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Effect of surface grinding on the strength of NiAl and Al_2O_3/NiAl composites

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Abstract

For structural applications, dimensional tolerance has to be controlled tightly. Surface grinding is thus frequently applied to match the requirement. For brittle material, improper surface grinding can degrade their strength considerably. In the present study, an alumina wheel and a diamond wheel were used to grind NiAl and Al_2O_3/NiAl composites. The surface quality, strength and toughness after grinding are investigated. Cracks are formed on the surface of NiAl ground with the alumina wheel. However, there is no crack found on the surface of NiAl ground with the diamond wheel. The strength of the NiAl machined with diamond wheel is three times that of the NiAl machined with alumina wheel. As Al_2O_3 particles are added into NiAl, the presence of weak Al_2O_3/NiAl interfaces limits the formation of large flaws. The strength of the Al_2O_3/NiAl composites is thus less sensitive to the grinding conditions. The present study demonstrates that the Al_2O_3/NiAl composites are tolerant to the surface grinding conditions.

Keywords: Grinding; NiAl; Composite

1. Introduction

The β-NiAl is a potential material for high-temperature applications [1,2]. Previous studies suggested that the toughness and strength of NiAl at room-temperature can be enhanced by adding ceramics inclusions [3,4]. For the Al_2O_3–NiAl system [3], the presence of Al_2O_3 inclusions limits the grain growth of NiAl. The strength of NiAl is thus increased. The Al_2O_3/NiAl interface in the composites is weak. The weak interfaces deviate the propagation of cracks. The toughness of NiAl is enhanced [3]. Therefore, the Al_2O_3/NiAl composites are potential candidates for structural applications.

During the manufacturing of structural components, surface grinding is frequently applied to match dimensional tolerance. However, improper grinding can result is surface cracks and sub-surface flaws [5,6]. For brittle materials, the presence of sub-surface flaws degrades their strength significantly. In the present study, Al_2O_3 particles are added into NiAl. The NiAl and Al_2O_3/NiAl composites are prepared by hot-pressing. The cost of alumina wheel is relatively low. Alumina wheel is thus frequently used to machine ductile metals. However, when the material to be machined is hard, such as ceramics, a diamond wheel is used. The intermetallic, such as NiAl, is not as hard as Al_2O_3; however, NiAl is brittle [1,2]. The machining behavior or NiAl has not been reported in the literature. Therefore, alumina and diamond wheels are both used in the present study. The effect of the grinding on the mechanical properties of NiAl and Al_2O_3/NiAl composites is investigated.

2. Experimental procedures

Nickel aluminide (β-Nial, Xform, New York) and 0–40 vol% alumina (α-Al_2O_3, TM-DR, Taimei Chem., Tokyo, Japan) were attrition milled together in ethyl alcohol. The milling time was 1 h. The grinding media used was zirconia balls. The slurry of powder mixtures was dried with a rotary evaporator. The dried lumps were crushed and passed through a plastic sieve with an aperture size of 74 μm. The sintering was performed by hot-pressing at 1450°C with a graphite die for 1 h. The pressure applied was 24.5 MPa. The vapor pressure during hot-pressing was kept below 5×10^{-3} torr. The dimensions of the hot-pressed specimen were 50 mm in diameter and roughly 4.5 mm in thickness.

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The hot-pressed specimens were cut into rectangular bars with a diamond saw. The surfaces of the rectangular bars were then ground longitudinally with a 120-mesh alumina wheel or a 325-mesh diamond wheel. The cutting depths were 5 μm per pass. The final dimensions of the specimens were $4 \times 3 \times 34\ mm^3$. The strength of the specimens was determined by the four-point bending technique at ambient conditions. The inner and outer spans were 10 mm and 30 mm, respectively. The loading rate was 0.5 mm/min. The fracture toughness was determined by the single-edge-notched-beam (SENB) technique. The notch was generated by cutting with a diamond saw. The size of the notch was roughly 1 mm in depth, which corresponds to one-third-to-one half of the thickness. Three to four specimens were used to determine the strength and toughness for each composition. The density was determined by the water displacement method. The polished surface was prepared by grinding with diamond slurry to 6 μm and polishing with silica suspension to 0.05 μm. The phase identification was performed by X-ray powder diffractometry (XRD). The microstructure was observed with optical microscopy (OM) and scanning electron microscopy (SEM). The size of NiAl grains was determined with the lineal intercept technique.

