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Investigation of superelastic behavior of NiTi alloy during cutting process

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Abstract

In this study, the superelastic behavior of NiTi alloy during orthogonal cutting process was investigated by digital image correlation (DIC) analysis and finite element method (FEM) analysis. The formation and disappearance of twins was confirmed from the observations recorded by a high-speed camera, thus confirming superplastic behavior during cutting process of the alloy. Furthermore, the superelastic area in the alloy during cutting was obtained from the results of DIC and FEM analyses.

NiTi alloy, super elasticity, phase transformation, shape recovery

1. Introduction

In addition to biocompatibility, wear resistance, and high strength, NiTi alloys have unique mechanical characteristics such as superelasticity and shape memory properties. Owing to these properties, NiTi alloys are used in the fields of communications, medicine, and home appliances, and are expected to play an active role across various fields in the future. However, cutting NiTi alloys is extremely difficult; moreover, when it is machined, it causes problems such as severe shortening of tool life, low dimensional accuracy, and significant burring. However, there are only a few research reports on the cutting of NiTi alloys, and the cutting phenomenon has not been clarified till date [1]. Superelasticity is a phenomenon wherein a load is applied to an austenite phase (phase A) material to the extent it undergoes a phase transformation to a stress-induced martensite (SIM) phase, causing considerable deformation yet recovering its shape when the load is removed and the material returns to phase A. As the cutting edge is subjected to high pressure during the cutting process, the phase transformation described above is inferred to occur during the cutting of NiTi alloys, inducing superelasticity and affecting the cutting properties. In light of the above, to elucidate the cutting phenomena of NiTi alloys, examining the superelastic behavior of NiTi alloy during cutting is necessary. Therefore, in this study, NiTi alloy with superelastic properties and Ti alloy (Ti-6Al-4V) without superelastic properties were subjected to orthogonal cutting experiments. Their strain distribution were analyzed through the digital image correlation (DIC) method using images captured via a high-speed camera. In addition, the cutting simulation of NiTi alloy was conducted to obtain the temperature and stress distributions to derive the region where superelasticity is induced and they were compared with the strain analysis results.

2. Experimental and analytical methods

2.1. Strain distribution analysis by DIC

In this study, cast and hot-forged 56Ni-44Ti (wt%) alloy and Ti alloy were used as workpiece materials. The dynamic scanning calorimetry (DSC) measurement results showed that the end of A-phase transformation temperature of the NiTi alloy used in the experiment was −2.5°C; thus, the alloy was stable in A-phase under room temperature and showed superelasticity. Figure 1 shows the experimental setup. The tool used in the experiment had a rake angle of 5 degrees, a clearance angle of 6 degrees, and a cutting edge roundness of 2 µm. Cutting was performed at a cutting speed of 20 m/min, a depth of cut of 0.05, and a workpiece thickness of 2 mm. In this experiment, the workpiece materials were machined into thin plates (20 mm long, 50 mm wide, and 2 mm thick), and orthogonal cutting was performed using a orthogonal cutting machine (Shinkikai Giken Co., Ltd.), and the vicinity of the cutting point was photographed with a high-speed camera. Orthogonal cutting machine used in this experiment was developed to perform orthogonal cutting experiments. A carbide tool was used as the cutting tool, and a high-speed camera was used to film at a frame rate of 16,000 fps. Post this, using the analysis software GOM correlate, DIC was performed on the continuous images obtained through filming to analyze the strain distribution.

2.2 Cutting simulation of NiTi alloy

The FEM analysis software DEFORM was used for the cutting simulation of an A-phase NiTi alloy. The cutting conditions for the cutting simulation are the same as those of the DIC analysis described above and the tool was defined as rigid. The stress-strain curves used in the analysis were obtained by referring to the reports by Gupta et al. [2] and Adharapurapua et al. [3]. Other material properties shown in table 1 were also taken from general values for NiTi alloys.

3. Experimental and analytical results

Figure 2 shows the results of a compressive strain analysis in the x-direction using DIC for Ti and NiTi alloys. The Ti alloy shows strain only near the cutting point, while the NiTi alloy shows strain over a wide area in front of the cutting point. Figure 3

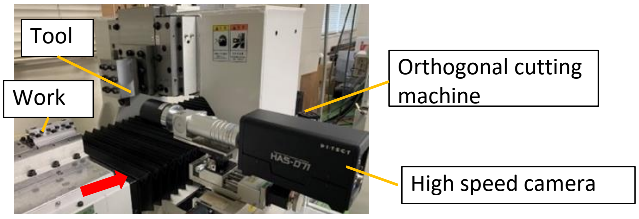

Figure 1. Experimental setup of orthogonal cutting

Table 1 Material properties of NiTi alloys used in FEM analysis

Young's modules (20C°)	75 GPa
Poisson's ratio	0.33
Thermal expansion coeficiente	11 µm/m･k
Heat transfer coefficient	18.0 W/m･K
Specific heat	837 J/kg･K
Emissivity	021
Mass density	6.45 g/cm^3

