Influences of Feedstocks and Laser Remelting on Erosion Resistance of Al₂O₃-13wt.%TiO₂ Coatings Prepared by Plasma Spraying

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Abstract. Conventional and nanostructured ceramic coatings were prepared with conventional and nanostructured aggregate Al₂O₃-13wt.%TiO₂ ceramic powders through plasma spraying and plasma spraying-laser remelting combined technique. Influences of feedstocks and laser remelting on erosion resistance of the prepared coatings were discussed, and the erosion failure mechanisms of four types of coatings were discussed. Results demonstrate that compared with coatings prepared by plasma spraying, the coating prepared by laser remelting has better erosion resistance. Given the equal conditions, nanostructured coating shows stronger erosion resistance than conventional coating. Conventional ceramic coating shows typical brittle erosion characteristics and nanostructured ceramic coating also shows brittle erosion characteristics, accompanied with certain degree of plastic erosion characteristics. Erosive wearing of plasma coating is mainly lamellar peeling, accompanied with certain degree of brittle ceramic particle crushing. Coating prepared by laser remelting present crack initiation and propagation on near surface, finally leading to crystal crushing and peeling of remelting layers.

1. Introduction
Erosive wear is a common form of wearing. With some inherent characteristics, ceramic materials are applied more and more as protective coatings in erosion environment. Plasma spraying is one of the most common technologies to prepare ceramic coatings in China and abroad [1-2]. However, inherent characteristics of plasma spraying determine that lamellar superposition structure of coating structures. Moreover, coating prepared by plasma spraying contains abundant pores and microcracks that restrict its application ranges and service life. Laser remelting is a laser surface strengthening technology that combines laser technology and thermal processing. It can eliminate lamellar structure and most pores of coating layers, thus enabling to form uniform and dense ceramic coatings. Coating prepared by laser remelting can protect workpieces and prolong service life of the workpiece [3-5]. Due to unique structure, nanomaterials have excellent performance beyond the capability of ordinary materials and provide favorable conditions to improve performance of ceramic coatings. Recent studies prove that nanostructural ceramic coating is significantly superior to traditional ceramic coating [6-8].

In this study, conventional and nanostructured ceramic coatings were prepared with conventional and nanostructured aggregate Al₂O₃-13wt.%TiO₂ ceramic powder through plasma spraying and plasma
spraying-laser remelting combined technique. Influences of feedstocks and laser remelting on erosion resistance of coating were discussed. The erosion failure mechanisms of coatings were investigated.

2. Experimental method

The γ-TiAl-based alloy (20 mm×20 mm×8 mm) melted by the High-temperature Material Research Institute of Iron and Steel Research Institute was used as the base material. The transition layer MCrAlY used the NiCoCrAl superalloy powder dispersed by Y2O3. NiCoCrAl superalloy powder was made by Metal Material Institute of Beijing General Research Institute of Mining and Metallurgy and its grain size ranged -140~+325 meshes. Ordinary ceramic materials chose the ordinary commercial Al2O3-13 wt.%TiO2 composite ceramic powder which was produced by Shenyang Ronghua, with a grain size of 15~45μm. Nanostructured aggregate powder applied the Nanox S2613P powder (Inframat, USA) prepared by spraying drying method. The nominal component of nanostructured aggregate powder was Al2O3-13 wt.%TiO2 and the size range was 10~50 μm. The original nanoparticle was 30~80 nm. The corresponding powder morphology is shown in Fig. 1.

![Fig. 1. SEM morphology of Al2O3-13 wt.%TiO2 powder: (a) Conventional powder and (b) nanostructured aggregate powder.](image)

The 3710 plasma spraying system made by Chemplex Company (USA) was applied for pre-manufacturing of conventional and nanostructured Al2O3-13 wt.%TiO2 ceramic coating. The technological parameters of plasma spraying are listed in Table 1. Before coating, samples were preprocessed through grinding, deoiling and abrasive blasting. Laser remelting applied SLCF-X12×25 CO2 laser machine. Technological parameters of laser remelting were introduced as follows. For conventional coating, the laser power, rectangular spot size, laser scanning direction, scanning rate and amount of overlap were 650 W, 5 mm×3 mm, along 3mm of the spot, 1200 mmꞏmin⁻¹ and 20%, respectively. For nano-coating, the laser power, rectangular spot size, laser scanning direction, scanning rate and amount of overlap were 500 W, 5×3 mm, along 3mm of the spot, 700 mmꞏmin⁻¹ and 20%, respectively.