3. Results and discussion

The X-ray diffraction patterns indicate that no phases other than α-Al_2O_3 and ß-NiAl are produced after hot-pressing. The relative density and the grain size of NiAl of the specimens are shown in Table 1. The relative density of the composites is >98%. The microstructures of the NiAl and Al_2O_3/NiAl composites are shown in Fig. 1. Alumina particles are attached to the surface of NiAl particles after attrition milling [7]. The alumina grains are thus located at the grain boundaries of NiAl after hot-pressing [3]. The Al_2O_3 particles exert pinning force on the grain boundaries of NiAl. The grain growth of NiAl is thus prohibited. The electrical resistance of the Al_2O_3/NiAl composites has been measured by Tuan et al [3]. They suggested that NiAl grains are still interconnected, despite NiAl grains being surrounded by Al_2O_3 particles.

The ground surface of NiAl and Al_2O_3/NiAl composites are shown in Fig. 2. The specimens in Fig. 2 are ground with a diamond wheel. For the NiAl specimens, scratches can be observed on the surface. It indicates that plastic deformation and subsequent tearing are the dominant material-removing mechanisms. As Al_2O_3 is added into NiAl, scratches are decreased. The surfaces of NiAl and Al_2O_3/NiAl composites, after grinding with alumina wheel, are shown in Fig. 3. Beside scratches, large cracks can be observed on the surface of the NiAl specimen. As 20 vol% Al_2O_3 is added int NiAl, the width of the large cracks is decreased. For the 40% Al_2O_3/NiAl composite, no large crack is observed.

Table 1
The relative density and grain size of NiAl of the hot-pressed specimens

Composition	Relative density/%	Grain size of NiAl/ μm
NiAl	99.2	11.6
5% Al_2O_3/NiAl	98.9	9.5
10% Al_2O_3/NiAl	99.3	8.8
20% Al_2O_3	99.0	8.5
40% Al_2O_3/NiAl	98.9	8.2

