Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 45 (2016) 207 – 210
www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

Effects of Chilled Air on Machinability of *NiTi* Shape Memory Alloy

Zainal A Zailani[a,b*] and Paul T Mativenga[a]

[a]*School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, United Kingdom*
[b]*School of Manufacturing Engineering, Universiti Malaysia Perlis, Perlis 02600, Malaysia*

* Corresponding author. Tel.:+ 44 161 306 3821; fax: +44 161 306 3803. *E-mail address:* zailani.zainalabidin@manchester.ac.uk

---

Abstract

Nickel titanium (NiTi) shape memory alloys show reversible diffusionless transition between phases, resulting in special properties and applications. They are ductile, temperature sensitive and their machinability is a major challenge. A new approach to improve their machinability was investigated through the application of chilled air. The temperature phase transformation of the workpiece was characterised by differential scanning calorimetry and micro-milling cutting tests were then undertaken using chilled air, minimum quantity lubricant and a mixture of both. Results showed that the application of chilled air, homogenised the dendritic structure of the workpiece, lower cutting forces and reduced burr height. Simultaneous use of chilled air and minimum quantity lubricant (MQL) showed significant potential for tool wear, burr size reduction and better surface finish.

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

Keywords: Micro machining; Nickel titanium alloys; Chilled air, Minimum quantity lubricant

---

1. Introduction

1.1. NiTi SMAs and their machinability

Shape Memory Alloys (SMAs) are materials, which when deformed by applying an external force, will recover to their original form when heated beyond a certain temperature either by external or internal heating; or other relevant stimuli such as a magnetic field [1]. Nickel titanium based alloys (*NiTi*) are the most widely used groups of SMAs due to their additional advantages such as biocompatibility, high ductility, high strength to weight ratio, good fatigue and corrosion resistance, and high damping capacities [2]. They are very appealing to medical and industrial engineering applications.

NiTi shape memory alloys are difficult to mechanically machine due to, among other factors, their high ductility, temperature sensitivity and strong work hardening [3]. Phase transformation is one of the major challenges. When a nickel titanium alloy is heated, it transforms from martensite into the austenite phase. Austenite is relatively harder and has a much higher Young's modulus. While the martensite structure, is softer and more malleable [1]. It was reported that when machining nickel titanium alloys large amounts of the material are not separated from the work-piece and appear as several layers of material or burrs [3,4] and the associated tool wear is high [5]. Micro machining, is more challenging due to the size effect, which drives material springback for ductile phases, and ploughing effects when undeformed chip thickness is comparable to the cutting edge radius or lower. Moreover, when multiphase materials are machined at the microscale, differential response of phases to cutting influences cutting forces and burr formation on grain boundaries. The fragile nature of micro tools makes tool breakage at critical constraint [6].

To-date, there is limited or no scientific enquiry on the effectiveness of chilled air systems in improving the

Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)
doi:10.1016/j.procir.2016.02.156

machinability of nickel titanium alloys. The hypothesis for this study was that effective cooling delivered by chilled air systems can help prevent the transition from martensite to austenite and hence improve the machinability of nickel-titanium SMAs. Cutting tests were defined as set below to test this hypothesis.

2. Experimental Details

2.1. Work material

The workpiece material was nickel titanium shape memory alloy block. The composition of alloy matrix of nickel to titanium was confirmed by scanning electron microscopy and Energy Dispersive X-ray Analysis (EDXA) measurement to be 55 to 45 wt% respectively. The material was 80 mm length, 20 mm width and 15 mm height in dimensions. The hardness was measured to be on average 214.2 HV with a standard deviation of 1.86.

To evaluate the material response to thermal loads, Differential Scanning Calorimetry (DSC) was used. The machine used was a TA Instruments Q100 Differential Scanning Calorimeter. The test involved a cooling-heating-cooling method in the range between -20°C and 150°C. A calorimetric diagram, Figure 1, was produced for the study of the phase transformation and the determination of the critical transformation temperatures. The temperatures for the start of transformation to martensite (martensite start), end of transformation to martensite (martensite finish), start of transformation to austenite (austenite start) and end of transformation to austenite (austenite finish) were characterised to be 37.85, -1.39, 39.90 and 73.84°C, respectively. These are the hump transition points of the curve as shown in Figure 1. This implies that the nickel titanium alloy was in martensitic phase at room temperature. The aim is to use the chilled air to keep the material at low temperatures so that it does not enter the austenite start phase.

