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Tool wear and machinability of X5 CrMnN 18 18 stainless steels

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Abstract

In this study, active wear and failure mechanisms of TiN-coated cemented carbide tools when machining X5 CrMnN 18 18 austenitic stainless steel have been investigated. By nitrogen alloying austenite is stabilised and the strength of austenitic stainless steel is increased and work hardening is promoted. Stainless steels are often considered as poorly machinable materials. High strength and work hardening rate cause difficulties from the machining point of view. In this study turning tests carried out by using a test lathe and a cutting force measuring device are presented. Chips were analysed by scanning electron microscopy. The machinability of X5 CrMnN 18 18 austenitic stainless steels is examined based on tool life and cutting speed presented by vT-diagrams. The effect of cutting speed and nitrogen content is also analysed by cutting force measurements. Based on the cutting tests, cutting speeds of 40–200 m/min, feed rate of 0.15–0.25 mm and depth of cut of 1.6 mm for X5 CrMnN 18 18 stainless steels can be applied from machinability point of view. Higher nitrogen content decreases cutting force and decreases machinability. Tool wear criterion, VB-value of 0.3 mm, is reached after turning time of 10 min, when 60, 65 and 70 m/min and 0.24 mm/r feed rates are utilised. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Tool wear; Machinability; Stainless steel

1. Introduction

Austenitic stainless steels are considered to be difficult to machine. Built-up edge (BUE) and irregular wear 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. Machinability is often compared to the pitting resistance equivalent to pre-value representing the alloying content of the steel. High nitrogen stainless steels are common ultra-high strength stainless steels.

Nitrogen alloyed stainless steels exhibit a variety of exceptional properties like high strength, high ductility and resistance to stress corrosion cracking [1]. It is known that the effect of nitrogen on the flow stress of the steel is due to two strengthening mechanisms [2,3]. Nitrogen acts as an obstacle against dislocation movement causing solid solution hardening and the other mechanism is grain size hardening [1].

Nitrogen alloyed stainless steels show a high cold work capacity. Increased work hardening rate decreases machinability. The work hardening rate increases with increasing nitrogen content [1]. X5 CrMnN 18 18 ultra-high strength stainless steels with grain size of 30 μm have typically yield strength of 660 MPa and high nitrogen austenitic steel is able to work harden to 0.2% yield strength levels as high as up to 3000 MPa [1].

2. Experimental part

2.1. Test materials

X5 CrMnN 18 18 trial materials were produced by VSG Energie- und Schmiedetechnik GmbH. X5 CrMnN 18 18 trial material samples examined in the turning tests are presented in Tables 1 and 2.

The mechanical properties of X5 CrMnN 18 18 trial materials were measured by tensile testing. Yield strength for X5 CrMnN 18 18 trial material with 0.91 wt.% N was 458 MPa. Microhardness values were tested for both X5 CrMnN 18 18 trial materials. The microstructures of X5 CrMnN 18 18 trial materials are presented in Figs. 1 and 2.

2.2. *Turning experiments*

The turning tests were carried out with a conventional lathe equipped for testing purposes. The VDF-lathe applied in experiments is powered by 100 kW main spindle motor and equipped with Kistler cutting force measuring device. Turning tests were carried out according to ISO standard for tool life testing of single point turning tools. Tool wear was measured by using optical microscope.

The cutting tools used in the tests were made by Sandvik Coromant AB, Sweden. Solid carbide inserts were of type

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Table 1
Workpiece dimensions of X5 CrMnN 18 18 trial materials and their melt numbers

Two bars of diameter 125 mm × 620 mm	Melt DDT63
One bar of diameter 130 mm × 400 mm	Melt G88216

Table 2
Chemical compositions (wt.%) of X5 CrMnN 18 18 trial materials

Melt	C	Si	Mn	Cr	Mo	Ni	V	N
G88216	0.05	0.29	18.89	18.13	0.11	0.43	0.08	0.57
DDT63	0.05	0.49	19.8	18.6	0.08	0.61	0.13	0.91

SNMG 120408-PM P15/K15. The insert was CVD coated with TiN and Al_2O_3 layers.