| Process parameters          | MCrAlY | Conventional Al2O3-13 wt.%TiO2 | Nanostructured Al2O3-13 wt.%TiO2 |
|----------------------------|--------|-------------------------------|----------------------------------|
| Current [A]                 | 710    | 850                           | 870                              |
| Voltage [V]                 | 42     | 42                            | 42                               |
| Primary gas (Ar) [PSI]      | 65     | 45                            | 45                               |
| Secondary gas (He) [PSI]    | 115    | 140                           | 140                              |
| Powder carrier gas (Ar) [PSI]| 45     | 45                            | 45                               |
| Powder feed rate [rꞏmin⁻¹]  | 2      | 3                             | 3                                |
| Spray distance [mm]         | 110    | 100                           | 100                              |
| Traverse speed [mmꞏs⁻¹]     | 100    | 100                           | 100                              |
| Coating thickness [μm]      | ~100   | ~350                          | ~350                             |

Solid particle erosion test was accomplished on an erosion tester which was improved from a sand-blasting machine. The working principle is shown in Fig. 2(a). Compressed air was used as the momentum to drive abrasive particle sprayed onto surface of specimens, thus realizing microcutting and
impact of sample surface. The erosion test was carried out by using natural adamantine spar (Al₂O₃) as the abrasive particles (particle size=150~250 μm, prismatic, HV=2000~2300 kg·mm⁻², Fig. 2(b)) under room temperature. Airflow speed was adjusted by controlling the inlet pressure valve and erosion angle was controlled by adjusting the support through the self-made erosion clamp. Erosion parameters included erosion surface size (Φ17.5 mm), inner diameter of nozzle (6 mm), distance from nozzle to samples (150 mm), air pressure (0.6 MPa), erosion angle (30°, 60° and 90°), and erosion time 30+30+60+60+60 s. Samples were cleaned by ultrasonic treatment with acetone before and after erosion, and weight loss after drying was weighted by a FA1004 analytical balance with a weighting sensing of 10⁻⁴ g (all results chose mean of 3 samples). Morphology before and after erosion was observed under JSM-7100F (JEOL) field emission scanning electron microscope and erosion failure mechanism of ceramic coatings was discussed.

![Fig. 2. (a) Erosion test and (b) pictures of abrasive particles.](image)

### 3. Experimental results and discussions

**Structure of ceramic coating.** Morphologies of conventional and nanostructured Al₂O₃-13 wt.%TiO₂ ceramic coatings prepared by plasma spraying and laser remelting are shown in Fig. 3. Conventional ceramic coating based on plasma spraying shows typical lamellar superposition characteristics, while the nanostructured coating based on plasma spraying is composed of fully melted region and partially melted region of nanoparticles, thus resulting in a two-phase structure. After laser remelting, most internal defects of the original coating prepared by plasma spraying have been deleted and coating surface forms dense, uniform and small isometric crystal remelting zone. Compared with conventional ceramic coating prepared by laser remelting, the isometric crystal tissues in the remelting zone of nano-coating prepared by laser remelting is smaller and denser. Due to fast heating and cooling of laser remelting, some remained nanoparticles in some melting regions of plasma coating are still retained in the remelting zone. Microstructure and formation mechanism of conventional and nanostructured Al₂O₃-13 wt.%TiO₂ ceramic coatings which are prepared by plasma spraying and laser remelting have been introduced in Reference [9-11]. These are not introduced in the present study.

