PUBLICATION VII

Deformation effects on the interface between X2CrNi 19 11 stainless steel and HIPed NiTi coating in machining

In: Proceedings of the 18th International Conference on Production Research. Salerno, Italy, 31st July – 4th August 2005. 5 p.

DEFORMATION EFFECTS ON THE INTERFACE BETWEEN X2CrNi 19 11 STAINLESS STEEL AND HIPED NiTi COATING IN MACHINING

J.A. Paro, T.E. Gustafsson, and J. Koskinen
VTT Industrial Systems, Technical Research Centre of Finland
P.O. Box 1703, 02044 VTT, Espoo, Finland

Abstract
This study investigated the deformation effects of the interface between conventionally produced stainless steel X2crNi 19 11 and HIPed NiTI coating (Hot Isostatic Pressed). Near-equiatomic nickel-titanium alloy (NiTi) has many attractive material properties, such as pseudo-elasticity and shape memory effects, which result into beneficial engineering properties e.g. as cavitation resistant coatings in addition to its well-known shape memory properties. Stainless steels are often considered to be poorly machinable materials; materials with high elasticity are also difficult to machine. In drilling stainless steel with a pseudo-elastic coating material, machinability difficulties are caused by the high strength and work hardening rate of steel and the pseudo-elastic properties of the coating material. The deformation effects were studied by analyzing cemented carbide drills and chips. The interface between stainless steel and NiTi coating was examined with SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive Spectroscopy) analysis. The effect of feed rate on chip formation was analyzed. The cutting tests indicated that cutting speeds of 50 m/min, a feed rate of 0.1-0.2 mm/rev, and solid carbide drills can be applied, from a machinability standpoint. A HIPed pseudo-elastic coating decreases machinability. When effective cutting speeds and feed rates were utilized, optimal tool life was achieved without severe decrease in coating properties.

Keywords:
machinability, stainless steel, NiTi coating

1 INTRODUCTION

Shape memory alloys (SMA) are functional materials which are well known for their unique mechanical properties. The shape memory effects of these materials are caused by a reversible martensitic transformation. This functional material is very difficult to machine because of its high ductility, its different shape memory properties in dependence on temperature and the strong work hardening when this material is deformed. Austenitic stainless steels area also considered to be difficult to machine. Built-up edge (BUE) and irregular wear situations are often faced in machining operations. Difficulties from the machining point of view increase when duplex and high-strength stainless steels are to be machined. [1] In the drilling operation, small, well-broken chips are desirable. During drilling and formation, the chips rotate with the drill and impact the hole wall or interior of the flute. In addition to this NiTi possesses a high ductility and tends to strong work hardening when deformed [2, 3].

Shape memory alloys based on NiTi have a large variety of applications. One of the principal challenges in NiTi coating is how to achieve adequate adhesion between NiTi and the substrate material. It is known that Hot Isostatic Pressing (HIP) can be used to produce bulk NiTi components from powders [4, 5, 6]. The objective is to investigate the machinability of NiTi coating. The machinability is evaluated with respect to chip deformations and stainless steel and NiTi coating interface studied from chip samples.

2 MATERIALS

The samples used in the drilling tests were produced from the stainless steel blocks. The nominal composition of the stainless steel (AISI 304) blocks was 0.03%C, 1.20%Mn, 0.015%S, 0.04%P, 18.4%Cr, 9.2%Ni, 0.4%Si and 0.06%V. The capsule for HIP operation was welded from stainless steel plate (AISI 316) onto this block. The capsule was filled with rotating disc atomised NiTi powder (FUKUDA®) with an average particle size of 0.23 mm and composition 49.4±4.7 at-% Ni and 50.6±4.7 at-% Ti. The target bulk material composition (Ni/Ti) in at-% is 50/50, which in wt-% is 55/45. After the HIPing of the NiTi powder onto the block, the capsule was removed and the sample face milled for drilling tests. The evacuation pressure for HIPing was 10^{-5} mbar and treatment parameters were 900 °C, 100 MPa, and 3 h. The cooling rate was 4.6 K/min.