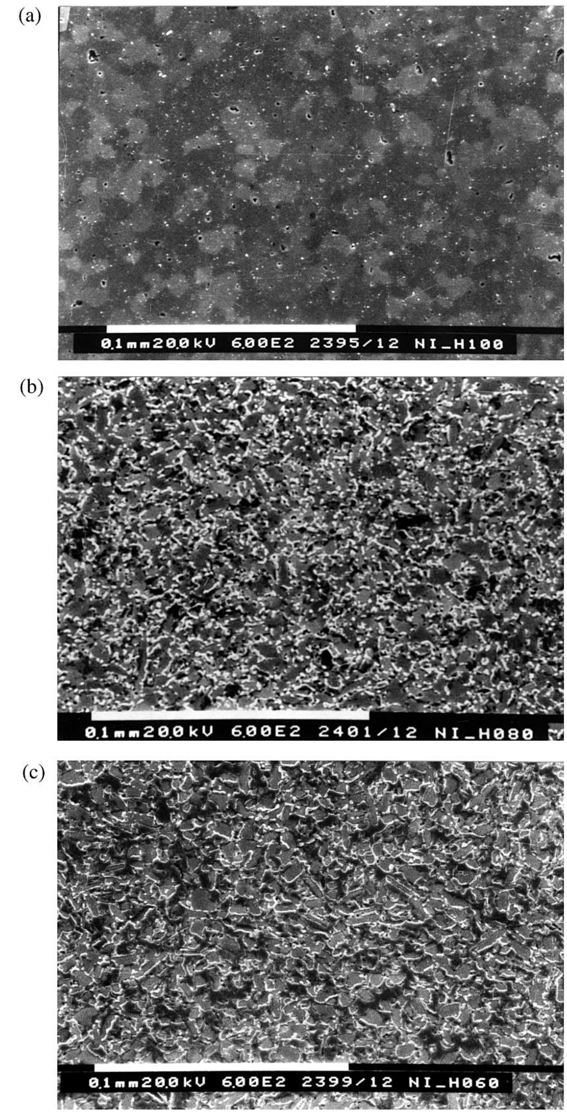

Fig. 1. Microstructures of the Al_2O_3/NiAl composites containing (a) 0, (b) 20 and (c) 40 vol% Al_2O_3.

The arithmetical average surface roughness height, R_a, and the maximum height of the surface profile, R_{max}, are shown as a function of Al_2O_3 content in Fig. 4. Although the grit sizes in the alumina and diamond wheels are different, the resulting average roughness is very close to one another. The maximum roughness of the 40% Al_2O_3 composite is close to the grain size of NiAl, Table 1. It indicates that the NiAl grains in the composite are pulled out from the surface

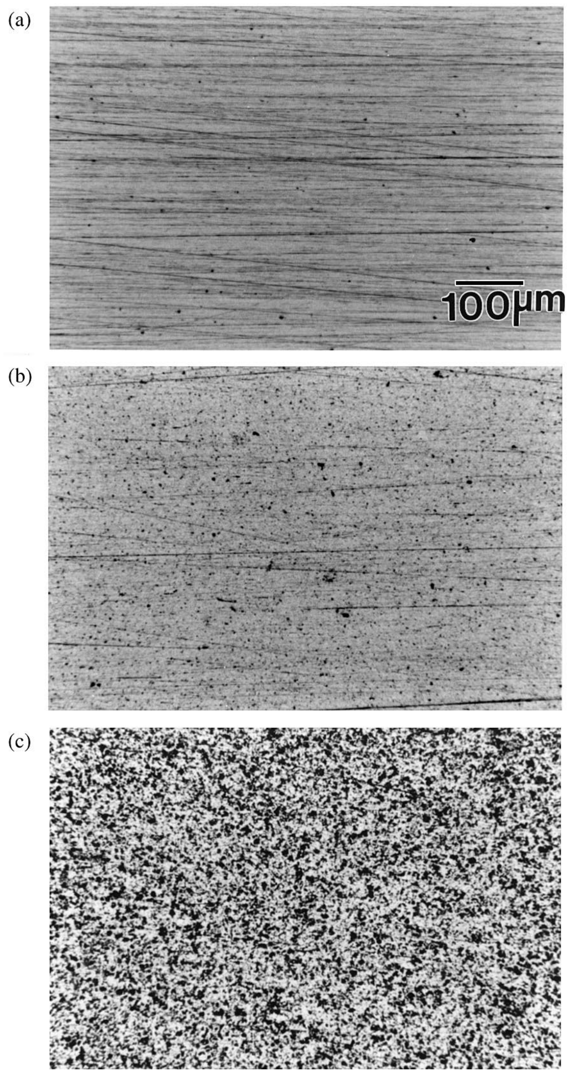

Fig. 2. The ground surface of the composites after grinding with 325-mesh diamond wheel. There are (a) 0, (b) 20 and (c) 40 vol% Al_2O_3 in the composites.

during grinding. Many pull-outs are observed on the surface of the composites, Fig. 3. Expect the 40% Al_2O_3 composite, the maximum roughness is smaller than the size of NiAl grains. From Figs. 2 and 3, it is seen that scratches are limited to the NiAl grains. Since Al_2O_3 is brittle, the Al_2O_3 grains are mainly removed by brittle fracture during grinding. It suggests that the material removing mechanism for composites is the combination of tearing of NiAl and brittle fracture of Al_2O_3.

