1. Introduction

Thermally sprayed ceramics coatings are widely used for structural components where high abrasion and heat resistance are required. Therefore, it is very important to elucidate the fatigue behaviour of structures with ceramics coatings. In general, ceramics coatings are thermally sprayed by an atmospheric plasma spraying (APS) method. Recently, however, a high velocity oxygen fuel (HVOF) process is considered to be the alternative for thermal spraying of ceramics. Although the spraying temperature of HVOF is lower than APS, higher velocity of ceramics powder in HVOF could form denser coating than APS, which results in lower porosity, better adhesion and higher strength of coating [1-3]. The coating properties such as porosity, abrasion resistance, strength, hardness and so on have been studied [1-3], but the fatigue behaviour of material with ceramics coatings sprayed by HVOF has not been known. In this study, Al₂O₃ was thermally sprayed by HVOF on type 403 stainless steel to form coatings with two different coating thicknesses of 150µm and 300µm. Rotating bending fatigue tests were conducted in order to understand the effect of coating thickness on fatigue behaviour. Furthermore, the fatigue behaviour was compared with that of material with Al₂O₃ coating sprayed by conventional APS, and the effect of spraying process on fatigue behaviour was investigated.

2. Experimental procedures

The material used is type 403 martensitic stainless steel whose chemical composition (wt.%) is C: 0.14, Si: 0.42, Mn: 0.56, P: 0.028, S: 0.027, Ni: 0.28, Cr: 11.64, Fe: bal. As-received material was heat-treated at 1223K (950°C) for 30min followed by oil quenching. Subsequently, the material was tempered twice at 873K (600°C) for 30min. Hourglass-shaped fatigue specimens with a reduced section of 5.5 mm diameter were machined from the heat-treated material. Al₂O₃ powder was blasted on the specimen surface at room temperature before spraying process in order to achieve better adherence of coating to the substrate. After blasting, Al₂O₃ powder was thermally sprayed by HVOF or APS. The coating thicknesses, t_c, of 150µm and 300µm were evaluated.

Fatigue tests were preformed using cantilever-type rotating bending fatigue testing machine operating at a frequency of 19Hz in laboratory air. The smooth specimens without coating, which were mechanically polished by emery paper, and those blasted by Al₂O₃ powder were also fatigue tested for comparison.
3. Results and discussion

SEM micrographs showing the surface appearances of coatings are revealed in Fig.1. In the APS coating (Fig.1(a), (b)), microcracks, which were formed due to the rapid cooling during solidification, are recognized in Fig.1(b). In the HVOF coating (Fig.1(c)), Al₂O₃ powders are seen because of the low temperature during spraying. Figure 2 shows the cross-sectional views of coatings. It is clear that the high velocity of powder results in lower porosity of HVOF coating than APS one.

Figures 3 and 4 represent the S-N diagrams characterized in terms of the stress including coating thickness, $\sigma_n$, and the stress excluding coating thickness, $\sigma_s$, respectively. The fatigue limit of the blasted specimen is comparable to that of the smooth one. However, the blasted specimens exhibit lower fatigue strength in finite life region than the smooth ones. These results could be attributed to rougher surface and higher compressive residual stress near the surface in the blasted specimens. In Fig.3, the fatigue strengths of the coated specimens are lower than those of the substrate, and decreases with increasing coating thickness. On the other hand, in Fig.4, the fatigue strengths of the coated specimens are improved compared with the substrate, when the stress was calculated from the nominal diameter of the uncoated specimen. Exceptionally, the HVOF sprayed specimens with the coating thickness of 300µm exhibit significantly lower fatigue strength than the substrate.

The longitudinal cross sections of fatigue fractured samples were observed by SEM in order to clarify crack initiation behaviour. Figure 5 reveals the cross sectional views of the APSed and HVOF sprayed specimens with the coating thickness of 150µm. Those specimens were subjected to the fatigue loading of $\sigma_n=600\mathrm{MPa}$. In both specimens, fatigue cracks initiated in the substrate, without cracking in the coating. This suggests that the coatings bear fatigue loading successfully, resulting in higher fatigue strength than the substrate as shown in Fig.4. It should be noted that
small notches formed during blasting process acted as crack nuclei due to their stress concentration. In Fig.4, the HVOF sprayed specimens exhibited higher fatigue strength than the APS ones when the coating thickness is 150µm. This implies that the HVOF coating can bare fatigue loading more effectively than the APS one, because the HVOF coating was denser as shown in Fig.2.

The cross-sectional views of the APSed and HVOF sprayed specimens with the coating thickness of 300µm are shown in Fig.6. In the APSed specimen, crack initiated in the substrate (coating thickness of 150µm, $\sigma_n=600\text{MPa}$). (a) APS coating, (b) HVOF coating.

In Fig.4, the fatigue strengths of the APSed specimens whose coating thicknesses are 150µm and 300µm were comparable, indicating that the load bearing ability of the coating decreases with increasing coating thickness, which can be attributed to crackings of the coating observed in the thick coating (Fig.6(b)). It is known that the strength of ceramics has the size effect, where larger volume results in lower strength because the probability of defects to be in the volume could be larger. Consequently, thicker coating is cracked more easily, resulting in the lower load bearing ability. In the HVOF sprayed specimen, many cracks were observed in the coating (Fig.6(c)). Those cracks were also observed on the specimen surface at the early stage of fatigue life. The lowest fatigue life of the HVOF sprayed specimens with the coating thickness of 300µm (Fig.4) can be attributed to crackings of the coating at the early stage of fatigue life. The HVOF coating exhibits lower porosity, resulting in higher elastic modulus, and higher adherent
strength to the substrate than the APS coating. Therefore, it is concluded that thick HVOF coating cannot accommodate to the deformation of the substrate due to the high elastic modulus and high adherent strength, resulting in crackings of the coating.

4. Conclusions

In this study, Al₂O₃ was sprayed by HVOF or APS on type 403 stainless steel with two different coating thicknesses of 150µm and 300µm. Rotary bending fatigue tests were conducted and the effects of coating thickness and spraying process on fatigue behaviour were investigated. The main conclusions are summarized as follows.

1. The HVOF coating exhibited lower porosity and smaller number of microcracks than the APS coating.
2. The fatigue strengths of the coated specimens were lower than those of the substrate, and decreased with increasing coating thickness when stress was calculated including the coating thickness in the specimen diameter.
3. The fatigue strengths of the coated specimens were improved compared with the substrate, when stress was calculated from the nominal diameter of the uncoated specimen. Exceptionally, the HVOF sprayed specimens with the coating thickness of 300µm exhibited significantly lower fatigue strength.
4. Fatigue cracks initiated at small notches formed during blasting process regardless of coating thickness and spraying process.

5. References