3 METHODS

Drilling tests were carried out using a horizontal machining centre equipped with 12 000 rpm, 22 kW spindle. The tests used TiCN- and TiN-coated cemented carbide drills with a diameter of Ø8.5 mm, at a cutting speed of 50 m/min and feed rates of 0.1, 0.15, and 0.2 mm/rev were used with through spindle coolant supply. In the tests used cemented carbide drill with built-up edge is presented in Figure 1.

The pseudo-elasticity of the HIPed NiTi coating was tested with Vickers hardness measurements, using a load of 9.81 N. From the chips cross-sectional samples were produced. These samples were polished and etched with picric acid and with a NaOH/water solution with electrolytic etching.

Samples were SEM and EDS analysed. The drill head and chip build-up was studied in detail with a scanning electron microscope (SEM) and analyzed with an X-ray analyzer (EDS), which can detect carbon (C) and elements heavier than that. The compositions were determined from the X-ray-spectra using a correction factor program $\Phi(\rho z)$. The X-ray lines used in the analysis were chromium (Cr), iron (Fe), nickel (Ni), and titanium (Ti). The quantitative result results were normalised to 100 %. To calibrate the magnification of the microscope and to perform the X-ray-analysis ASTM E766-98 and E1508-98 were used.

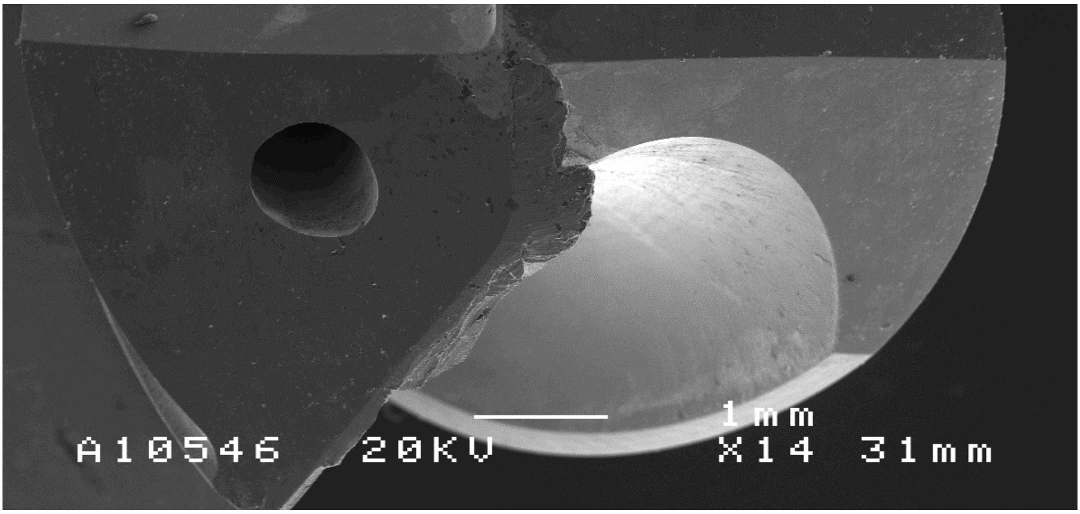

Figure 1: The drill used in cutting tests. The formation of built-up edge (BUE) is present.

In SEM-images obtained with a 25 kV acceleration voltage at a working distance of 39 mm, the error in the magnification is ± 4 %. The smallest detectable content in the X-analysis is approx. 0.3-0.5 % for metals depending on the composition of the analyzed material. Quantitative line scans were obtained utilizing Point Tagged Spectroscopy (PTS) in X-ray analysis. The quantitative line scans were used to estimate Cr-rich surface layer thickness on the in the stainless steel and Fe diffusion depth into the NiTi coating. The measurements were performed across the NiTi/Stainless Steel-interface. Chip thickness was measured from nine positions from both 0.1 and 0.2 mm/rev chips.

4 RESULTS

The microstructure of HIPed NiTi coating is shown in Figure 2. The NiTi powder has sintered into solid material, in which only some inter-granular pores could be detected.