The strength of the Al_2O_3/NiAl composites is shown as a function of Al_2O_3 content in Fig. 5. Fig. 5 suggests that the strength of NiAl depends strongly on the grinding conditions employed. For example, the strength of the NiAl machined with a diamond wheel is threefold that of the NiAl machined with an alumina wheel. As for the composites ground with alumina wheel, the strength is increased with the increase of Al_2O_3 content. As Al_2O_3 is added into NiAl, the strength difference between the composites

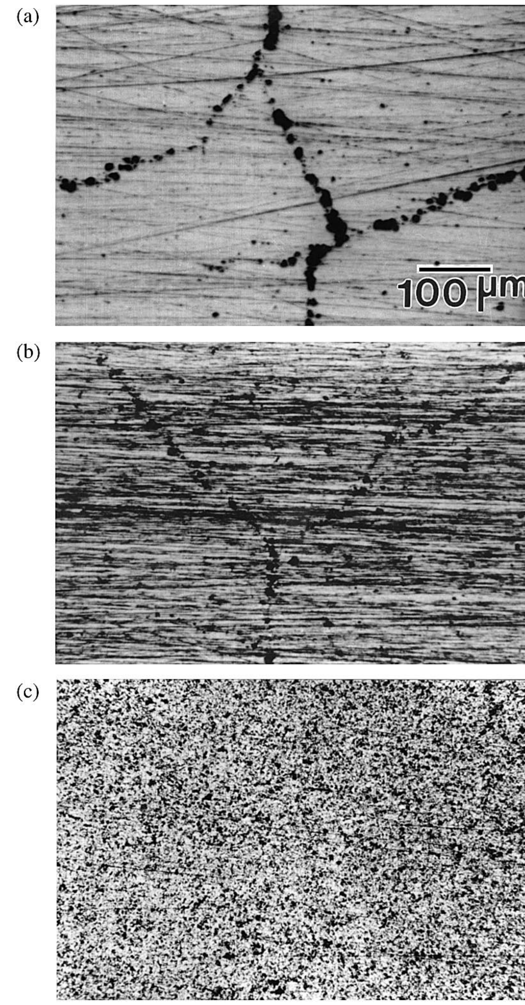

Fig. 3. The ground surface of the composites after grinding with 120-mesh alumina wheel. There are (a) 0, (b) 20 and (c) 40 vol% Al_2O_3 in the composites.

machined with diamond and alumina wheels is reduced. For the 40 vol% Al_2O_3 composite, the grinding condition has little effect on the resulting strength. The toughness of the Al_2O_3/NiAl composites is shown as a function of Al_2O_3 content in Fig. 6. The toughness of the specimens is less sensitive to the grinding condition.

For brittle materials, the failure is originated from their critical flaw. The size of critical flaw, C, can be estimated by using the Griffith law as [8]

$$\sqrt{C} = \frac{K_{IC}}{Y\sigma} \tag{1}$$

where σ is the strength, K_{IC} the toughness and Y a dimensionless constant. By knowing the values of strength and toughness, the size of critical flaw can be calculated from Eq. (1). The critical flaw sizes of NiAl and Al_2O_3/NiAl composites are shown as functions of Al_2O_3 content in Fig. 7. The size of critical flaw is much bigger than the surface roughness. The strength is thus determined by the sub-surface flaws. The flaws within the specimens are either

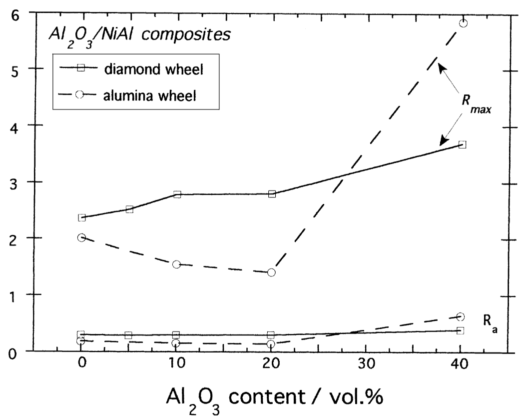

Fig. 4. The average surface toughness (R_a) and maximum roughness (R_{max}) of NiAl and Al_2O_3/NiAl composites as functions of Al_2O_3 content.

