechanical strength is justified by the elimination of surface cracking.
3. Composite coating consisting of 30% 17-4PH exhibits the smallest corrosion current, the lowest corrosion potential and corrosion rate and therefore the best corrosion resistance.

Acknowledgement

The authors would like to acknowledge the financial support provided by the National Key Research and Development Program of China (No.2018YFC0310400), the National Natural Science Foundation of China (Grant Nos. 51775254 & 51405206) and the China Postdoctoral Science Foundation (Grant No. 2017M611750).

Reference

[1] M. Yue, D. Zhuping, Y. Zhixing, and W. Chengkang, “Application of laser cladding technology to improve the interface of thermal barrier coatings,” 2000.

[2] F. Weng, C. Chen, and H. Yu, “Research status of laser cladding on titanium and its alloys: A review,” *Mater. Des.*, vol. 58, pp. 412–425, Jun. 2014.

[3] X. Luo, J. Li, and G. J. Li, “Effect of NiCrBSi content on microstructural evolution, cracking susceptibility and wear behaviors of laser cladding WC/Ni–NiCrBSi composite coatings,” *J. Alloys Compd.*, vol. 626, pp. 102–111, Mar. 2015.

[4] F. Fu, Y. Zhang, G. Chang, and J. Dai, “Analysis on the physical mechanism of laser cladding crack and its influence factors,” *Optik (Stuttg).*, vol. 127, no. 1, pp. 200–202, Jan. 2016.

[5] J. ZHANG, Y. HU, X. TAN, L. GUO, and Q. ZHANG, “Microstructure and high temperature tribological behavior of laser cladding Ni60A alloys coatings on 45 steel substrate,” *Trans. Nonferrous Met. Soc. China*, vol. 25, no. 5, pp. 1525–1532, May 2015.

[6] A. N. Grezev and A. N. Safonov, “Cracking and microstructure of laser-deposited chromium-boron-nickel alloys,” *Weld. Int.*, vol. 1, no. 1, pp. 50–52, Jan. 1987.

[7] T. Yu, Q.-L. Deng, W. Zhang, G. Dong, and J.-G. Yang, “Study on cracking mechanism of laser clad NiCrBSi coating,” *J. Shanghai Jiaotong Univ.*, vol. 46, pp. 1043–1048, 2012.

[8] T. Yu, Q. Deng, G. Dong, and J. Yang, “Effects of Ta on microstructure and microhardness of Ni based laser clad coating,” *Appl. Surf. Sci.*, vol. 257, no. 11, pp. 5098–5103, Mar. 2011.

[9] C. Chen and T. Lei, “Problems and the improving measures in laser remelting of sprayed ceramic coatings,” *Mater. Sci. Technol.*, vol. 10, no. 4, pp. 431–435, 2002.

[10] J. Wang, H. Zou, C. Li, S. Qiu, and B. Shen, “The effect of microstructural evolution on hardening behavior of type 17-4PH stainless steel in long-term aging at 350 °C,” *Mater. Charact.*, vol. 57, no. 4–5, pp. 274–280, Dec. 2006.

[11] Z. Pi, C. Qiu, and X. Fan, “Study of Crack Control for CoNiCrWC Composite Coating by Laser Cladding,” *RARE Met. Mater. Eng.*, vol. 40, pp. 283–285, 2011.

[12] J. Leunda, C. Sanz, and C. Soriano, “Laser cladding strategies for producing WC reinforced NiCr coatings inside twin barrels,” *Surf. Coatings Technol.*, vol. 307, pp. 720–727, Dec. 2016.

[13] R. Rashid, S. H. Masood, D. Ruan, S. Palanisamy, R. A. Rahman Rashid, and M. Brandt, “Effect of scan strategy on density and metallurgical properties of 17-4PH parts printed by Selective Laser Melting (SLM),” *J. Mater. Process. Technol.*, vol. 249, pp. 502–511, Nov. 2017.

[14] Z. Liu, X. Liu, and L. Li, “Erosion damage of last stage long blade of large steam turbine in China in recent years,” *Power Eng.*, vol. 23, no. 1, pp. 2201–2204, 2003.

[15] C. Tassin, F. Laroudie, M. Pons, and L. Lelait, “Improvement of the wear resistance of 316L stainless steel by laser surface alloying,” *Surf. Coatings Technol.*, vol. 80, no. 1–2, pp. 207–210, Mar. 1996.

[16] J. Yao, L. Yang, B. Li, and Z. Li, “Characteristics and performance of hard Ni60 alloy

coating produced with supersonic laser deposition technique," *Mater. Des.*, vol. 83, pp. 26–35, Oct. 2015.

[17] L. Chen, R. Tao, D. Liu, and E. Al., "Analysis and Control of the Cracking Tendency on Helical Tooth Surface During Laser Cladding," *Chinese J. Lasers*, vol. 11, pp. 69–75, 2014.

[18] W. Chen, H. Chen, C. Li, X. Wang, and Q. Cai, "Microstructure and fatigue crack growth of EA4T steel in laser cladding remanufacturing," *Eng. Fail. Anal.*, vol. 79, pp. 120–129, Sep. 2017.

[19] C. J. Qiu, J. Zhou, X. F. Fan, and B. He, "Influence of High-Frequency Micro-Forging on the Surface Microstructure and Cracking Behavior of Laser Cladding," *Adv. Mater. Res.*, vol. 154–155, pp. 1614–1617, Oct. 2010.

[20] F. Bourahima, A. L. Helbert, M. Rege, V. Ji, D. Solas, and T. Baudin, "Laser cladding of Ni based powder on a Cu-Ni-Al glassmold: Influence of the process parameters on bonding quality and coating geometry," *J. Alloys Compd.*, vol. 771, pp. 1018–1028, Jan. 2019.

[21] C. Li, Z. Yu, J. Gao, J. Zhao, and X. Han, "Numerical simulation and experimental study of cladding Fe60 on an ASTM 1045 substrate by laser cladding," *Surf. Coatings Technol.*, vol. 357, pp. 965–977, Jan. 2019.

[22] H. Liu, C. Wang, X. Zhang, Y. Jiang, C. Cai, and S. Tang, "Improving the corrosion resistance and mechanical property of 45 steel surface by laser cladding with Ni60CuMoW alloy powder," *Surf. Coatings Technol.*, vol. 228, pp. S296–S300, Aug. 2013.