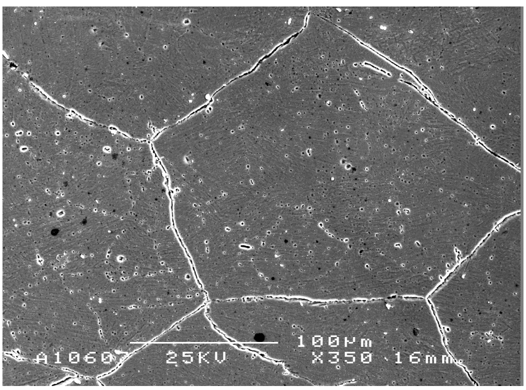

Figure 2: NiTI coating after HIPing-magnification 240x.

On the cutting edge of in Figure 1. presented solid carbide drill with TiN and TICN coating was SEM and EDS analysed. It was found that NiTi between TiN-coating and steel built-up edge (BUE) acts as an adhesive. Cutting speed 50 m/min and feed rate 0.2 mm/rev was used. Figure 4a shows a SEM image of a chip with a cutting speed of 50 m/min and feed rate of 0.1 mm/rev. Figure 4b shows the EDS line scan location resulting in Figure 4c. Figure 5a shows a SEM image of a chip with a cutting speed of 50 m/min and feed rate of 0.2 mm/rev. Figure 5b. shows the EDS line scan location resulting in Figure 5c. In Table 1. is presented the influence of feed rate on the thickness of Cr-rich layer and the diffusion of Fe into NiTi and chip thickness. It was found a wider Cr-rich interface in Figure 5b and Figure 5c with feed rate of 0.2 mm/rev was used in drilling than in Figure 5b and Figure 5c when feed rate of 0.1 mm/rev was used in drilling. Chip thickness with feed rate of 0.1 mm/rev was 88.8 µm and 171 µm with feed rate of 0.2 mm/rev. Figure 6 presents the micro hardness measurements performed across the NiTi/stainless steel interface with drilling feed rate value of 0.1 mm/rev and Figure 7 presents the micro hardness measurements performed across the NiTi/stainless steel interface with drilling feed rate value of 0.2 mm/rev. In Table 1 is presented dimensions of Fe-diffusion and Cr-rich layers are also approximately marked in Figure 6 and Figure 7. Figure 6 shown micro hardness values are between 420 HV and 501 HV. The measured micro-hardness value near the interface is higher than the value of NiTi chip. In Figure 7 shown micro hardness values are between 402 HV and 420 HV.

Table 1: Characteristics of the chip and NiTi/Steel interface.

Chip thickness (µm)	88.8	171
Feed rate (mm/rev)	0.1	0.2
Cr-rich layer (µm)	2.1	4.5
Fe-diffusion layer (µm)	4.3	27

