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# Aluminizing mechanism on a nickel-based alloy with surface nanostructure produced by laser shock peening and its effect on fatigue strength

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## ABSTRACT

A nanocrystalline surface layer with grain sizes ranging between 30 and 150 nm was fabricated on a K417 nickel-based cast alloy by means of laser shock peening (LSP). The effect of the surface nanostructure on the gas aluminizing process was investigated through microstructure characterizations, carried out by transmission electron microscopy (TEM), scanning electron microscopy (SEM) and X-ray diffraction (XRD). The results showed that, following the LSP treatment, a higher amount of Al diffused into the matrix and a thicker-aluminizing layer was produced. The diffusion mechanism was that the thermal stability of surface nanostructure and high-density dislocation induced by LSP increased its surface activity and made more channels available for element diffusion during the high temperature gas aluminizing processing. The specimens in different surface treatments (aluminizing and LSP + aluminizing) were then subjected to vibration fatigue load. The fatigue strengths of the aluminizing specimens and LSP + aluminizing specimens were 226 MPa and 335 MPa, respectively. All the results indicated that LSP-induced surface nanostructure increased the efficiency of the aluminizing process and the fatigue resistance.

## 1. Introduction

The nickel-based alloys blades of modern gas turbine aero-engines operate in the extreme rigorous conditions, exposed to severe mechanical and thermal stress, which would cause fatigue failure. In the absence of protective coatings, these may cause fatigue failure, oxidation and hot corrosion, seriously damaging the components of the aero-engine and potentially leading to its failure. Nickel aluminide coatings are commonly applied on nickel-based alloys to improve their fatigue, oxidation and corrosion resistance [1–4].

The gas aluminizing process is one of the most cost-effective processes used to form a nickel alumina coating on the surface of engine components. In particular, due to the possibility of using this technique on the components with different sizes and shapes, it is widely used to form a dense aluminum compound protective layer on the surface of metallic alloys. During the process, the diffusing Al atoms react with the substrate elements and form the more strengthening $\gamma'$ phases. Consequently, the global mechanical properties and fatigue resistance are improved. Many investigations have been carried out and it has been found that the thickness and concentration of the diffusion layer developed during the thermochemical treatment process depend on the processing conditions and the surface microstructure of the substrate alloy [3–6]. For example, Gleiter [7] and Lu et al. [8] suggested that a large number of grain boundaries in the ultrafine grains, especially in nanocrystalline materials, act as fast atomic diffusion channels and enhance the surface activity. Shen et al. [9] found that the atomic diffusivity was enhanced in nanocrystalline materials compared to their coarse grained counterparts. Moreover, various kinds of non-equilibrium defects presented in the nano-grain boundaries could act as a high-energy storage and further enhance the surface diffusivity [10,11]. Hence, we believe that surface microstructure change, especially surface nanocrystallization, is a good option for accelerating the production of diffusion layers.

Severe plastic deformation (SPD) induced by surface mechanical treatments, such as surface mechanical attrition treatment (SMAT) and shot peening, is recognized as an effective method to produce a surface nanostructure that can promote diffusion [12–19]. Xiang et al. [15] found that the SMAT treatment induced the formation of nanoscale grains and high-density dislocations, and promoted the diffusion process as well as the formation of a thicker diffusion layer. Hong et al. [16] utilized ultrasonic nanocrystal surface modification on Pt-modified aluminide coatings of nickel-based alloys to form a surface nanostructure layer, which resulted in higher Al concentrations in the coating. Similar results had also been reported in previous works

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[17–19]. These studies indicated that surface refined-grains or surface nanocrystallization induced by SPD could effectively improve the atomic diffusivity and mechanical properties of diffusion layers. However, the industrial application of these methods to turbine blades is limited by their uncontrollability and the significant surface toughness deriving from the severe plastic deformation.

Laser shock peening (LSP) is one of the most commonly SPD methods and has been previously proposed as a technique to produce the surface nanocrystalline layer on nickel-based alloys, titanium alloys and stainless steels [20–30]. Compared with other surface mechanical treatment technologies, LSP has the advantages of not requiring contact with the substrate, of affecting a deep layer, and having excellent controllability. In addition, this technique results in a surface with lower toughness, making it applicable to complex aero-engine components [31]. In our previous works, we found that the surface nanostructure produced by LSP in nickel-based alloy has good thermal stability at 900 °C [24,25]. On the other hand, LSP can introduce compressive residual stress that improves the resistance to fatigue and hot corrosion [32–36]. Thus, laser shock peening is considered as one of the most promising methods for improving the atomic diffusion of Al in nickel-based alloy turbine blades.

In this work, we investigated the surface nanostructure produced by laser shock peening and the atomic diffusion of Al in a modified gas aluminizing process. The microstructure of the coatings was characterized and the effect of surface nanostructure on the gas aluminizing process was investigated. Moreover, the fatigue strength of the aluminide coatings was examined.