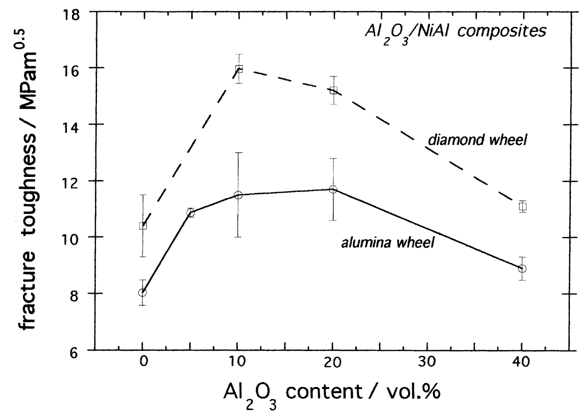

Fig. 6. The fracture toughnesses of NiAl and Al_2O_3/NiAl composites as functions of Al_2O_3 content.

originated from the processing stage or from the grinding stages. In the present study, the specimens are prepared by hot-pressing. As the Al_2O_3 content is the same, the size of the flaws formed during the processing stage should be very similar. For the 40% Al_2O_3/NiAl composite, the size of critical flaw is independent of grinding conditions. This suggests that the critical flaw in the 40% Al_2O_3 composites is formed during the processing stage. The critical flaw size of the NiAl ground with an alumina wheel is much larger than that of the NiAl ground with a diamond wheel. It indicates that the critical flaw in the NiAl ground with alumina wheel is formed during the grinding stage. The size of the critical flaw in the composites ground with alumina wheel decreases with the increase of Al_2O_3 content. The strength of the composites is thus increased with the increase of Al_2O_3 content. For specimens ground with a diamond wheel, the flaw size is independent of the Al_2O_3 content. It indicates that the critical flaw in the specimens ground with diamond wheel is formed during the specimen preparation stage. No large flaw is generated during the grinding with diamond wheel.

The hardness of Al_2O_3 is higher than that of NiAl [3]. Therefore, the alumina wheel should be able to grind the surface of NiAl. However, the size of alumina grit is larger than that of diamond grits. Furthermore, the hardness of alumina is lower than that of diamond. The grinding force during machining while using the alumina wheel is thus larger than that while using the diamond wheel. Since NiAl is a brittle material, a larger grinding force can induce a larger sub-surface flaw [9], as shown in Fig. 8(a). The presence of flaws reduces the strength of NiAl significantly. As Al_2O_3 is added into NiAl, weak Al_2O_3/NiAl interfaces are presented in the composites [3]. During machining, the sub-surface flaw is deflected along the weak interfaces. The propagation of crack is thus twisted along the interface, Fig. 8(b). No long, straight crack is formed. The strength is determined by the largest flaw. As no large flaw is formed during grinding, the strength of Al_2O_3/NiAl composites is less affected by the grinding conditions employed.

The notch in the SENB specimens is around 1000 μm. The notch is much larger than the size of critical flaw. The toughness should thus be independent of the grinding

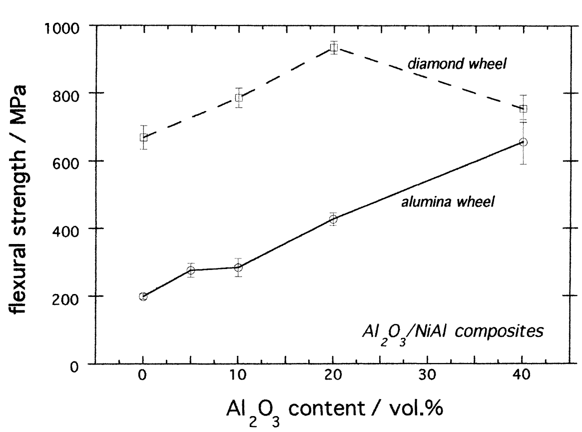

Fig. 5. The flexural strength of NiAl and Al_2O_3/NiAl composites as functions of Al_2O_3 content.