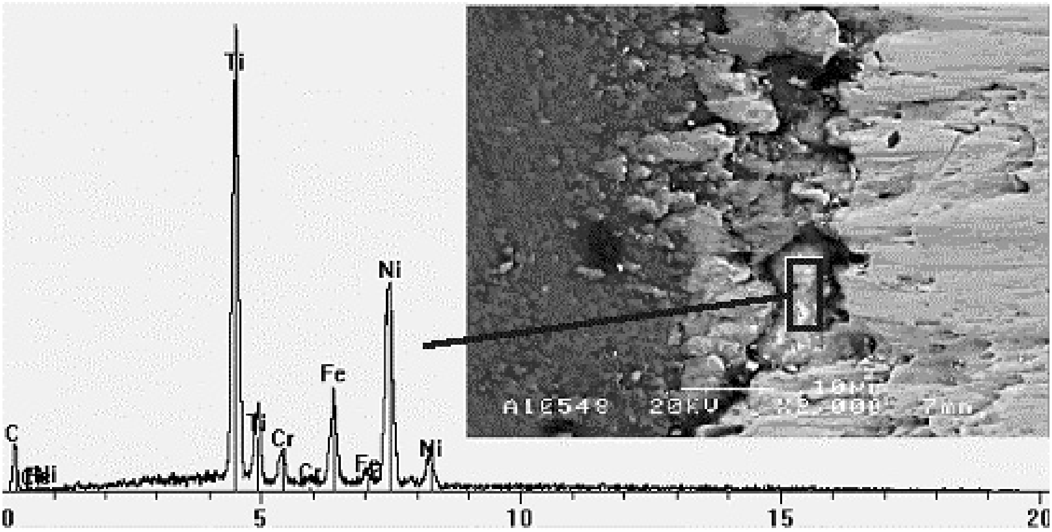

Figure 3: SEM image and EDS mapping of the built up edge formed in the cutting edge of the drill. Cutting speed 50 m/min and feed rate 0.2 mm/rev. Magnification-2 000x.

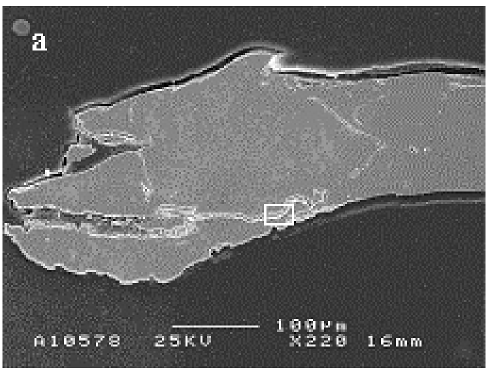

Figure 4a: NiTi and stainless steels interface with cutting speed of 50 min and feed rate of 0.1 mm/rev.

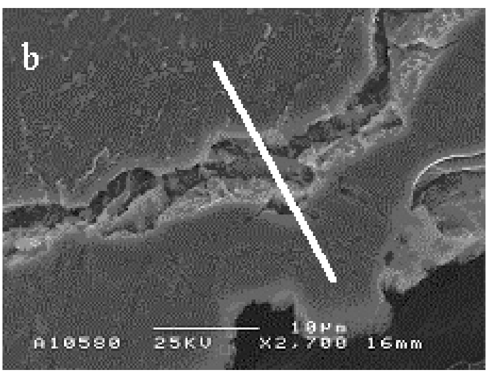

Figure 4b: Line scanning location across the NiTi and stainless steel interface.

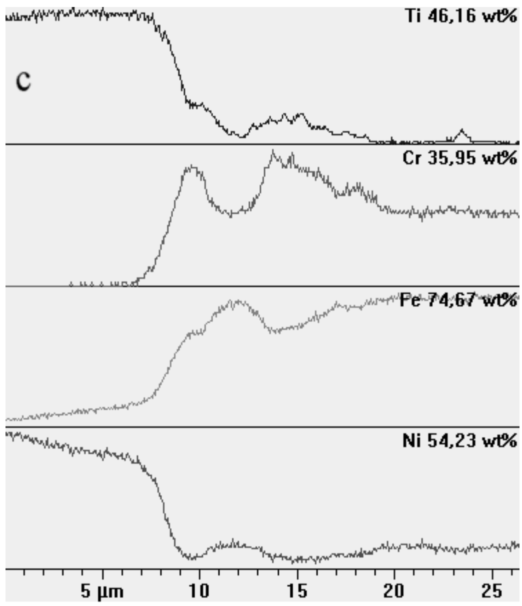

Figure 4 c: Element wt% along the line presented in Figure 4b.

It is also observed a strong deformation of NiTi coating and stainless steel chip. Grain boundaries were formed. The interface also seems to withstand the deformation without break down with feed rates of 0.1 mm/rev and 0.2 mm/rev.

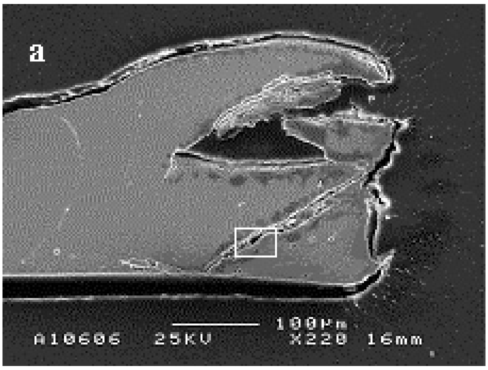

Figure 5a: NiTi and stainless steels interface with cutting speed of 50 min and feed rate of 0.2 mm/rev.

