Analysis of Tool-wear and Cutting Force Components in Dry, Preheated, and Cryogenic Machining of NiTi Shape Memory Alloys

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Abstract

The present study focuses on tool-wear behaviour and cutting forces in machining of NiTi shape memory alloys (SMAs) under various machining conditions, namely dry, preheated, and cryogenic cooling at three different cutting speeds. Obtained results show that cryogenic cooling plays a significant role on reducing notch wear at higher cutting speeds in comparison with machining under dry and preheated conditions. It is also found that cryogenic cooling substantially decreases the cutting force requirement compared with machining under dry and preheated conditions. Chip thickness is not significantly affected by machining conditions. Based on these experimental findings, cryogenic machining is considered a promising approach for improving machining performance of NiTi shape memory alloys.

Keywords: Cryogenic machining; NiTi shape memory alloys; tool-wear, phase transformation

1. Introduction

Application of shape memory alloys (SMAs) continue to increase as they are recognized as possible and better alternative design solutions for engineers facing new technical challenges. These alloys represent one type of several promising materials known as ‘active’ or ‘multifunctional’ materials [1]. With increased emphasis on, both reliability and multifunctionality in the aerospace industry, active materials are fast becoming an enabling technology capturing the attention of an increasing number of engineers and scientists worldwide [2]. However, one of the issues limiting aerospace applications of SMA technology is the lack of availability of suitable manufacturing and fabrication techniques [3].

Machining processes, in particular turning operations, are one of the important manufacturing techniques of actuators made of NiTi SMAs commonly used in the aerospace industry [4]. However, according to the literature, there are some difficulties in machining NiTi shape memory alloys such as extremely high tool-wear, particularly notch and flank wear, high cutting forces, poor chip breakability, etc., due to the high ductility and the high degree of work hardening of NiTi alloys during the machining process, and the unconventional stress-strain behavior of shape memory alloys [5, 6].

Identifying the difficulties in machining of NiTi shape memory alloys is a very significant first step as some researchers have already done [5, 6]; however, further steps need to be taken to develop improved approaches to resolve or reduce the difficulties faced in the machining of NiTi.

Since NiTi shape memory alloys are temperature-sensitive, difficult-to-machine materials, and the phase transformation temperatures of binary alloys are relatively low, the resulting effect of machining on the material’s thermo-mechanical response, especially due to high strain, strain-rate processes, is much more complex in comparison with other engineering materials. This study focuses on machining of NiTi shape memory alloys at low and high temperature cutting conditions.
through cryogenic machining and a preheated process, respectively. The major objective of this study is to identify the effect of temperature on two key machining performance measures, namely, tool-wear and cutting forces. In addition, the effect of dry cutting and the effect of cutting speed on selected performance criteria are also examined experimentally and compared.

2. Experimental Procedures

2.1. Work material

The material used in this study was a commercially available, Ni49.9 Ti50.1 (at %) alloy. The material was received as round bars of 10 mm diameter, in the hot-rolled/hot-drawn and hot-straightened condition. Cutting length in all machining experiments was 26 mm. The NiTi alloy was in its martensitic phase at room temperature as determined by Perkin Elmer Differential Scanning Calorimetry (DSC). The martensite start, martensite finish, austenite start and austenite finish temperatures were determined from Figure 1 to be 73, 49, 86 and 109 °C, respectively.

2.2. Cutting tools and machining parameters

A DCGT 11T308HP cutting tool insert, KC5410 grade with TiB2 coating, was used in the experiments. According to the tool manufacturer, KC5410 has a PVD TiB2 coating over a very deformation-resistant unalloyed substrate. The TiB2 coating is harder than TiN and TiAlN coatings and has an extremely smooth surface. This results in reduced surface friction, faster chip flow, and outstanding wear resistance. The substrate is unalloyed and fine-grained, and offers sharp edges, and excellent thermal deformation resistance [7]. Edge radius of the tool inserts used in the experiments was very consistent and varied between 18 to 20 µm. The tool holder was SDJCL 12 3B H5M. Machining experiments were conducted on a Mazak CNC turning center. In machining tests, constant feed rate, \( f = 0.1 \text{ mm/rev} \), and depth of cut, \( d = 0.5 \text{ mm} \), were used. Selected cutting speeds were 12.5, 25, and 50 m/min.

2.3. Machining conditions

The cryogenic coolant was liquid nitrogen (LN2), applied at 1.5 MPa pressure. Application of cryogenic cooling is shown in Figure 2. For preheating, a cryofurnace system - DMP CryoTemper - was used. The temperature range of the CryoTemper is -300 to 500 °F (approximately -185 to 260 °C). For the preheating process, the chosen temperature was 175 °C, which is well above \( A_f \) temperature of the work material. Our DSC test (Figure 1) confirms that at this temperature, the material is in the B2 austenite phase, and at room temperature it is the B19' martensite phase.

Tool-wear rate was measured using an optical microscope. Cutting force components were measured using a KISTLER 9121 three-component piezoelectric dynamometer.