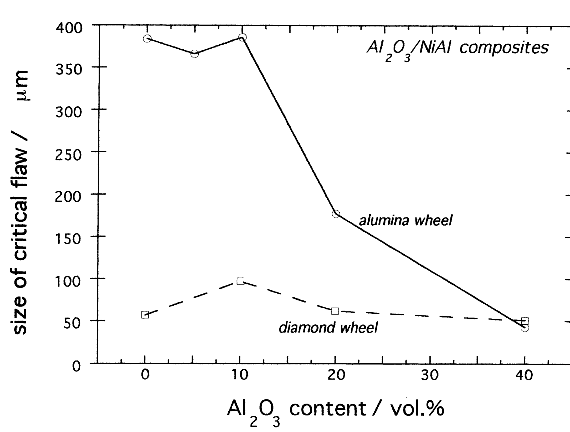

Fig. 7. The sizes of critical flaws in NiAl and Al_2O_3/NiAl composites as functions of Al_2O_3 content.

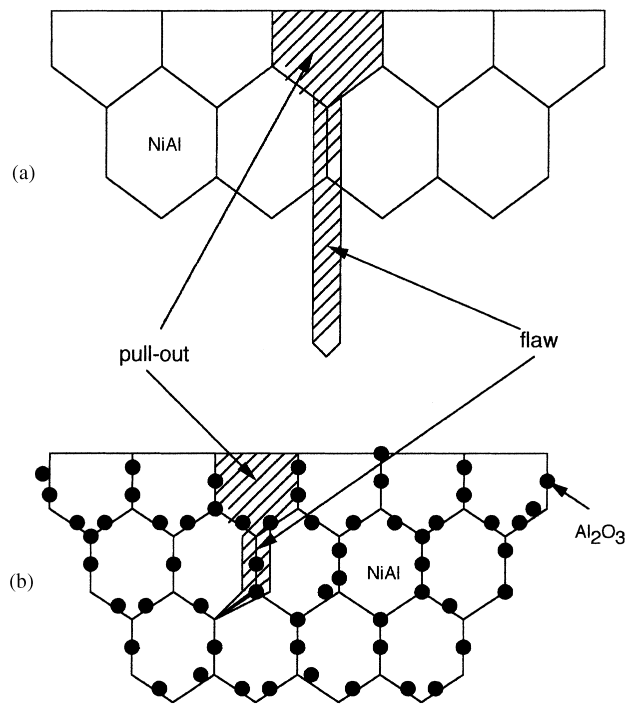

Fig. 8. Schematic diagrams for the formation of flaws during the grinding of (a) NiAl and (b) Al_2O_3/NiAl composites.

condition. However, the toughness of the specimens ground with the diamond wheel is slightly higher than that of the specimens ground with the diamond wheel. The grinding process can induce residual stresses near the surface region [10,11]. A higher contact force during grinding can induce higher residual stresses. The four surfaces of the testing bars were all ground before the notch is introduced. The presence of residual stresses affects the resulting values of fracture toughness. The toughness of the specimens ground with the alumina wheel is thus lower than that of specimens ground with the diamond wheel.

4. Conclusions

In the present study, the effect of surface grinding on NiAl and Al_2O_3/NiAl composites is investigated. Since the grinding force applied by the alumina wheel is larger than that applied by the diamond wheel, sub-surface flaws are formed in NiAl specimens after machining with the alumina wheel. Nevertheless, no cracks are formed in the NiAl specimens ground with the diamond wheel. The strength of the NiAl specimen ground with the diamond wheel is, therefore, three times that of the NiAl specimens ground with the alumina wheel. As Al_2O_3 is added into NiAl, the formation of a long crack is limited by the presence of the weak interfaces. The strength of Al_2O_3/NiAl composites is thus less sensitive to the machining conditions.

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