An Experimental Study on MQL Assisted High Speed Machining of NiTi Shape Memory Alloy

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Abstract. Nickel Titanium (NiTi) shape memory alloy is a prominent material for biomedical implants. Machining of shape memory alloy is challenging and requires intervention of sustainable techniques to produce quality products with minimum environmental footprints. This paper details the results of experimental investigation conducted on MQL assisted high speed machining of shape memory alloys. It reports the effect of MQL parameters on surface roughness and tool wear during turning (at speed 90 m/min) of NiTi shape memory alloy. Experiments are conducted based on Taguchi's robust design of experiment technique with L9 orthogonal array. Rhomboid shaped simple carbide tool is selected for experimentation. Green lubricant which is a blend of natural, synthetic and sulphurized esters is used as MQL fluid. Three important MQL parameters such as flow rate, air pressure, and nozzle distance are varied at 3 levels each. Parameters are optimized to secure the optimum combination producing best surface finish (Ra~1.39µm) and tool flank wear 1.6 mm.

Keywords. Machinability; MQL, Shape memory alloy Sustainability; Tool wear

1. Introduction

Shape memory alloys (SMAs) are "smart" materials possess the ability to change their form and return back to original form under the influence of heat, stress, or magnetic field due to the inherent properties like shape memory effects and pseudoelasticity [1, 2]. They are not only environmentally-friendly, light-weight and biocompatible, but also superior in actuation, vibration damping and sensing. Due to these properties, SMAs are extensively used in industrial, scientific, automotive, aerospace, and biomedical applications. Nickel titanium (NiTi) shape memory alloy is a prime candidate for biomedical applications such as dental and prosthetic implants, stents, and surgical equipment.

But, shape memory alloys are considered as difficult-to-machine (DTM) materials due to typical stress-strain behaviour, low thermal conductivity, and high degree of work hardening. This may result in poor machinability i.e. poor chip breaking; burr formation; progressive tool wear; and deteriorated work surface quality [3-5]. These all consequently results in high machining/manufacturing cost, high consumption of energy and resources, and environmental footprints.

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The challenges in machinability of DTM materials such as SMAs can be overcome by using appropriate tool materials and coatings, green lubricants and lubrication techniques, and optimization of process parameters etc. [5-7].

An experimental study conducted by Weinert et al. [8] recommends the use of coated (multilayer) carbide tools to minimize tool wear while turning NiTi alloy. By selecting the best machining practices such as the use of coated tools and machining at optimum parameters etc. They successfully machined a pipe coupling of NiTiNb to connect hydraulic lines. Lin et al. [9] successfully improved the machinability of NiTi alloys during their drilling and mechanical cutting. The best drilling ability in terms of optimum values of cutting forces, machining time, and service life of the tool was observed with tungsten-carbide twist drill at 163 rpm rotational speed and 0.07 mm/rev feed rate. Shyha et al. [10] performed machinability improvement tests for Kovar SMAs during their drilling with HSS twist drills. Experiments were conducted in dry condition at a speed range of 450-3750 rpm on unbacked and backed workpieces of Kovar alloy. Lower feed rate and cutting speed together with smaller drill sizes are suggested to minimize the cutting temperature and thereby improving the surface integrity i.e reduction in thermal hardening and burr size, and minimizing the chances of generation of micro-cracks etc.

The research work on use of advanced cooling and lubrication techniques to improve the machinability of SMAs was majorly contributed by Kaynak et al. [11, 12]. Kaynak et al. found cryogenic machining as a promising approach for improving machining performance of NiTi SMAs. Liquid nitrogen at 1.5 MPa was used as cryogenic coolant whereas, 175^0 C was chosen as preheating temperature for preheated machining, and 60ml/h as flow rate and 0.4 MPa as air pressure for MQL at different combinations of machining parameters. It was investigated that, at high speed, the surface integrity of cryogenically machined samples are much better than the dry samples. The reduced tool-wear and thermal distortion were recognized to be the main reason behind the generation of smoother surface in cryogenic machining at high cutting speed.

In a recent research, Kuppuswamy and Yui [13] successfully improved the machinability of NiTi alloy in the form of reduction in machining forces and burr formation during high speed micro-milling at optimum machining parameters. MQL technique with Johnson Baby oil at 4 bar air pressure and 80 ml/h flow rate was used for micro-milling at various levels (4.7-30 m/min) of cutting speed. This resulted in low cutting forces and reduced burr size was achieved at 15 m/min of cutting speed and it was concluded to be due to the transition of NiTi alloy from B2 phase to B19 phase.

