Study on NiCr-Cr$_3$C$_2$ Deposition Efficiency of Two Supersonic Spraying

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Abstract

NiCr-Cr$_3$C$_2$ coatings were made by High-efficiency Ultrasonic PlazJet (HEPJet) and JP-5000 Supersonic Flame Spraying (JP5000). The instruments of SEM and EDS were used to analyze the composition and structure of NiCr-Cr$_3$C$_2$ coatings and spraying particles. The results show that the oxidization of coatings is more serious for JP-5000 than HEPJet. The deposition efficiency of HEPJet NiCr-Cr$_3$C$_2$ coatings is 54%, which is 1.5 times as higher as JP-5000. And the oxidation of spraying particle in the flame is the main reason that caused low deposition efficiency of NiCr-Cr$_3$C$_2$ coatings by JP-5000 spraying.

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1. Introduction

NiCr-Cr$_3$C$_2$ metal ceramic coatings with outstanding resistance to high temperature oxidation and wear have extensive application in machinery and metallurgy industries [1,2]. At present, supersonic flame spraying technology is deemed to be the main thermal spraying technology of industrialized production of NiCr-Cr$_3$C$_2$ coatings. However, supersonic flame spraying is of low deposition efficiency and high
consumption of fuel and gas which greatly increases production cost of NiCr-Cr₃C₂ coatings thereby restrict the popularization and application of supersonic flame spraying.

Supersonic Plasma Spraying technology solves the problem of carbon-lose of metallic carbide ceramic coatings by atmospheric plasma spraying in an efficient way due to dramatically increasing of efflux velocity, which is similar with supersonic flame spraying [3]. This article analyses NiCr-Cr₃C₂ deposition efficiency by JP-5000 supersonic flame spraying and supersonic plasma spraying, providing evidence for selecting the way of spraying NiCr-Cr₃C₂ in project.

2. Experimental method

NiCr-Cr₃C₂ coatings were made by High-efficiency Ultrasonic PlazJet (hereinafter referred to as HEPJet) and JP-5000 Supersonic Flame Spraying (hereinafter referred to as JP-5000) respectively. Stainless steel pipe (Φ80-Φ75) ×300 mm as substrate and NiCr-Cr₃C₂ powder (Model# KF-70) developed by Beijing Mining and Metallurgical Research Institute were used in experiment. Deposition efficiency is measured through imitating actual production condition, in which substrate does back and forth movement on rotary table at the speed of 120 rad/min and spray gun at 0.5 m/min on matrix. Powder feeder and transmission pipe should be cleaned before placing the powder. Meanwhile, put an electronic balance with accuracy of 0.1g under the powder feeder (measuring the weight of transmitted powder). Transmitting time is 3 minutes. Remove the spray gun from matrix in 10 sec after stopping sending the powder to make sure there is no powder in transmission pipe. Deposition efficiency is measured by weight method formulated as below: \( \eta = \frac{g_1}{g_2} \times 100\% \), \( \eta \): deposition efficiency, \( g_1 \): coatings weight \( g_2 \): output powder weight. The experiment analyzed spray particle spreading feature and composition using Quanta 2000 SEM and EDS. Spraying technology parameter is showed in Table 1 and Table 2, in which JP-5000 spraying technology parameter is standard parameter provided by TAFA.

| Table 1 Process parameters of HEPJet |
|-------------------------------------|
| Spray distance (mm) | Voltage (V) | Current (A) | Ar pressure (MPa) | Ar flow rate (m³·h⁻¹) |
| 100 | 140 | 400 | 1.1 | 4.0 |
| H₂ pressure (MPa) | H₂ flow rate (m³·h⁻¹) | N₂ pressure (MPa) | N₂ flow rate (m³·h⁻¹) | Powder feed rate (g·min⁻¹) |
| 1.0 | 0.22 | 0.7 | 0.60 | 40 |

| Table 2 Process parameters of JP-5000 |
|-------------------------------------|
| Spray distance (mm) | O₂ pressure (MPa) | O₂ flow rate (m³·h⁻¹) | kerosene pressure (MPa) | kerosene flow rate (l·h⁻¹) | N₂ pressure (MPa) | N₂ flow rate (m³·h⁻¹) | Powder feed rate (g·min⁻¹) |
| 380 | 1.4 | 53 | 1.2 | 23 | 0.6 | 0.64 | 60 |