Cutting parameters for the turning tests of X5 CrMnN 18 18 trial materials were selected to achieve appropriate tool life. Tool wear criteria were the width of flank wear value of VB = 0.3 mm or catastrophic failure. Cutting speeds in tests were $v_c = 60$, 65, 70 and 100 m/min, depth of cut was $a = 1.6$ mm and feed rate was $v_f = 0.24$ mm/r.

2.3. Tool life testing

Tool life testing vT-curves are presented in Fig. 3. When turning with the cutting speed $v_c = 60$ m/min the breaking

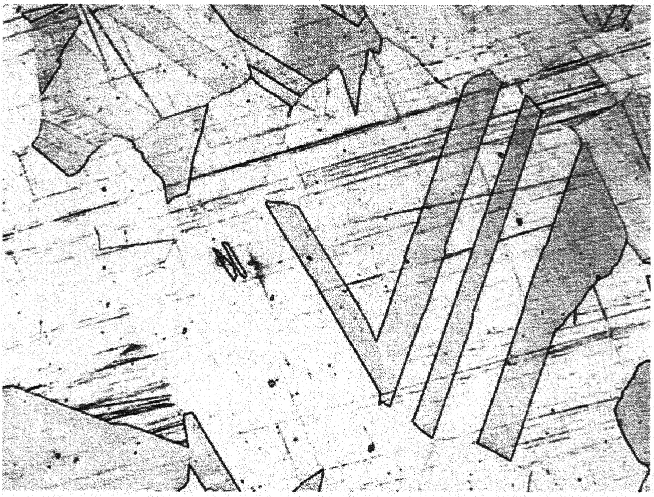


Fig. 1. Microstructure of X5 CrMnN 18 18 trial material with 0.91 wt.% N.

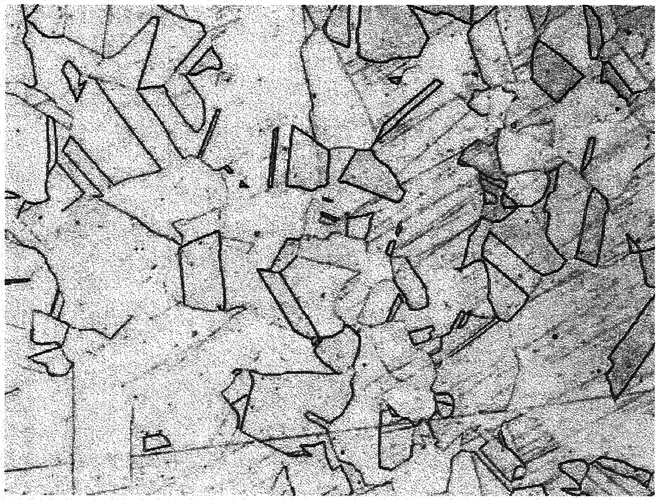


Fig. 2. Microstructure of X5 CrMnN 18 18 trial material with 0.57 wt.% N.