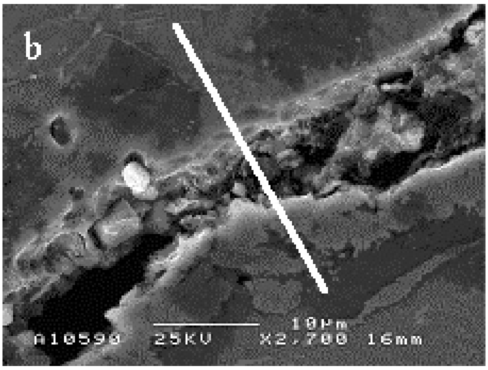

Figure 5b: Line scanning location across the NiTi and stainless steel interface.

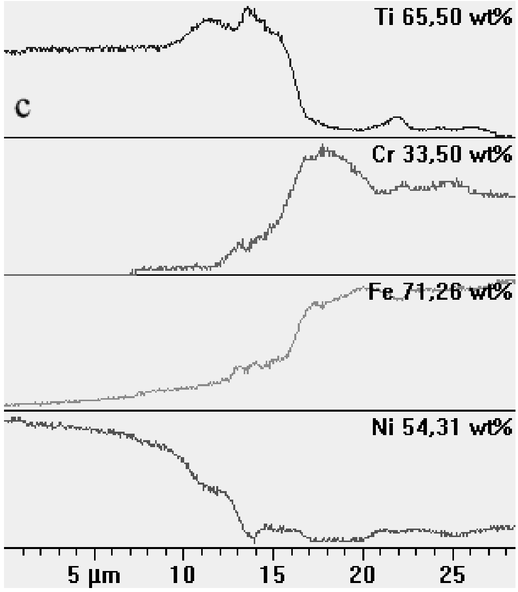

Figure 5c: Element wt% along the line presented in Figure 5b.

Chip thicknesses of deformed chips were measured from SEM images using in Figure 4a and Figure 5a shown chip samples. A chromium rich layer on the steel side and iron diffusion layer into the NiTi were detected from both 0.1 and 0.2 mm/rev feed rate chips. Measured chip thickness, thickness of Cr-rich layer and Fe-diffusion layer were found increasing when feed rate was increased.

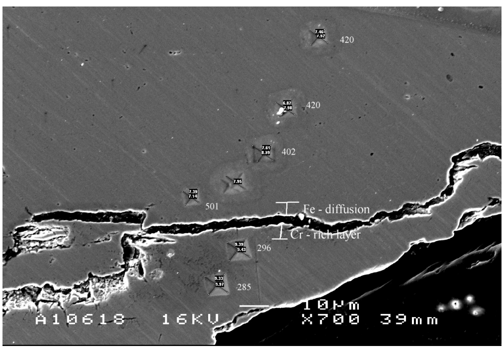

Figure 6: Micro hardness measurements across NiTi and stainless steel interface with feed rate of 0.1 mm/rev.

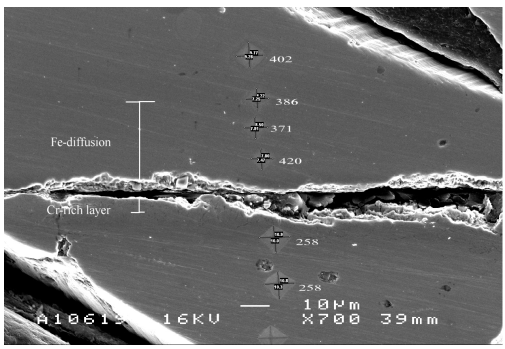

Figure 7: Micro hardness measurements across NiTi and stainless steel interface with feed rate of 0.2 mm/rev.

5 DISCUSSION

The machinability of stainless steel work piece with HIPed NiTi coating with solid carbide drill was examined. The experiments showed that the tool wear mechanism affected by built-up edge formation on the cutting tool for NiTi-coated stainless steel was similar to that with conventional stainless steel. Also according to Weinert et al. (2004) the special properties of NiTi shape memory alloys lead to a difficult processing of these intermetallic compounds [7].