**Erosion test results.** Erosive wear test results of four Al₂O₃-13 wt.%TiO₂ ceramic coatings under different erosion angles are shown in Fig. 4. Generally, the nanostructured ceramic coating prepared by laser remelting shows the highest erosion resistance, followed by the nanostructured ceramic coating prepared by plasma spraying, conventional ceramic coating prepared by laser remelting and conventional ceramic coating prepared by plasma spraying. However, erosion-induced weight loss of coatings prepared by laser remelting increased significantly as the erosion time prolongs, especially the conventional ceramic coating prepared by laser remelting. Given 90° erosion angle, the erosion-induced weight loss of conventional ceramic coating prepared by laser remelting is the highest after 240s of erosion. Besides, it can be seen from Fig. 4(a), (b) and (c) that weight loss of all ceramic coatings is the lowest when the erosion angle is 30° and it reaches the highest when the erosion angle is 90°. This reflects that the erosion-induced weight loss is positively related with erosion angle and coatings represent typical erosion characteristics of brittle materials. Take the conventional ceramic coating prepared by plasma spraying for example. The total weight losses at 240s are 40.4 mg, 72.3 mg and 110.3 mg when the erosion angle is 30°, 60° and 90°, respectively.
Erosion results analysis of coatings. The erosive surface morphology of conventional Al₂O₃-13 wt.%TiO₂ coating prepared by plasma spraying is shown in Fig. 5(a). Clearly, coating surface after erosion presents evident peeling behaviors and micro-breakage to some extent. For the conventional ceramic coating prepared by plasma spraying, its structure is composed of embedding and superposition of lamellar particles and particles are mainly combined through mechanical riveting. Due to the weak binding force, the bonding interface of particles is easy to be damaged. In the process of erosive wear, cracks propagate from the uncombined interface to the combined interface along inter-lamella structure under repeated impact of erosion particles, thus making the upper lamellar tissues under direct impact peeling off continuously [12]. The erosive failure of conventional Al₂O₃-13 wt.%TiO₂ ceramic coating prepared by plasma spraying is shown in Fig. 6. Moreover, conventional ceramic has low tenacity and high brittleness, and erosive energy cannot be consumed by plastic deformation. Under the alternative compressive-tensile stresses produced by impact of erosive particles, the coating is easy to be broken and separated from the base significantly. Therefore, erosive wear of conventional ceramic coating prepared by plasma spraying is dominated by lamellar peeling, accompanied with certain degree of brittle ceramic grain breakage.

![SEM morphology Al₂O₃-13 wt.%TiO₂ ceramic coating: (a) conventional coating prepared by plasma spraying, (b) nano-coating prepared by plasma spraying, (c) conventional coating prepared by laser remelting and (d) nano-coating prepared by laser remelting.](image)
Fig. 4. Erosive wear test results of ceramic coatings under different erosion angles ($\alpha$): (a)30°, (b)60° and (c)90°.

Fig. 5. Typical morphology of erosive surface of Al$_2$O$_3$-13 wt.%TiO$_2$ ceramic coating under 60°: (a) conventional coating prepared by plasma spraying, (b) nano-coating prepared by plasma spraying, (c) conventional coating prepared by laser remelting and (d) nano-coating prepared by laser remelting.
Fig. 6. Erosive failure of conventional Al₂O₃-13 wt.%TiO₂ coating prepared by plasma spraying.

SEM morphology of the Al₂O₃-13 wt.%TiO₂ nanostructured coating prepared by plasma spraying after erosion is shown in Fig. 5(b). Compared with erosion morphology of conventional ceramic coating prepared by plasma spraying, the erosion surface of nano-structured ceramic coating presents similar peeling and breaking features, but the degree of peeling and breaking features is lower. In addition, there’s obvious plastic deformation (cutting traces) on the erosion surface, especially in partial melting region (micro-nanostructure region). This is not observed on erosion surface of conventional coating. Such plastic deformation is because nanostructure can improve plasticity and tenacity of ceramic coating. The erosive failure of Al₂O₃-13 wt.%TiO₂ nanostructured coating prepared by plasma spraying is shown in Fig. 7.