3. Result and Discussion

3.1. Measurement of NiCr-Cr₃C₂ deposition efficiency

Table 3 is the results of NiCr-Cr₃C₂ coatings deposition efficiency by two technologies. From the table we know that the powder feed of JP-5000 is 180 g, which is 1.5 times than HEPJet, but the coatings
quality and spraying efficiency of the two technologies are more or less. NiCr-Cr$_3$C$_2$ coatings deposition efficiency by HEPJet is 54%, approximately 1.5 times as higher as JP-5000. That is why HEPJet needed less powder have equivalent with spraying efficiency and coatings quality of JP-5000.

Table 3 the result of the deposition efficiency

| Spray system | Powder quality (g) | Coatings quality (g) | Deposition efficiency (%) | Spray efficiency (g·min$^{-1}$) |
|--------------|--------------------|----------------------|---------------------------|----------------------------------|
| JP5000       | 180                | 63                   | 35%                       | 21                               |
| HEPJet       | 120                | 64.8                 | 54%                       | 21.6                             |

3.2. Coatings Organization Structure Analysis

Fig.1 list two types of NiCr-Cr$_3$C$_2$ coatings Cross–sectional SEM and EDS made by two different technologies. From Fig.1 (a) & (c) we know that the two types of coatings are both compact, well bonding with substrate and presenting spotted shape which is the result of crossed distribution of alloy phase and ceramic phase. By examination, the bonding strength and micro-hardness of HEPJet coatings is 60MPa and 884HV$_{0.3}$ respectively, and the JP-5000 coatings’ is 65MPa and 876HV$_{0.3}$ respectively. Compared with the coatings of atmospheric plasma spraying [4～6] (35MPa and 755HV$_{0.3}$), the coatings of HEPJet is better than atmospheric plasma spraying’s and equivalent with JP-5000’s.

![Fig.1Cross–sectional SEM and EDS of NiCr-Cr$_3$C$_2$ coatings](image)

Table 4 the component of powder and coatings

|                      | $\omega$(C) % | $\omega$(Ni) % | $\omega$(Cr) % | $\omega$(O) % |
|----------------------|---------------|----------------|----------------|----------------|
| NiCr-Cr$_3$C$_2$ powder | 10            | 18.5           | 71.5           | -              |
| Coatings of HEPJet   | 8.20          | 18.4           | 71.35          | 2.05           |
| Coatings of JP-5000  | 7.10          | 17.15          | 68.62          | 7.13           |

A few of un-melted particles were found in Fig.1(a). There were more pores around these unmelted particles, which means unmelted particle has direct influence to the increasing of pore. Result of analysis of the two types of coatings is showed in Fig.1 (b) and (d), composition of powder and two types of coatings list in Table 4. From the table we can know that carbon content of JP-5000 spraying coatings is lower than HEPJet coatings, oxygen content obviously higher than HEPJet. That’s to say JP-5000 coatings oxidation and carbon-lost is more serious than HEPJet coatings.

Analysis recognized that heating conditions and flame atmosphere are the main reasons that caused the results stated above: (1) HEPJet spraying particle instantaneously heated and melted; The time from heating to hit with substrate is more short than JP-5000. But JP-5000 is long heating distance, which is approx 5.5 times as far as HEPJet, and heating time is 5 times as long as HEPJet. So the oxidation time of JP-5000 spraying particles is longer than HEPJet’s. (2) HEPJet flame is inert atmosphere, protecting
spraying particle from oxidation. JP-5000 flame flow is oxidizable atmosphere. With relatively long heating time, oxidation and carbon-lose of spraying particle is obviously serious than HEPJet spraying coatings.