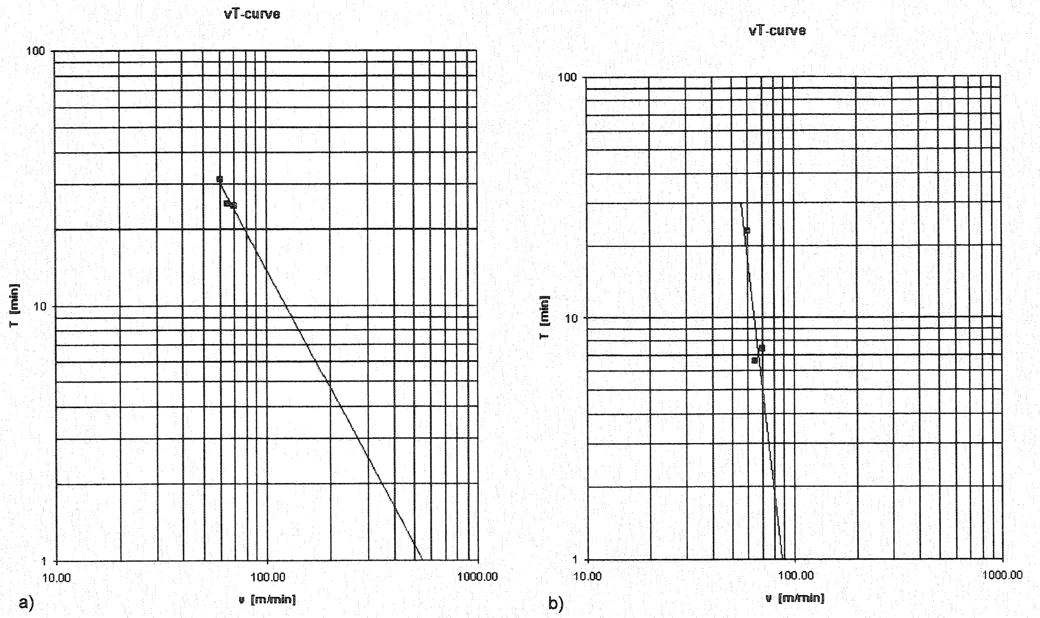


Fig. 3. Tool life testing vT-curves when machining X5 CrMnN 18 18 trial materials: (a) 0.91 wt.% N; (b) 0.57 wt.% N.

and chipping of tool nose begins after 20 min turning time. Continuous turning of the rapid tool wear proceeds and the surface roughness worsens and the chip formation becomes irregular. Increasing cutting speed v_c to a value of 65 m/min shows serrated chip formation until turning is to be interrupted after 25 min turning. The cutting speed v_c value of 70 m/min shows more problems in chip formation and surface roughness is decreased.

When turning the material with higher nitrogen level with the cutting speed of 60 m/min tool nose breaking occurs after 12 min tool life. Increasing the cutting speed to 70 m/min, the tool life is shortened and surface roughness

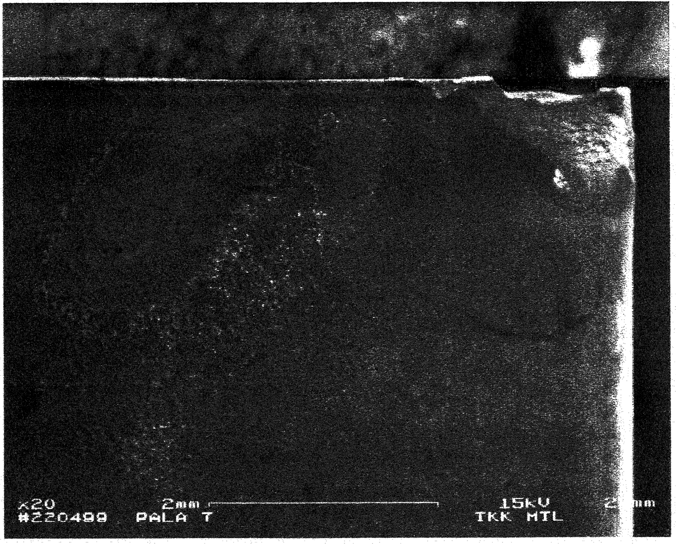


Fig. 4. The flank edge of solid carbide insert after machining time, $T = 4\,\mathrm{min}$ in turning of X5 CrMnN 18 18 trial material, 0.91 wt.% N. Cutting speed, $v_c = 65\,\mathrm{m/min}$.

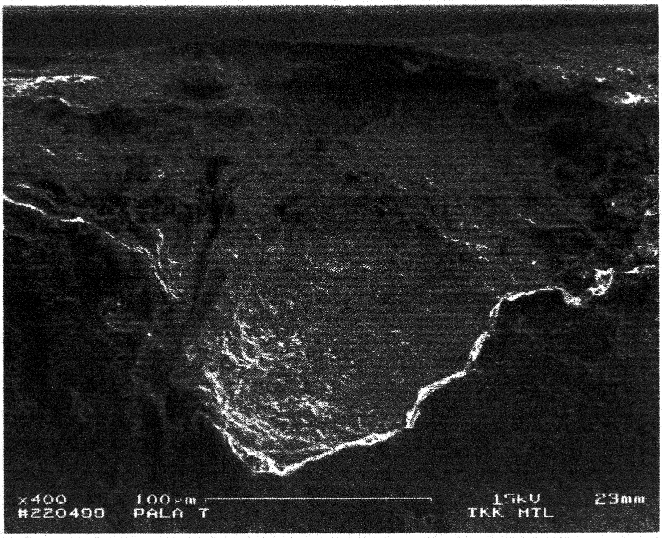


Fig. 5. The chipping of solid carbide insert in turning of X5 CrMnN 18 18 trial material with 0.57 wt.% N.

becomes worse. The main tool wear mechanisms are tool nose breaking and chipping of the cutting edge.