shows the temperature and stress distributions of NiTi alloy during cutting according to FEM analysis. NiTi alloys are known for their vanishing phase change to M-phase when the temperature exceeds approximately 150°C. That temperature is known as the Martensitic loss temperature [4]. When an applied stress to this material is between 490 and 882 MPa, superelastic deformation occurs due to the phase transformation from the A-phase to the M-phase. This stress is called superelastic stress. Based on the above properties, the condition for NiTi alloy to exhibit superelasticity is that the temperature must be below 150°C and the stress must be between 490 and 882 MPa. The region that satisfies this condition is shown in the green box in Figure 4, that region will show the area wherein the NiTi alloy exhibits its superelasticity. Here, as the interface of the twinned structure of an M-phase NiTi alloy is linear, when a phase transformation to M-phase occurs, it will produce a linear pattern. Figure 5 shows an image of the NiTi alloy being machined as captured by a high-speed camera. As the aforementioned straight-line pattern is generated in the white frame within the figure, it confirms that SIM phase transformation (superelasticity) occurs. Furthermore, the area wherein the M-phase transformation occurs is the superelastic region obtained by FEM analysis (in the yellow frame), indicating that the results of the experiment and FEM analysis are in agreement. Furthermore, from the time-lapse diagram of the high-speed camera shown in Figure 6, the twinned structure on this line appears during cutting (B) and disappears after the tool passes by (C). This also indicates that the twin structure shows superelasticity. Figure 7 shows the results of the strain analysis of the NiTi alloy by DIC superimposed on the superelastic region obtained via FEM analysis. The figure shows that the strains occur within the superelastic region obtained by FEM analysis, suggesting that the wide range of strains characteristic of the NiTi alloy is due to superelasticity. The wide range of strain in front of the cutting point is expected to have various effects on the machinability. In particular, the recovery of the strain after cutting will lead to tool wear and deterioration of dimensional accuracy owing to contact with the tool relief surface. These results suggest that superelasticity has considerable effect on machinability such as tool wear and dimensional accuracy.

4. Summary

In this study, we investigated superelastic behavior during cutting. The results confirmed that the NiTi alloy undergoes strain due to superelasticity in a wide area in front of the cutting point. In addition, martensitic transformation was observed in the superelastic region estimated via FEM analysis.

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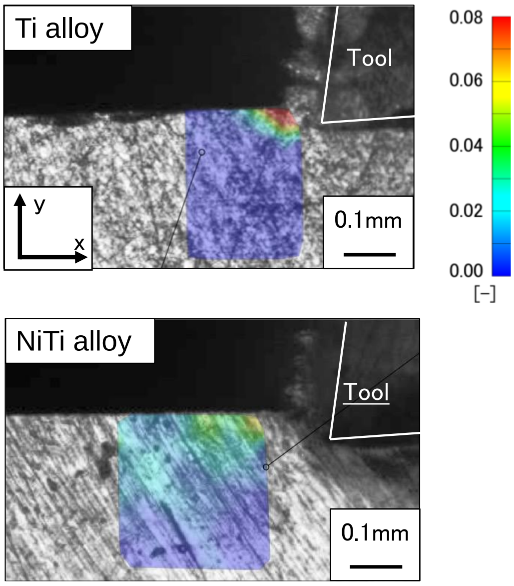

Figure 2. DIC analysis results for compressive strain in x-direction (upper: Ti alloy, lower: NiTi alloy)

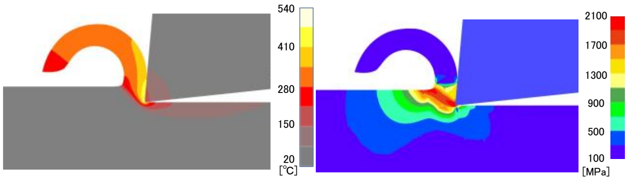

Figure 3. Temperature sistribution and stress distribution of NiTi alloy by FEM analysis

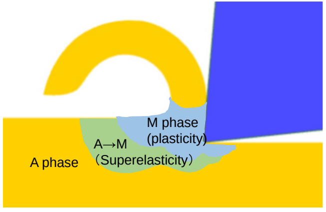

Figure 4. Temperature distribution (upper) and stress distribution (lower) by FEM analysis

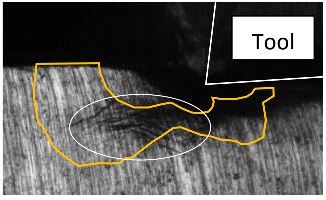

Figure 5. Martensitic Transformation of NiTi Alloy

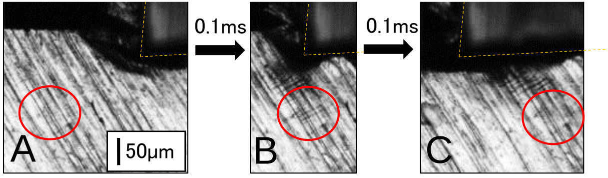

Figure 6. Appearance and Disappearance of Twinned structure

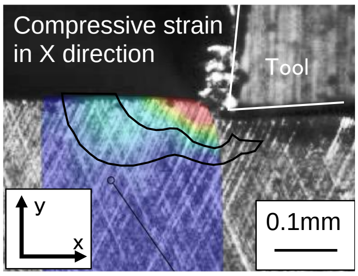

Figure 7. Comparison of the superelastic region between simulation and DIC analysis