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Mechanism of shape recovery phenomenon of work material in cutting of NiTi alloy

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Abstract
In this study, the shape recovery phenomenon of the NiTi alloy work material during its cutting process was observed using a high-speed camera. The shape recovery in terms of the radius was measured, and the mechanism of this phenomenon was investigated by X-ray diffraction (XRD). Observation results from the high-speed camera demonstrated that during the cutting process, the NiTi work material recovered naturally. The shape recovery measurement results showed that at relatively low cutting speeds, the shape recovery of the NiTi work material decreased with an increase in the cutting speed, whereas there was almost no shape recovery at the highest cutting speed. The XRD results indicated that the phase state of the work material transformed after cutting at a relatively low cutting speed; however, there was no obvious phase transformation in the work material after cutting at the highest cutting speed. Therefore, it can be concluded that in cutting of the NiTi alloy, the shape recovery phenomenon of the work material is caused by the phase transformation, and increasing the cutting speed could decrease the shape recovery of the NiTi work material.

NiTi alloy, super elasticity, phase transformation, shape recovery

1. Introduction

In recent years, NiTi alloys have been used in a wide range of engineering applications in various fields such as mechanical parts and household appliances, owing to their unique functional properties, such as the shape memory effect and super elasticity. In the austenite phase state, the NiTi alloy undergoes a phase transformation from austenite to stress-induced martensite when loaded, and a reverse phase transformation from stress-induced martensite to austenite when unloaded. Owing to this reversible phase transformation, the NiTi alloy can recover a strain of up to 8% which is quite large when compared to other metallic materials [1]. Additionally, it is also an excellent engineering material for biomedical devices owing to its good biocompatibility and corrosion resistance. Cutting is used to form the final shapes of NiTi products; however, research has reported difficulties in cutting NiTi alloys, such as the rapid wearing out of cutting tools, high cutting force requirements, and poor chip breakability [2, 3].

It has also been reported that when cutting NiTi alloys, a unique phenomenon was observed, in which chips were discharged and cutting forces were detected continuously after stopping the feed when the cutting tool was not withdrawn from the work material. This phenomenon was thought to be caused by the recovery of the NiTi work material, and deteriorated the dimension accuracy in cutting of NiTi alloys [4]. In this study, the shape recovery phenomenon of the NiTi work material during cutting was observed using a high-speed camera, and the shape recovery was measured under several selected cutting speed conditions. Moreover, the corresponding phase transformation of the NiTi work material after cutting was observed by XRD. Results showed that this phenomenon was caused by the phase transformation, and increasing the cutting speed could decrease the shape recovery of the NiTi work material.

2. Work material and experimental procedures

The work material used in this study was the $Ni_{56}Ti_{44}$ (wt.%) alloy in the form of a disk with a diameter of 78 mm and thickness of 2 mm. The phase transformation temperatures of the work material were determined using differential scanning calorimetry responses where the M_S, M_f, A_S and A_f temperatures were determined as −23.6 °C, −41.2 °C, −17.9 °C, and −2.5 °C respectively. Before the cutting experiments, the work material was in austenite state at room temperature and was super elastic. Cutting experiments were also conducted for the Ti-6Al-4V work material with the same shape under the same cutting conditions for comparison with the NiTi alloy.

The cutting experiments were conducted by orthogonal cutting on an OKUMA general purpose lathe. The cutting insert used was TPGN160304 grade K10 non-coated cemented carbide with an edge radius of approximately 4 µm. The rake angle and clearance angle of the cutting tool were 5° and 6° respectively. Cutting speeds of 10 m/min, 25 m/min, 50 m/min, and 100 m/min, and a feed rate of 0.05 mm/rev were used. The cutting width was 2 mm, which was the same to the thickness of the work material disks. All cutting experiments were performed in dry conditions at room temperature.

The images of the cutting point were captured by a high-speed camera at a frame rate of 10000 frames/s. The theoretical decrease in radius was calculated by the feed rate and cutting time, whereas the actual decrease in the radius was measured by a micrometer. The difference between these reductions was calculated as the radius recovery. To observe the phase transformation of the NiTi work material, XRD measurements were conducted on the machined surface of the work material. A multipurpose XRD system with a Cu-Kα radiation source operated at 40 KV and 40 mA was used for this purpose. The diffraction angle was set from 30° to 50°, and the sampling and scan speeds were 0.02° and 2°/min respectively.

3. Results and discussions

3.1. Shape recovery of NiTi work material

Figure 1 shows the images of the unmachined surface near the cutting point during cutting for both the NiTi alloy and Ti-6Al-4V alloy at a cutting speed of 25 m/min. Compared with Ti-6Al-4V, there was an obvious concave deformation on the unmachined surface of the NiTi work material. Figure 2 shows the images of the machined surface at the same cutting speed. Similarly, an obvious concave deformation was observed on the machined surface of the NiTi work material near the cutting point. Additionally, the shape of the NiTi work material that was far from the cutting point recovered with the rotation of the work material. Figure 3 shows the radius recovery measurement results of the NiTi work material. There was a slight decrease in the shape recovery of the NiTi work material when the cutting speed increased from 10 m/min to 50 m/min; however, the shape recovery decreased to almost 0 when the cutting speed increased to 100 m/min.