Literature review on machining of shape memory alloys reveals that manufacturing sector is still looking for more sustainable solution for machinability enhancement of shape memory alloys and therefore further research and development efforts are required to be done.

This paper presents the results of experimental investigation conducted on minimum quantity lubrication assisted high speed machining of NiTi shape memory alloy. The subsequent sections present the experimental details and results of this investigation.

2. Experimental Details

NiTi is a work material in this experimental investigation. A CNC turning centre has been used to conduct the experiments. An MQL device (Producut APL 005/03) has been used to supply green lubricant to the machining zone. The available range of pressure and flow rate with the MQL system are 1-6 bar and 10-540 ml/hr respectively. The experimental setup is illustrated in Figure 1. The details of MQL and machining parameters along with lubricant properties are given in Table 1.

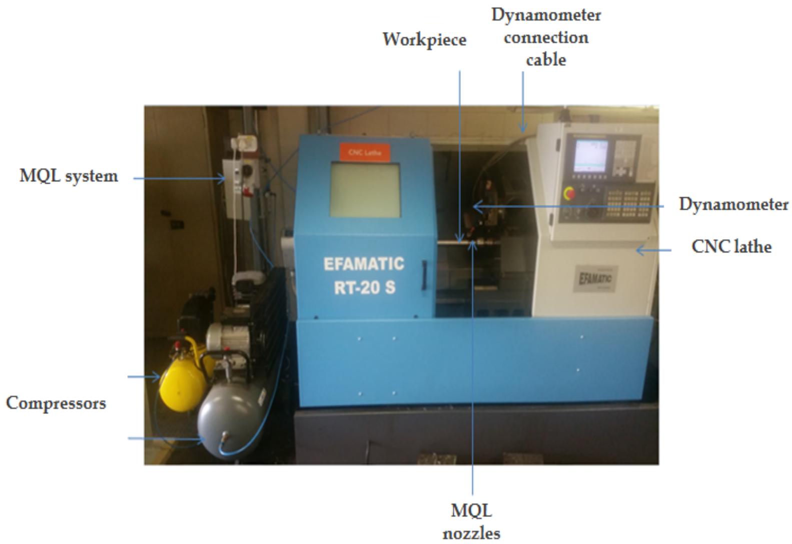

Fig 1. Experimental setup used for MQL assisted high speed machining of NiTi alloy.

Table 1 Details of MQL and machining parameters

Variable parameters				
Parameter	**Unit**	**Level**		
		-1	**0**	**1**
Flow rate 'F'	ml/hr	50	70	90
Air pressure 'P'	Bar	20	30	40
Nozzle distance 'D'	mm	4	5	6
Fixed parameters: Cutting speed-110 m/min; Feed rate-0.2 mm/rev; Depth of cut-1 mm				
Lubricant properties: Pour point- 8^0C; flash point- >290^0C; kinematic viscosity- 39.11 mm^2/s at 40^0C; density- 0.9199 g/cm^3 at 20^0 C				

The effect of the three most important MQL parameters i.e. flow rate, nozzle distance and air pressure were evaluated at three levels each. These levels were selected based on literature review, results of some preliminary experiments, machining constraints and recommendations of the MQL device manufacturer. Cutting speed, feed and depth of cut were fixed at the values considered as the median levels for a subsequent next phase of experimentation. A cutting speed of 90 m/min implies a speed in the high range for machining of NiTi. Average surface roughness and tool flank wear were considered as the output or response parameters. Experiments were designed and conducted based on Taguchi's robust design of experiment technique where L_9 orthogonal array has been selected which directly saves the time and experimental cost by minimizing the experimental runs from 27 (of full factorial) to 9. A total of nine experiments have been conducted. The run time for each of nine experiments was fixed at 30 seconds.

3. Results and Discussion

Table 2 presents the values of surface roughness and tool flank wear corresponding to all 9 set of experiments. Figures 2 and 3 depict the effect of MQL parameters on average roughness and maximum flank wear respectively.