The test material with lower nitrogen level was much more complicated to machine. Tool lives shorter than 10 min were achieved. Catastrophic failure was the tool wear criterion interrupting the tool life testing experiment. Tool nose being partially damaged because of high stresses and forces, cutting circumstances are worsened at the cutting edge and BUE due to workpiece material adhesion to broken flank edge areas occurs.

2.4. Tool wear mechanisms

Solid carbide inserts used in turning test of trial materials are shown in Figs. 4 and 5, examined by scanning electron microscopy (SEM). Fig. 4 illustrates damaged insert representing typically worn tool in turning tests. Turning both X5 CrMnN 18 18 trial materials broken tool nose, chipping of the cutting edge and missing coating were observed.

It can be observed from Fig. 4 that tool nose breaking, chipping of cutting edge and wear of the coating occurred. Also deformation of the insert can be seen. In Fig. 5 on the small chipping area near the beginning of tool nose breakage area is observed adhered X5 CrMnN 18 18 trial material with 0.57 wt.% N.

The flow line like test material particles fixed into solid carbide insert indicates the incidence on BUE formation in the rake face area of turning tool.

2.5. Chip morphology

To analyse chip morphology SEM was used for X5 CrMnN 18 18 trial materials. Chips from cutting speeds of 60, 65 and 70 m/min from both testing materials were

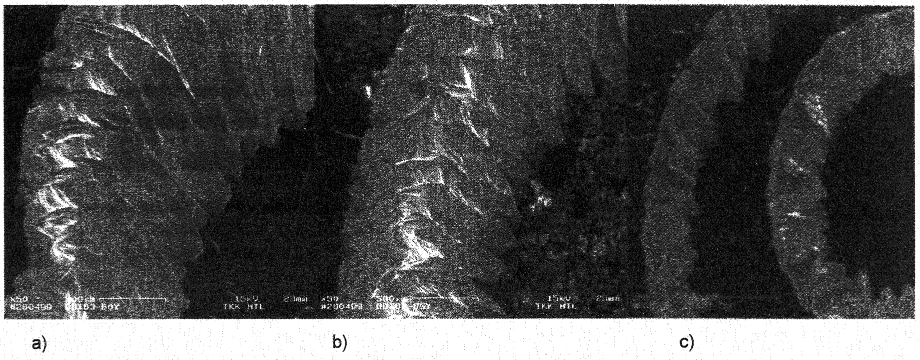
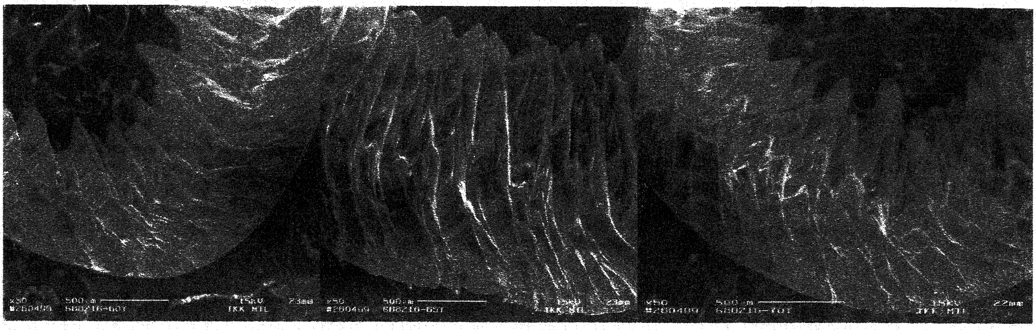