The interface between steel and the NiTi coating was studied via SEM and EDS analyses. It was noticed that the chips became work hardened during drilling process for both cutting parameters. The deformation of the chips has been studied and micro hardness alteration has been found because of work hardening and the diffusion of Fe into NiTi. Chromium rich layer forms on the steel during HIPing, when also iron diffuses into NiTi. The work hardening of NiTi observed in this study is due to the drilling. The increase of feed rate increases the depth of work hardened layer of NiTi coating.

The interface between NiTi and steel is strong enough to withstand shear stresses caused by drilling forces and therefore the drilling process can be optimised according to difficult to machine base materials.

The diffusion mechanism during HIPing and work hardening merits further investigation.

According to Weinert et al. (2004) best results concerning work piece quality and tool costs can be obtained when applying coated cemented carbide tools is used. Common cutting materials for machining Ni- or Ti-based alloys can be applied [8,9] This work also shows machinability of NiTi-alloy and tool wear mechanism affected by BUE and deformation capability of NiTi coating and stainless steel interface detected from chips.

6 CONCLUSIONS

From the results obtained in the study, the following conclusions were drawn.

The work hardening rate of NiTi coating chip is increased when feed rate is increased from 0.1 mm/rev into 0.2 mm/rev. The NiTi coating adhesion into stainless steel is not affected by diffusion of Fe into NiTi or Cr-rich layer in the steel.

The drilling of NiTi coated stainless steel with appropriate cutting parameters is possible without severe tool wear. A cutting speed of 50 m/min and feed rate between 0.1 and 0.2 mm/rev with solid carbide multilayer coated drills and through-spindle cooling should be applied.

Tool wear mechanisms are affected by built-up edge (BUE) formation of NiTi and stainless steel on the TiN coating of solid carbide drill.

7 ACKNOWLEDGEMENTS

The authors are thankful to Sulzer Pumps Finland for providing the stainless steel materials that were tested.

8 REFERENCES

[1] L. Jiang, H. Hänninen, J. Paro, and V. Kauppinen, Active Wear and Failure Mechanisms of TiN-Coated High Speed Steel and TiN-Coated Cemented Carbide Tools When Machining Powder Metallurgically Made Stainless Steels. Metallurgical and Materials Transactions, 27A (1996) 9, 2796-2808.

[2] K. Weinert, V., Petzoldt, V., D. Kötter, Truning and Drillign of NiTi Shape Memory Alloys. Annals of the CiRP 53/1/2004 pp. 65-68

[3] D. Starosvetsky and I. Gotman, TiN coating improves the corrosion behaviour of superelastic NiTi surgical alloy. Surface and Coatings Technology 148 (2001), 268-276.

[4] G. Wang, Welding of Nitinol to Stainless Steel. Proceedings of SMST-97, 1997, 131-136.

[5] J. Koskinen, E. Haimi, A. Mahiout, V. Lindroos, and S-P. Hannula, Superelastic NiTi coatings with good corrosive wear resistance. Proceedings of the International Conference on Martensitic Transformations (ICOMAT 02). Espoo, 2002, 10-14.

[6] J. Koskinen, E. Haimi, Method for Forming a Nickle-Titanium Plating, US Patent 6,458,317 (2002).

[7] H., Schulz, Hochgeschwindigkeitsfräsen metalischer und nichtmetallischer Werkstoffe. Carl Hanser Verlag 1989. München Wien. 348 p.

[8] Hanasaki, S., Fujiwara, J., Touge, M., Hasegawa, Y., 1990, Tool Wear of Coated Tools when Machining of a high Nickels Alloy, Annals of the CIRP, 39/1: 77-80

[9] Corduan, N., himbert, T., Poulachon, G., Dessoly, M., Vigneau, J., Payoux, B., 2003 Wear Mechanisms pf New Tool Materials of Ti-6Al-4V High Performance Machining, Annals of the CIRP, 52/1: 73-76