Table 2 Experimental combinations of MQL parameters and corresponding values of surface roughness and tool wear

Expt. No	F (ml/hr)	P (bar)	d (mm)	R_a (µm)	T_w (mm)
1	50	4	20	1.45	0.76
2	50	5	30	1.12	1.41
3	50	6	40	3.84	0.82
4	70	6	20	1.09	0.80
5	70	4	30	1.17	0.76
6	70	5	40	1.29	1.63
7	90	5	20	1.96	1.39
8	90	6	30	1.03	0.98
9	90	4	40	1.57	1.28

As shown in Fig. 2, machining at least value of flow rate resulted in the highest roughness. Flow rate is the rate of flow of lubricant droplets on the work surface. It determines the accuracy of droplets distribution in the machining zone [14-16]. Least flow rate causes the improper distribution of the lubricant droplets that do not cover the tool-chip interface properly. That resulted in the deteriorated work surface due to the formed built-up edge and tool abrasion. Medium flow rate at 70 ml/hr ensures the proper reach of the lubricant droplets without dispersion and wastage directly to the machining zone and hence ensures high finish. As shown in Fig. 3, the difference between the tool wear at lowest and highest values of flow rate is not significant. Generally, the reason of high tool wear is the insufficient lubrication (oil droplets) which is failed to reduce the friction and thereby heat generated between tool-chip interfaces.

The nozzle distance is the distance of the nozzle from the work surface. It determines the divergence tendency of the lubricant jet. Longer the distance, higher the divergence tendency of the jet is and hence poor finish and high tool wear [14-16]. Figure 2 and 3 show the effect of nozzle distance on surface roughness and tool wear as aforementioned. In MQL, air pressure is the pressure of the air that carries lubricant droplets to the machining zone. High air pressure helps the oil mist to penetrate into the cutting zone where a cushion like arrangement is made that prevents tool wear [14-16]. But, lubrication continuing at high air pressure may also lead to droplets bouncing off the work and tool surfaces because of conservation of momentum effects thereby not being available for effective lubrication and consequently resulting in surface finish deterioration [14-16].

After a detailed analysis of the results, it has been found that the trends are conflicting in nature and requires multi-performance optimization to secure the best set of MQL parameters so as to enhance the machinability of NiTi with best values of surface finish and tool wear. Desirability analysis [17], an efficient and most extensively used statistical optimization technique, with 'smaller the better' type of desirability function has been used for multi-performance optimization in this work. Table 3 presents the desirability based optimum values of MQL parameters as well as average roughness and tool wear after confirmation experiment confirmation experiment.

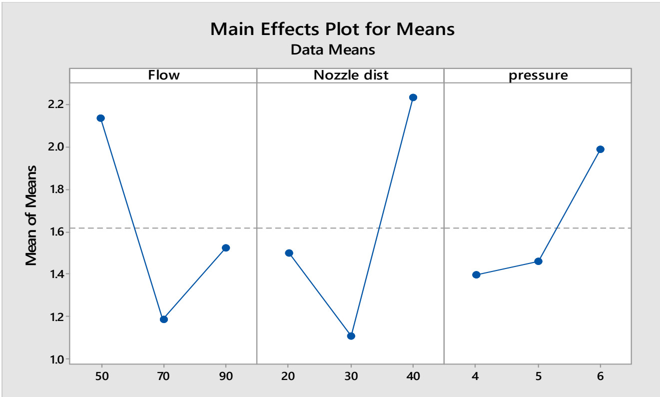

Fig. 2 Effect of MQL parameters on average roughness

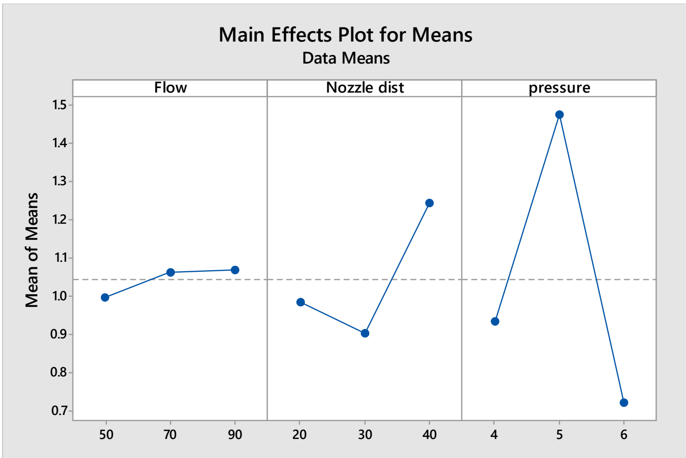

Fig. 3 Effect of MQL parameters on tool flank wear

Table 3 Optimum parameters and results of confirmation experiments

Optimal parameters	Optimal responses at confirmation expt	
Machining condition	R_a (μm)	T_w (mm)
Flowrate-Pressure-Nozzle distance 70-6-30	1.39	1.6

