Surface remelting treated high velocity arc sprayed FeNiCrAlBRE coating by Tungsten Inert Gas

H.L. Tian\textsuperscript{a,b}, S.C. Wei\textsuperscript{b}, Y.X. Chen\textsuperscript{b}, H. Tong\textsuperscript{b}, Y. Liu\textsuperscript{b}, B.S. Xu\textsuperscript{b,a}\textsuperscript{*}

\textsuperscript{a} School of Materials Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100037, China
\textsuperscript{b} National Key Laboratory for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China

Abstract

This study aims at evaluating the effect of the TIG (Tungsten Inert Gas) remelting treatment of self-fluxing FeNiCrAlBRE alloy coatings, formed by means of high velocity arc spraying on steel surfaces. The treated and untreated samples were subjected to comparative structural examination using scanning electron microscopes. For quantitative investigation of porosity, a computer image analyser was used. Additionally, the wear resistance and wear volume loss of the worn tracks before and after the remelting process were contrastively evaluated in details. After the sprayed coatings were treated by TIG remelting in a proper conditions, the microstructure examination of the remelted coatings showed that a change of the microstructure from lamellar to cellular structure. Also, the results show that the remelting process decrease the coating defects and make the coating more wearable.

© 2013 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of the Chinese Heat Treatment Society

Key Word: high velocity arc spraying, FeNiCrAlBRE alloy coatings, TIG remelting process, microstructure

1. Introduction

The unique combination of excellent corrosion resistance and mechanical properties of FeAl-based alloys make them working in conditions that involve the interaction of mechanical and corrosive factors. In order to utilize their excellent properties, the FeAl-based alloys are often used as protective coatings on the surface of carbon steels (Wang and Li, 2008). The major drawbacks of this family of compounds are low ductility and creep resistance (Ji and Grosdidier, 2005). The brittleness can be solved by adding some alloying elements such as boron, nickel, chromium and RE which modifies the fracture mode from intergranular to transgranular (Guilemany and Cinca, 2007) or by reducing the grain size. The poor creep resistance can be improved by precipitation and solid solution hardening or even by dispersing particles (Ji and Grosdidier, 2005).

* Corresponding author. Tel.: +86 10 66718541; fax: +86 10 66717144
E-mail address: haoliangtian@163.com.
In this work, the arc spraying technique was used to deposited the FeNiCrAlBRE coatings which present a sum of porosity originated from the solidification porosities (due to the thermal shrinking) and formation of oxide interlayers, which impairs to obtain full benefits of the coatings properties. To reduce the porosity and to improve the properties of as-sprayed coatings, the surface remelting process is widely employed. Tungsten Inert Gas (TIG) (Dubourg and Lima, 2007) a high-energy source, is used to fuse an alloy layer to freely spread and freeze over a workpiece surface. The remelted coatings are usually free of the laminar architecture which is responsible for higher susceptibility to spalling and delamination. Furthermore, it can give measurable economic profits such as longer coating life and better protective properties.

2. Materials and experiment details

Fe-based cored wires (composition Fe-12wt.%, Ni-8wt.%, Cr-6wt.%, Al-1wt.%, B-6wt.%RE) were used as the spraying feedstock. A HAS-02 type arc spraying device was applied for spraying the FeNiCrAlBRE coatings on the surface of the AISI 1045 steel. The wire arc spray process parameters were as follows: spraying voltage 30-34 V, spraying current 14-160 A, compressed air pressure 600 kPa, the stand-off distance 200 mm. The surface remelting treatment of the coatings by the TIG method was done using a WSME-500AC/DC apparatus (Shanghai, China). The distance between the surface of the coating and electrodes was established between 2 and 3 mm. The optimal current was established as 70–90 A. Coating morphologies and element analysis were examined using Quant 200 type scanning electron microscope (SEM) coupled with an energy dispersion spectrooscope (EDS). The dry sliding wear resistance properties of the AISI 1045 steel matrix and the FeNiCrAlBRE coating were studied on the CETR Micro-tribological testing machine under a load of 50N. In the last case, every worn morphology characterization photo and volume loss of the samples was observed by VK-9700 3D Laser scanning microscope.

3 Results and discussions

3.1 Microstructure

Fig.1 (a) presents the microstructure of the cross-section coating, coating thickness ~150μm. A typical thermally sprayed laminar architecture which is responsible for higher susceptibility to spalling and delamination can be seen. Parallel to this, the existence of numerous pores and micro-cracks present in the as-sprayed coating. Also, coalescence and spheroidizing of pores in the spraying coatings were attributed to the circulation of the melted droplet and finally rapid solidification generates thermal shrinking (Józef and Iwaszko, 2006).
Fig. 1 The structure and morphology of cross-section samples:

(a) arc spraying coating, (b) after remelting treatment (c) top of the remelting coating

Fig. 1 (b) shows the same coating after TIG remelting. The structure of the remelted coatings was characterized by a more homogenous structure, elimination of the structure lamination and porosity. In contrast to Fig. 1 (a), the interface characteristic between the remelted coating and the substrate was not obvious revealed in Fig. 1 (b). The analysis of the porosities quantitatively of the remelted coating, in contrast to the unremelted coatings accounted for 27%, showed a dramatically reduced porosity accounting for only 2%.