3. Results

3.1. Tool-wear

In machining of difficult-to-machine aerospace materials, such as Ni-based and Ti-based alloys, controlling tool-wear plays a key role in improving machining performance and in turn reduces any adverse effect on the machining process. Since tool-wear is extremely rapid in machining NiTi, in comparison with machining of other engineering materials, the cutting tool reaches the end-of-life in a short time. Consequently, machining performance measures, such as force components, workpiece qualities, and surface

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As received

Applying LN2 from rake face

Applying LN2 from flank face

Fig. 1. Phase transformation temperatures of NiTi SMAs

Fig. 2. The liquid nitrogen delivery system with two nozzles placed at the tool rake face and the flank face
roughness, are affected by the rapid tool-wear. Although tool-life is an overall measure of machining performance, tool-wear rate as a function of cutting speed is the key machining parameter governing tool-wear. Consequently, it needs to be investigated to understand the wear mechanism(s) and establish feasible conditions where tool-wear is relatively easy to control. Therefore, tool-wear with varied cutting speeds in machining of NiTi shape memory alloys is investigated and presented in this work.

Figure 3 exhibits the tool-wear rate at the nose region of cutting tools under dry, preheated, and cryogenic cooling conditions at varied cutting speeds. The tool-wear at the nose region at low speed - 12.5 m/min - seems low and reasonable in all three conditions. However, increased cutting speed leads to significant increase in tool-wear at the nose region in dry and preheated conditions when compared with cryogenic machining.

Fig. 3. Tool-wear patterns at varying cutting speeds and cooling/preheated conditions (f = 0.1 mm/rev; d = 0.5 mm)

As seen in Figure 3, the dominant wear is notch wear at the depth of cut boundary region. Notch wear at the major and minor cutting edges is measured for each cutting condition. The measured maximum notch wear is presented in Figure 4, where it is evident that there is a remarkable difference among different machining conditions.

In particular, at the higher cutting speeds, cryogenic machining significantly reduces the notch wear in comparison with dry and preheated conditions. However, it must be noted that at the lowest cutting speed of 12.5 m/min, cryogenic machining produces the largest notch wear at the major cutting edge in comparison with dry and preheated conditions. Also, the variation of notch wear at the major and minor cutting edge is related to the chip flow direction.

Fig. 4. Comparison of notch wear with various cutting speeds and conditions (f = 0.1 mm/rev; d = 0.5 mm)

Numerous wear mechanisms are observed in cutting tools, including adhesive wear, abrasive wear, diffusion wear, fatigue, delamination wear, micro-chipping, gross fracture, and plastic deformation [8]. However, the dominant wear mechanism varies depending on the cutting conditions, cutting tool and work materials [8, 9]. The wear mechanism generally observed in machining Ni and Ti based alloys with carbide tools are diffusion [10, 11], adhesion [11, 12], and abrasion [11].

Figure 5 shows 3-D images of worn tools at 50 m/min cutting speed. Three different wear mechanisms can be seen. Abrasive wear is apparent in all three conditions. Deep grooves, on the flank surface and depth of cut boundary region can be clearly observed. These grooves are good indicators of the extreme abrasive wear mechanism.

Fig. 5. Wear patterns observed on the flank face of cutting tools under different conditions at 50 m/min
Chipping (flaking), particularly, in dry and preheated conditions, is a major problem (see Figures 3 and 5). It should be noted that in cryogenic machining at the chosen parameters, chipping was not observed.

Chipping flow damage was observed at high speed in preheated and dry conditions; however, cryogenic machining helped to eliminate chipping flow damage at these cutting conditions. The length of damage along the major cutting edge in preheated conditions is approximately 4.6 mm as shown in Figure 6.

Fig. 6. Typical pattern of chip flow damage (preheated, V = 50 m/min)

1.1. Cutting forces and chip thickness

Cutting force components (main cutting force, radial force, and feed force) are significant indicators of machining performance. Thus determining cutting force trends as influenced by the machining parameters and cooling/preheated conditions is helpful to understanding the cutting mechanism(s) of the work material. There is a well-established correlation between the cutting forces generated and lubrication in machining for most engineering materials, including hard-to-cut materials. Lubrication can get very close to the tool-chip and tool-workpiece interfaces, particularly the sliding contact areas. Therefore, it reduces friction and adhesion between the tool and workpiece and/or chip, which usually results in reduced force components in machining [13, 14]. Some studies emphasize that cryogenic cooling also reduces friction between cutting tool and chip [15]. However, the experimental findings show that cryogenic cooling lowers the cutting temperature, and makes the workpiece material stronger and harder, which results in increasing force components in machining of Ti-6Al-4V [15]. In contrast, other studies actually report that cryogenic cooling reduces some force components [16, 17]. It has also been shown that a preferred method to improve machining performance with reduced forces is laser-assisted machining (LAM) [18, 19], which is used to increase the temperature and thus reduce the yield strength of the workpiece.