The nanostructured coating prepared by plasma spraying maintains a considerable proportion of nanostructure, which increases tenacity of ceramic coating [6,13]. Therefore, this is beneficial to improve erosion resistance of nanostructured coating. Moreover, erosion resistance of coating is related with bonding strength of coating. At plasma spraying onto the nanostructured aggregate powder, the powder surface is easy to be heated and melted due to the high specific surface and high activity, and powder surface is melted well. Therefore, nano particles develop great deformation after impacting onto the base or the deposited surface, and the pavement of nano particles is better than conventional powder [14]. Therefore, bonding of lamellar structure of nanostructured coating is better than that of the conventional coating prepared by plasma spraying, manifested by the high bonding strength. A good combination increases the resistance of nanostructured coating to cracks on the bonding interface, thus enabling to increase erosion resistance of nanostructured coating accordingly.

Fig. 7. Erosive failure of Al₂O₃-13 wt.%TiO₂ nanostructured coating prepared by plasma spraying.

Typical erosion morphology of conventional Al₂O₃-13 wt.%TiO₂ coating prepared by laser remelting is shown in Fig. 5(c). Compared with samples prepared by plasma spraying, samples prepared by laser remelting develop significantly smaller degree of peeling and breaking after erosion. However, there are still serious breakages in local regions. After laser remelting, ceramic coating prepared by
plasma spraying develops remelting crystals on the uneven and porous surface layer, and the lamellar structure disappears. Instead, a dense remelting layer was formed. Due to high cohesion in coatings prepared by laser remelting, it is difficult to have peeling during the erosion, but cracks initiate and propagate on near surface, finally resulting in coating breakage. The erosion failure principle is shown in Fig. 8. During initial stage of erosion, the dense remelting layer with strong bonding and hardness shows high resistance to crack initiation and propagation, leading to the small erosion-induced weight loss and high erosion resistance [5]. However, ceramic materials which have poor impact resistance and low breaking tenacity are easy to produce cracks, pores and even peeling under dramatic heating and cooling conditions during laser remelting. Given repeated impacts of erosive particles, there’s a large region with defects and deep macroscopic cracks on local remelting surface, which further causes peeling in a large area and high peeling thickness in some positions. Some peeling even reaches the interface between remelting layer and residual plasma spraying layer. This differs significantly from stepwise lamellar peeling mechanism of the coating prepared by plasma spraying after erosion. Therefore, the erosion-induced weight loss of coatings prepared by laser remelting is accelerated under erosion conditions for a long period.

Erosion morphology of Al₂O₃-13 wt.%TiO₂ nanostructure coating prepared by laser remelting is shown in Fig. 5(d). Obviously, the coating develops the slightest peeling and breaking. This is because the nanostructured ceramic coating prepared by combining laser remelting and plasma spraying is equipped with not only surface hardness and high density of samples prepared by laser remelting, but also high tenacity of nanostructured coating. The tenacity and hardness are unified well, so that the coating is equipped with the strongest erosion resistance. Although erosion-induced weight loss of nanostructured ceramic coating prepared by combining laser remelting and plasma spraying is accelerating slightly, the erosion-induced weight loss is significantly smaller than that of conventional ceramic coating prepared by laser remelting. Therefore, nanostructured ceramic coating prepared by laser remelting has good erosion resistance in early erosion and after erosion for a long period.

4. Summary
Conventional and nanostructured ceramic coatings were prepared with conventional and nanostructured aggregate Al₂O₃-13 wt.%TiO₂ ceramic powders through plasma spraying and plasma spraying-laser remelting combined technique. Influences of feedstocks and laser remelting on erosion resistance of the prepared coatings were discussed, and the erosion failure mechanisms of four types of coatings were discussed.

(1) Compared with conventional ceramic coating prepared by plasma spraying, nanostructured coating has stronger erosion resistance to some extent and the erosion resistance of nanostructured coating can be further improved after laser remelting. The nanostructured ceramic coating prepared by laser remelting presents the best erosion resistance.
(2) Conventional ceramic coating presents typical brittle erosion characteristics and nanostructured ceramic coating presents obvious brittle erosion characteristics, accompanied with certain plastic erosion characteristics.

(3) Erosive wear of coating prepared by plasma coating is dominated by lamellar peeling. Moreover, the brittle ceramic particles are crushed to some extent. However, coating prepared by laser remelting mainly develops crack initiation and propagation on the near surface, finally resulting in breaking and peeling of crystal grains on the remelting layer.

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