4. Conclusions

Results of experimental investigation conducted on MQL assisted high speed machining of NiTi are reported in this paper. MQL environment assisted to reduce the adverse effects of high speed machining conditions and produced good surface finish. The optimum values of MQL parameters recommended to be fixed for further investigations are: flow rate-70 ml/hr, air pressure- 6 bar and nozzle distance- 30 mm. Further investigations are recommended to improve tool wear conditions.

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References

[1] Kumar PK, Lagoudas DC (2008) Introduction to shape memory alloys. In Lagoudas, DC (edited) Shape memory alloys. pp. 1–51, Springer, New York
[2] Jani JM, Leary M, Subic A, Gibson MA (2014) A review of shape memory alloy research, applications and opportunities. Mater Des 56: 1078–1113
[3] Guo Y, Klink A, Fu C, Snyder J (2013) Machinability and surface integrity of Nitinol shape memory alloy. CIRP Ann 62:83–86
[4] Hassan MR, Mehrpouya M, Dawood S (2014) Review of the Machining Difficulties of Nickel-Titanium Based Shape Memory Alloys. Appl Mech Mater 564:533-537
[5] Weinert K, Petzoldt V (2004) Machining of NiTi based shape memory alloys. Mater Sci Eng: A 378:180–184
[6] Gupta K, Laubscher RF (2017) Sustainable Machining of Titanium Alloys- A Critical Review. Proc IMechE B J Eng Manuf. 231 (14) 2543-2560.
[7] Gupta K, Laubscher RF (2016), "MQL Assisted Machining of Grade-4 Titanium", In Proceedings of International Conference on Competitive Manufacturing (COMA), pp 211-217, Jan 27-29, 2016, Stellenbosch (South Africa).
[8] Weinert K, Petzoldt V, Kötter D (2004) Turning and Drilling of NiTi Shape Memory Alloys. CIRP Ann 53 (1):65-68.
[9] Lin HC, Lin KM, Chen YC (2000) A study on the machining characteristics of TiNi shape memory alloys. J Mater Process Tech 105(3):327-332
[10] Shyha I, Patrick M, Elgaly I (2015) Machinability analysis when drilling Kovar shape memory alloys. Adv Mater Sci Eng 1(3-4):411–422
[11] Kaynak Y, Noebe RD, Karaca HE, Jawahir IS (2013) Analysis of Tool-wear and Cutting Force Components in Dry, Preheated, and Cryogenic Machining of NiTi Shape Memory Alloys. Proc CIRP 8:498-503
[12] Kaynak Y, Karaca HE, Noebe RD, Jawahir IS (2013) Tool-wear analysis in cryogenic machining of NiTi shape memory alloys: A comparison of tool-wear performance with dry and MQL machining. Wear 306:51–63
[13] Kuppuswamy R, Yui A (2016) High-speed micromachining characteristics for the NiTi shape memory alloys. Int J Adv Manuf Technol. 93 (1-4), 11-21.
[14] Liu, Z. Q., Cai, X. J., Chen, M., An, Q. L., 2011, Investigation of cutting force and temperature of end-milling Ti–6Al–4V with different minimum quantity lubrication (MQL) parameters, Proc. IMechE Part B: Journal of Engineering Manufacture, 225:1273-1279.
[15] Duchosal, A., Leroy, R., Vecellio, L., Louste, C., Ranganathan, N., 2013, An experimental investigation on oil mist characterization used in MQL milling process International Journal of Advanced Manufacturing Technology, 66:1003–1014.
[16] Nath, C., Kapoor, S.G., DeVora, R.E., Srivastava, A.K., Iverson, J., 2012, Design and evaluation of an atomization-based cutting fluid spray system in turning of titanium alloy, Journal of Manufacturing Processes 14:452–459.
[17] G. Derringer, R. Suich, "Simultaneous Optimization of Several Response Variables", Journal of Quality Technology 12 (1980) 214–219.