3.3. Deposition Efficiency Analysis

In the forming process of coatings, single melted particle is the smallest basic unit of coatings. Its performance reflects the characteristic of coatings forming. Performance of single particle includes three basic processes [7]: (1) thermal spraying particle forming process; (2) forming process of molten or half-molten state of thermal spraying particle interacting with heat source; (3) cross-flow flattening and quick cooling and solidification process when hitting the matrix at high speed after accelerated heating thermal spraying particle. Analyze coatings forming situation through the transformation of spreading and composition of NiCr-Cr$_3$C$_2$ particle on the substrate.

Fig. 2 is spreading image and energy spectrum of NiCr-Cr$_3$C$_2$ particle on the substrate. Fig. 2 (a) and (b) is for HEPJet spraying particle and the rest for JP-5000. In Fig. 2 (a), it’s very clear that HEPJet particle transformation is complete on the substrate and in disc shape and spraying particle is well flattened. Its energy spectrum picture Fig. 2(b) shows that the main composition of spraying particle spread on the matrix is C, Cr, Ni and extremely small amount of O, which means HEPJet inert atmosphere well protects spraying particle from oxidation. From Fig. 2 (c) and (e) we can see JP-5000 spraying particle is in half-spread state on the matrix, bulge in the middle and flat on the side. Spot diameter is equivalent to powder particle, obviously not well flattened. 2(d) and (f) energy spectrum shows that the main composition of the bulge part is C, Cr and O, Ni, Cr around the side also with some C and O as well. Fig. 2(h) energy spectrum represents that the main composition of coatings is Ni, Cr and O but no C. Analysis recognizes that only alloy phase and partial Cr oxide left and most of Cr$_3$C$_2$ is lost after NiCr-Cr$_3$C$_2$ crashed in high-speed impacting.

3.4. Discussion

NiCr-Cr$_3$C$_2$ itself is easy oxidized and carbon-lost exposed to oxygen at 1100°C. Though the spraying particle speed of JP-5000 (550m/s) is faster than HEPJet (460m/s), its spraying distance is 5.5 times as far as HEPJet and particle heating time in flame 5.5 times as long as HEPJet’s , plus strong oxidizing atmospheres, so NiCr-Cr$_3$C$_2$ particle oxidation (7.1% of oxygen content in coatings) and carbon-lost is relatively more serious than HEPJet’s. Main oxidative products of NiCr-Cr$_3$C$_2$ are Cr$_2$O$_3$ and Cr$_7$C$_3$ phase [8,9]. Cr$_2$O$_3$ is mainly formed in two ways, one through metal bonding phase NiCr oxidation which
reduced the toughness of bonding phase; the other way through aerobic degradation of Cr$_3$C$_2$. Cr$_7$C$_3$ phase of higher brittleness and lower plasticity was produced at the same time. They directly effected NiCr-Cr$_3$C$_2$ deposition performance and reduced its efficiency.

On the other hand, Oxidation of NiCr-Cr$_3$C$_2$ will effect heat transfer performance of particle in the flame, especially when particle inner melt state is restricted thereby effect flattening level after particle hit on matrix (Fig.2(c)). Moreover, part of JP-5000 spraying particle spurs or bounces away under high-speed impact (Fig. 2(g)), which to some extent caused the decrease of NiCr-Cr$_3$C$_2$ deposition efficiency. While HEPJet spraying particle is well melted with low oxidation. Oxide in the coatings is about one third of JP-5000 (Table 3). From above discussion, oxidation of spraying particle in the flame flow is the main reason of low NiCr-Cr$_3$C$_2$ deposition efficiency of JP-5000.

4. Conclusion

1. NiCr-Cr$_3$C$_2$ coatings made by High-efficiency Ultrasonic PlazJet is compact, high micro-hardness (884HV$_0.3$) and bonding strength (60MPa).
2. NiCr-Cr$_3$C$_2$ deposition efficiency of High-efficiency Ultrasonic PlazJet is about 54% which is 1.5 times as high as JP-5000, and its spraying efficiency is 21.6 g/min.
3. JP-5000 spraying coatings oxidation and carbon-lost is much serious than High-efficiency Ultrasonic PlazJet spraying coatings.
4. Oxidation of spraying particle in the flame flow is the main reason that caused NiCr-Cr$_3$C$_2$ deposition efficiency of High-efficiency Ultrasonic PlazJet higher than JP-5000.

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