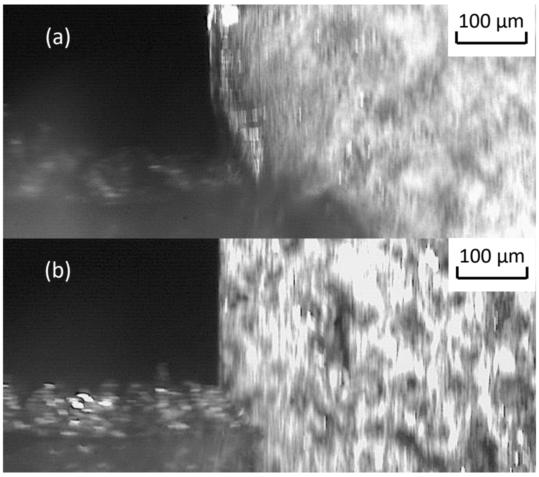

Figure 1. Images of the unmachined surface of (a) NiTi and (b) Ti-6Al-4V work materials at a cutting speed of 25 m/min

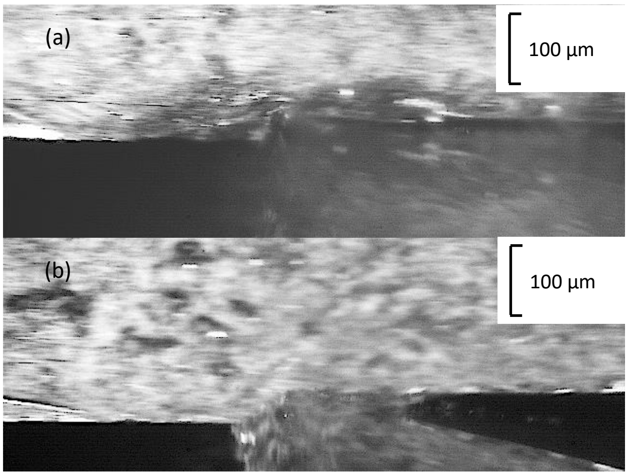

Figure 2. Images of the machined surface of the (a) NiTi and (b) Ti-6Al-4V work material at a cutting speed of 25 m/min

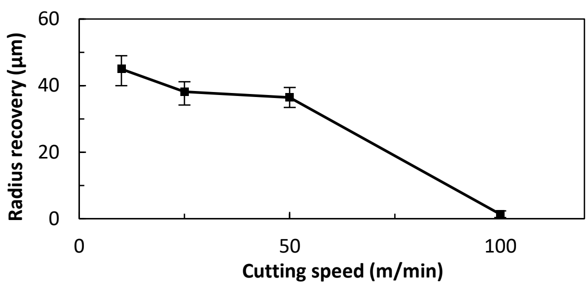

Figure 3. Radius recovery of the NiTi work material

3.2. Phase transformation of NiTi work material

The XRD patterns of the as-received NiTi alloy and the work material after cutting are shown in Figure 4. There was an obvious diffraction peak at 42.5°, which is typical for the diffraction peak of the (110) crystal plane of the austenite (B2) phase. In addition to this diffraction peak, at cutting speeds of 10 m/min, 25 m/min, and 50 m/min, another peak was observed in the XRD pattern of the work material near the diffraction angle of 40°. This peak could be attributed to the (002) crystal plane of the martensite (B19') phase. However, only the B2 peak was observed after increasing the cutting speed to 100 m/min. This shows that after cutting at relatively low cutting speeds, martensite and austenite phases coexist in the work material. This could be attributed to the stress-induced transformation of the NiTi alloy from austenite to stress-induced martensite during cutting. However, after cutting, not all martensite phases transform reversely to austenite due to plastic deformation. At the highest cutting speed 100 m/min, the NiTi work material did not undergo any form of phase transformation because the temperature of the work material near the machined surface exceeded the M_d temperature, which has been reported as the threshold temperature for phase transformation [5, 6].

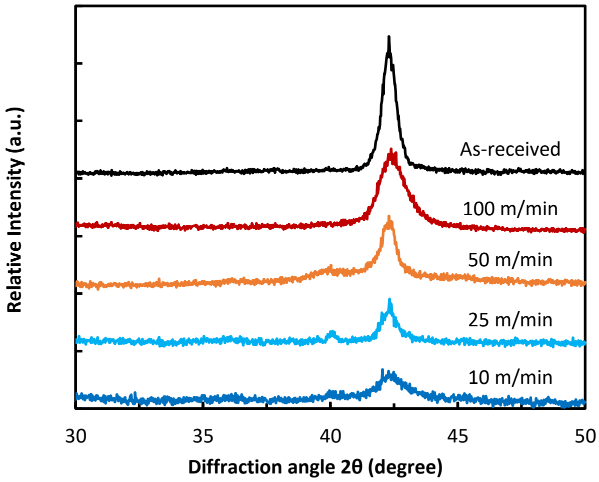

Figure 4. XRD pattern of the NiTi work material

4. Conclusion

During cutting at relatively low cutting speed conditions, there is an obvious shape recovery of the NiTi work material because the material undergoes a reversible phase transformation. When the cutting speed increase to a certain extent where the temperature of the work material exceeds the M_d temperature, the work material does not undergo any form of phase transformation during cutting; thus, there is no any obvious shape recovery of the NiTi work material. Therefore, it can be concluded that the shape recovery phenomenon of the NiTi work material is caused by the phase transformation. Moreover, cutting at relatively high cutting speed conditions could improve the dimension accuracy in cutting NiTi alloys.

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