This study provides the recorded cutting forces as a function of varied cutting speed under cryogenic cooling, preheated, and dry cutting conditions. The effect of cutting speed on force components is evident in all three conditions. Figure 7 shows the recorded main cutting force under dry, cryogenic, and preheated conditions at various cutting speeds. In dry cutting conditions, main cutting force was slightly influenced by the cutting speed, and shows an increasing trend. Also, in machining of preheated samples, the main cutting force increases with increasing cutting speed.

Fig. 7. Variation of main cutting force with cutting speeds and cooling/preheated conditions (f = 0.1 mm/rev; d = 0.5 mm)

However, the main cutting force decreases with increasing cutting speeds in cryogenic machining, as opposed to dry and preheated conditions. Similar trends in the dry and preheated conditions, except some small variation, are observed with the radial and feed force components, as seen in Figures 8 and 9, respectively.

Fig. 8. Variation of radial force with cutting speeds and cooling/preheated conditions (f = 0.1 mm/rev; d = 0.5 mm)

Fig. 9. Variation of feed force with cutting speeds and cooling/preheated conditions (f = 0.1 mm/rev; d = 0.5 mm)
In cryogenic machining, radial and feed force components slightly increase at 50 m/min cutting speed in comparison with 25 m/min cutting speed. Increasing force components with increased speed is attributed to significantly increased tool-wear, which was discussed in the previous section. In addition to cutting speed effect, machining conditions also significantly influence the generated force components. Quite notably, cryogenic machining, within the selected cutting conditions, always generates lower force components in comparison with dry and preheated conditions. An interesting finding in this research is the recorded force components in preheated conditions. Preheated machining almost always generates the highest force components in comparison with dry and cryogenic machining. Since there is a significant temperature difference between cryogenic machining and machining with preheating, chip thickness needs to be analyzed to identify whether the response of material to temperature variation influences the trend of generated force due to shrinkage or expansion of work material. Image of chips generated under different conditions at 12.5 m/min is illustrated in Figure 10.

Fig. 10. Image of chips generated under different cooling/preheated conditions ($V = 12.5$ m/min, $f = 0.1$ mm/rev)

Measured chip thickness as a function of cutting speed is illustrated in Figure 11. As seen, different conditions (dry, cryogenic, and preheated) did not significantly alter the chip thickness. However, the effect of cutting speed on chip thickness variation is apparent with its decreasing trend, consistent with other materials.

4. Discussion

Our experimental work shows that in machining of NiTi shape memory alloys, the major problem is rapid tool-wear, in particular, notch wear, similar to machining of other Ni and Ti based aerospace alloys. However, the major difference between NiTi shape memory alloys and other Ni and Ti based high temperature alloys is the solid-state phase transformation that occurs just above room temperature, which appears to significantly influence the machining performance. Controlling the phase transformation will play an important role in improving the machining performance of NiTi shape memory alloys. This can be done through controlling the temperature of the work material and cutting temperature, which in turn influences the “yield” stress of this material. The most favourable temperature for machining is usually one where the yield strength is reduced. For NiTi, this is just below the austenite start temperature, where the material’s yield strength is a minimum [20]. However, when temperature exceeds the austenite finish temperature, the yield strength of material increases very dramatically [20]. In addition, ductility and brittleness depend on the phase of this material. These are key points, which can help us interpret the experimental findings. Lowered flow strength with the lower temperature during cryogenic machining helped make deformation of the material easier thus reducing the tool notch wear. In contrast, dry and preheated machining conditions promote formation of the austenite phase, which has a much higher yield strength, which results in increased tool-wear.

This analysis can be extended by examining the obtained force components. As mentioned in previously, heating the work sample usually reduces the cutting force components due to a reduced flow stress [18, 19]. However, in our experiments preheating condition significantly increased not only the force components, but also the tool-wear, which is in contrast to these previous studies for a different work material [18, 19]. In our case, by heating the work material, the NiTi’s phase is changed concurrent with dramatic changes in mechanical behaviour [20], which result in an increase in both the force components during machining and ultimately tool wear.

The current study shows that, in addition to machining parameters and conditions, solid-state phase transformation has a significant effect on machining
performance measures such as tool-wear rate and cutting forces in machining of NiTi shape memory alloys. Therefore, it is proposed that through modeling and simulation of the machining process, supported by validation, reduced tool-wear and cutting forces can be achieved.

5. Conclusion

This work shows the effect of machining conditions (dry, preheated, and cryogenic) and cutting speed on the machining performance of a NiTi shape memory alloy. The following conclusions can be drawn from this study:

- The solid-state martensitic phase transformation, which provides shape memory alloys with their unique functional properties, plays a vital role on the machining performance measures such as cutting forces and the tool-wear rate.
- Controlling the phase of the NiTi during machining can make a substantial contribution to improving the performance of the cutting tool with a significant reduction in tool-wear when machining proceeds in the martensitic state.
- Machining of NiTi in the martensite state leads to a reduction in force components, which is achieved through cryogenic machining.
- Chip thickness is not significantly influenced by the active phase of the work material during the machining process.

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