Fig. 1 (c) shows the top section of the remelted coating, indicated that most of the arc voids and oxides disappear and only a small quantity of micro-cracks existed on the surface of the coating after parts of internal pores coalescence due to the rapid solidification. At the same time, a cellular structure displaced to the superficial remelted coating attributed to the nucleation rate was higher than that of the inner molten coating for the upper melted coating has the rapid solidification (Sexton and Lavin, 2006).

3.2 Phase composition

Aiming to study the morphology, oxide shape and micro-zone composition of the coatings before and after the remelting process, the EDS was applied in the experiment. The chemical element analysis of different zones, marking in Fig. 2 (a), (b) and (c), was shown in Table 1. The results reveal that the lighter particles (marked A) size in 20 \( \mu \text{m} \) diameter was Al and O concentrations which confirm the location of the \( \text{Al}_2\text{O}_3 \) phase. This observation is consistent with results previously published by J.M. Fernández-Pradas (Fernández-Pradas and Cléries, 2001). Although the high hardness \( \text{Al}_2\text{O}_3 \) ceramic phase embedded in the coatings will be benefit to improve the wear resistance, the hardness compound will be the origination of the cracks while the coating working for a long time (Edrisy and Alpas, 2002). Contrast with region A in Fig. 2 (a) and region F in Fig. 2 (b), the well phenomena was found in remelted coating is that the shape of the \( \text{Al}_2\text{O}_3 \) transited from irregular block to slender strip for quantity of heat input to the coating in the remelting process. At the same time, the dark grey structure (zone E shown in Fig. 2 (b)) surrounding at the strip (zone D existed in Fig. 2 (b)) which is \( \text{Al}_2\text{O}_3 \) and the component was revealed in table 1. Therefore, the surrounding structure will absorb amount of energy while the coating bearing high load and release the residual stress.

Fig. 2 The micro-zone chemical composition analysis:

(a) coating before remelting treatment, (b) remelted coating, (c) higher magnification zone of remelted coating
That mainly elements are Fe, Ni, Cr, Al consisted in zone B (Fig. 2 (a)) indicates that the spraying coating was not half oxidizing. This is attributed to the deoxidize elements such as B, Nb and RE were added in the cored wire (Mishra, S.B., Chandra, 2008). The other result is that the composition of region C (Fig. 2 (a)) consisted of Fe, Al and O transited to Fe, Ni and Al consisted in region F (Fig. 2 (b)). This observation is similar said that the atoms were diffused in the heat treatment process (Newbery and Grant, 2006). We can estimate the regions where some Fe-Al or Ni-Al intermetallic phase maybe formed and expect that the coating cohesive strength will improve.

Finally, clearly cellular structure was shown in Fig. 2 (c). At the grain boundary, the content of dark region G was of Fe, Ni, Cr, Al and lighter region H was of Cr, Al, O. Contrast with the composition of zone B in Fig. 2 (a), the content of grain (zone G in Fig. 2 (c)) was of Fe, Ni, Cr, Al and the Fe was sharply transited from a very high value to a low one, and the content of Ni, Cr, Al are more uniformity. The highly homogeneous distribution of the remelted coating composition is the result of the uniformity nucleation while the coating melted in the remelted process. Well-known that the equilibration structure will benefit to heighten the corrosion and wear resistance.

### 3.3 Dry sliding wear behavior

As shown in Fig. 3, we can conclude that the worn track width and length of the coating (Fig. 3 (b)) is higher than that of the remelted coating (Fig. 3 (c)). From the calculated on the values of every worn track, the widths of the substrate, spraying coating, and remelted coating are 0.63 mm, 1.24 mm and 0.37 mm respectively. Also the lengths of the substrate, spraying coating, and remelted coating are measured as 3.47 μm, 3.24 μm and 2.87 μm respectively.

Fig. 3 Two-dimensional morphology of worn track: (a) substrate, (b) coating before remelted, (c) remelted coating

Fig. 4 shows the three-dimensional worn track morphology of every sample. The worn track depths of the spraying coating and remelted coating are measured as 37.8 μm and 17.6 μm respectively. Meantime,
the wear volume loss for the substrate, spraying coating, and remelted coating are measured as $3.78 \times 10^{-6} \text{m}^3$, $2.46 \times 10^{-6} \text{m}^3$ and $1.13 \times 10^{-6} \text{m}^3$ respectively. The results show that the wear resistance of remelted coating is the best one.