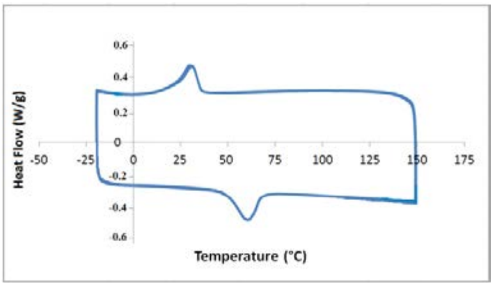

Fig. 1. Phase transformation temperatures of nickel titanium alloy (55:45 wt %) shape memory alloys.

To observe the microstructure, as-received and machine samples were ground with different grit of abrasive paper from 600 to 2400 and polished with 6, 3 and 1 microns diamond slurry monocrystalline paste. Then, the sample was etched using solution of 3.2% of hydrofluoric acid (HF), 14.6% nitric acid (HNO_3) and 82.2% of de-ionised water for 10 seconds. Essential safety precautions were taken. HF and HNO_3 can cause serious injuries, e.g. fatalities, skin burn and eye damage if swallowed, inhaled and in contact with skin.

2.2. Cutting tools and machining conditions

The cutting tool selected was 2-flutes fine grain solid carbide end mill cutter of 0.5 mm diameter coated with AlTiN. The flat end mill cutter was selected to ensure easier tool wear measurement. A zero rake angle was chosen to increase the strength of the cutting edge and minimise the effect of tool wear since a pilot study had been conducted using positive rake angle cutting tools and the results showed rapid tool wear and chipping. All micro tools were inspected using Quanta 200 SEM to examine their geometry and cutting edge radius quality.

Micro milling experiments were conducted on a Mikron HSM 400 high speed machine and a Kistler mini-dynamometer type 9256C was used. A constant cutting velocity of 35 m/min, table feedrate of 184 mm/min and depth of cut of 30 µm were used as established from pilot cutting tests. Twenty consecutive passes of 15 mm length each were milled with 40% of tool diameter step over. The material removal rate was 1.1 mm^3/min compared to previous studies 3.15 mm^3/min [3] and 0.25 mm^3/min [4].

Three different modes of cooling/lubricant systems were researched for this experiment, namely, chilled air, minimum quantity lubricant and chilled air concurrently applied with minimum quantity. Each test was repeated three times with new cutting tools. Under chilled air system, a VORTEC adjustable cold air gun was used to produce temperature between - 8.5°C to -10°C at flow velocity of 14 m/s velocity.

The system used was supplied by VorTech UK, and it was Model: 610BSP, Adjustable Cold Air Gun System, which has a magnetic base and filter. Cold air guns use filtered compressed air and vortex tube technology to produce sub-zero air for industrial spot cooling applications. For MQL 100% biodegradable Coolube® 2210 cutting lubricant was selected. The minimum quantity lubricant nozzle was located at the tool entry point to enable oil droplets to adhere to the tool face during the cutting process. While, the chilled air was jetted directly at the work-piece to control the workpiece temperature. The nozzle exit was positioned 15 mm away from the workpiece and directed at 60° angle to the spindle and tool axes. Tool wear and burr characterisation was done using Quanta 200 SEM and Keyence VHX-5000 digital microscope, while a Wyko NT3300 optical profiler was used to analyse surface roughness. Microstructures were imaged using a Carl Zeiss optical microscope.

3. Results and Discussions

3.1. Microstructure

Figure 2 shows the microstructure of the *NiTi alloy*. The microstructures of as-cast nickel titanium alloy shape memory alloy consist of dendritic grains and show severe segregation. For the as-received sample, the EDX spectra of the sample in area A revealed that it was Ni_{54} and Ti_{46} wt% which according to phase diagram is in the *NiTi* phase. The dendritic structure in area B precipitated from the grain boundary was richer in *Ti* compared to the bulk grain.