## 2. Experiments and methods

### 2.1. Materials

The experimental material is the K417 nickel-based cast alloy, which has been broadly applied in aero-engine turbine blades due to its excellent fatigue, corrosion and creep resistance. It mainly consists of $\gamma$ solid solution, strengthening phase $\gamma'$ and ($\gamma + \gamma'$) eutectic, as shown in Fig. 1a. To further justify the presence of the $\gamma$ and $\gamma'$ phases, TEM observation was adopted, as shown in Fig. 1b and c. The nominal chemical composition is listed in Table 1 and the atomic scale structure of $\gamma$ and $\gamma'$ phases can be seen in reference [36]. The alloy elements, such as Co, Cr, Mo, V, play a positive role in solid solution strengthening; the precipitation phase can be formed by the additions of alloy elements, such as Ti and Al, which has precipitation strengthening effect; and the alloy elements, such as B, C and Zr, have a beneficial effect on the grain boundary strengthening.

### 2.2. Experimental process of LSP

To evaluate the effect of surface nanostructure on the gas aluminizing process, LSP treatment was adopted previously. Prior to LSP treatment, the samples surface was polished with SiC paper with the grit number from 500 to 2400, and then ultrasound cleaning in ethanol was used to degrease the surface of samples. The LSP procedure was performed on a Q-switched Nd:YAG laser designed by the company of TYRIDA, Xi'an, Shaanxi (SGR-EXTRA/25J). The corresponding experimental set-up and detail procedures were previously described in the literature [37]. A laser with the following listed parameters was used: energy is 10.8 J, pulse width is 20 ns, laser beam diameter is 3.4 mm, and power density is 6 GW/cm$^2$. In order to avoid the bend by one-sided LSP and improve the efficiency of LSP process, two-sided LSP was used on the standard vibration specimens. The paths of laser spots and LSP region are shown in Fig. 2.

### 2.3. Gas aluminizing process

Both the samples pre-treated or pre-untreated by LSP treatment were washed carefully using the acetone and absolute alcohol and then immediately being subjected to gas aluminizing treatment, carried out in a homemade device, as shown in Fig. 3. Gas aluminizing process was carried out in a special pit furnace with a pre-evacuated vacuum mechanical pump and the materials were embedded in a birdcage clamp. Al-Fe powder was used as infiltration agent, ammonium chloride ($NH_4Cl$) was used as activator and aluminum oxide ($Al_2O_3$) powder was used as filler. Subsequently, the samples were aluminized at high temperature condition. To avoid surface oxidation and ensure inert atmosphere conditions during the whole process duration, the furnace was vacuumed to $10^{-3}$ mbar and then filled with argon. The process was carried out at 900 °C + 10 °C and lasted 2 h.

### 2.4. Microstructural observations

The phase analysis of aluminide coatings was characterized by MFS-7000 X-ray diffraction (XRD) equipment with Cu-kα radiation ($\lambda = 1.5406$ nm), operated at a voltage of 50 kV, a current of 40 mA and a take-off angle of 6°. The diffraction data were collected over a $2\theta$ range of 20°–100°, with a step width of 0.02°. The grain sizes and integrated areas for β-phase and δ-phase diffraction peaks in the XRD spectra were determined by using the MDI Jade 6 software.

To precisely characterize the surface microstructure of K417 nickel-based alloy after LSP treatment, transmission electron microscopy (TEM) observation was used. TEM was performed in JEM 2100F with the experimental parameters: FEG (field emission gun): 200 kV; point resolution: 0.23 nm and line resolution: 0.14 nm. The thin foils for TEM observations were cut by electro-spark discharge from the surface layer with a thickness of 1 mm, then mechanically grinded on the untreated sides to obtain thin plates with a thickness of about 20 μm, and finally single electro-polished from the untreated side. Microstructural morphological images were observed by JEOL/JSM-6360LV scanning

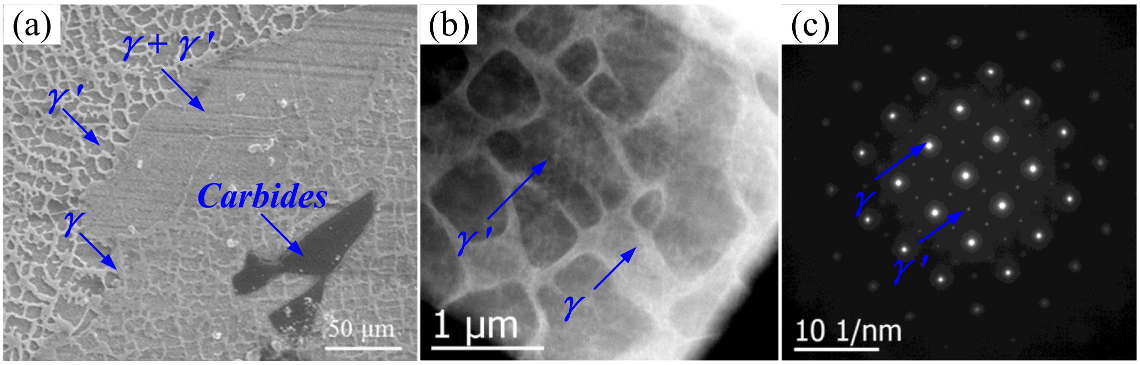

**Fig. 1.** Surface microstructure in the substrate of K417 nickel-based alloy. (a) SEM image, (b) TEM image and (c) the corresponding SAED image of (b).