![Fig.4 Three-dimensional morphology of worn track: (a) substrate, (b) coating before remelted, (c) remelted coating](image)

As shown in Fig.1 (a), the spraying coating consists of oxides, micro-cracks and many pores. That some pores are more existed in the interface between coating and substrate than in coating is obvious. From the EDS analysis, there are many irregular shape oxides embedded in the coating (Fig.2 (a)). Although the presence of oxide will increase the hardness of the coating, which may be beneficial to improving the wear resistance, the micro-cracks often initiate from the oxide boundaries. With the increase of sliding distance, the initiated micro-cracks, together with the inherent micro-cracks, grow up and extent along the coating, the cracks should become crippling and shear break off from the coating, which results in the wear volume loss is higher than that of the remelted coating (Pokhmursk and Dovhunyk, 2002). The best results are that cellular structure was formed in the top of the remelted coating and the atoms diffused between the oxide layers and the coating matrix. The SEM analysis from the cross-section remelted coating indicated that the coating is dense and no cracks or pores can be observed. Therefore, this type of structure can be prevent debris from cracking or disintegrating and the remelted treatment is beneficial to improve the microstructure and wear resistance.

4 Conclusions

The surface remelting of the arc sprayed FeNiCrAlBRE coatings produces modified structure characterized as reduction in porosity, increase in the structure dispersion and material homogenization contributed to enhanced wear resistance. After the remelting treatment, the shape of the $\text{Al}_2\text{O}_3$ transited from irregular block to slender strip for quantity of heat input to the coating. The atoms diffused between the oxide layers and the coating matrix. Remelted coating is dense and no cracks or pores can be observed. The worn volume, worn track width, length and depth of the remelted coating are all smaller than that of the spraying coating. The TIG method presents an attractive and comparative method of improvement in the properties of the arc sprayed coatings.

Acknowledgements

The authors are grateful for the support provided by 973 Project (2011CB013403), and Natural Science Foundation of China (51105377, 50971132), National science and technology supporting project (N0.2011baf11B07).

References

Wang, H.T., Li, C.J., Yang, G.J., 2008. Cold spraying of Fe/Al powder mixture: Coating characteristics and influence of heat
treatment on the phase structure. Applied Surface Science 7, 1-7.
Ji, G., Grosdidier, T., Liao, H.L., Morniroli, J., Coddet, C., 2005. Spray forming thick nanostructured and microstructured FeAl deposits. Intermetallics 13, 596-607.
Guilemany, J.M., Cinca, N., Dosta, S., Lima, C.R.C., 2007. High-temperature oxidation of Fe40Al coatings obtained by HVOF thermal spray. Intermetallics 15, 1384-1394.
Ji, G., Grosidierm, T., Liao, H.L., Morniroli, J.P., Coddet, C., 2005. Spray forming thick nanostructured and microstructured FeAl deposits. Intermetallics 13, 596–607.
Dubourg, L., Lima, R.S., Moreau, C., 2007. Properties of alumina-titania coatings prepared by laser-assisted air plasma spraying. Surface and Coating Technology 201, 6278-6284.
Józef., Iwaszko., 2006. Surface remelting treatment of plasma-sprayed Al2O3+13wt.% TiO2 coatings. Surface Coating Technology 201, 3443-3451.
Sexton, L., Lavin, S., Byrne, G., Kennedy, A., 2002. Laser cladding of aerospace materials. Material Process Technology 122, 63-68.
Fernández-Pradas, Cle’ries, J.M., Martínez, L.E., 2001. Influence of thickness on the properties of hydroxyapatite coatings deposited by KrF laser ablation. Biomaterials 22, 2171–2175.
Edrisy, A., Alpas, A.T., 2002. Microstructures and sliding wear resistances of 0.2% carbon steel coatings deposited by HVOF and PTWA thermal spray process. Thin Solid Films 420-421, 338-334.
Mishra, S.B., Chandra, K., Prakash, S., 2008. Characterization and erosion behavior of NiCrAlY coating produced by plasma spray method on two different Ni-based super alloys. Material Letter 62, 1999-2002.
Newbery, A.P., Grant, P.S., 2006. Oxidation during electric arc sprays forming of steel. Journal Material Process Technology 178, 259-269.
Pokhmurska, H., Dovhuny, V., Student, M., Beilanska, E., Beltowska, E., 2002. Tribological properties of arc sprayed coatings obtained from FeCrB and FeCrB-based powder wires. Surface and Coating Technology 151, 490-494.