Fig. 6. SEM-images of chips in the direction away from the workpiece. X5 CrMnN 18 18 trial material with 0.91 wt.% N. Cutting speeds: (a) $v_c = 60$, (b) 65 and (c) 70 m/min, depth of cut $a = 1.6\,\mathrm{mm}$ and feed rate $v_f = 0.24\,\mathrm{mm/r}$.



a) b) c)

Fig. 7. SEM-images of the chips in the direction away from the workpiece. X5 CrMnN 18 18 trial material with 0.57 wt.% N. Cutting speeds: (a) $v_c = 60$, (b) 65 and (c) 70 m/min, depth of cut $a = 1.6$ mm and feed rate $v_f = 0.24$ mm/r.

analysed. Chips were strongly deformed to small short conical–helical chips or arc type chips. The chips from the test material with lower nitrogen content are presented in Fig. 6 and the chips from the test material with higher nitrogen content in Fig. 7. Chips are presented in the direction away from the workpiece.

The chips presented in Figs. 6 and 7 are machined from both X5 CrMnN 18 18 trial materials: increasing the cutting speed the chip changes from arc-like chip to spiral-like chip. Fig. 6 shows the chips from turning X5 CrMnN 18 18 trial material with 0.91 wt.% N; the chip becomes at the cutting speed $v_c = 60\,\mathrm{m/min}$ arc-like and the cutting speed value $v_c = 70\,\mathrm{m/min}$ spiral-like. In Fig. 6 X5 CrMnN 18 18 trial material with 0.57 wt.% N shows smaller arc-like chips and by the cutting speed $v_c = 70\,\mathrm{m/min}$ spiral-like chips having smaller radius than chips of X5 CrMnN 18 18 trial material with 0.91 wt.% N. The serrated structure of chips can be observed. The thickness of serrated structure observed by means of optical microscopy is about 0.2 mm.

Chip surface sliding against the rake face of the tool was examined by SEM and it is shown in Figs. 8 and 9. Outside the chips in the direction of the workpiece shear bands and

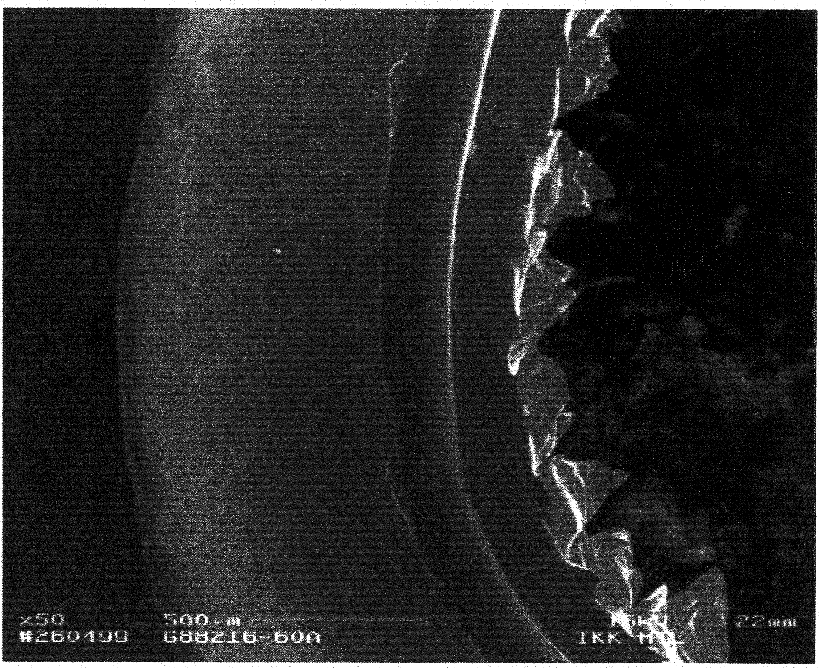


Fig. 8. SEM-image in the direction towards the workpiece. X5 CrMnN 18 18 trial material with 0.91 wt.% N. Cutting speed $v_c = 65\,\mathrm{m/min}$, depth of cut $a = 1.6$ mm and feed rate $v_f = 0.24\,\mathrm{mm/r}$.

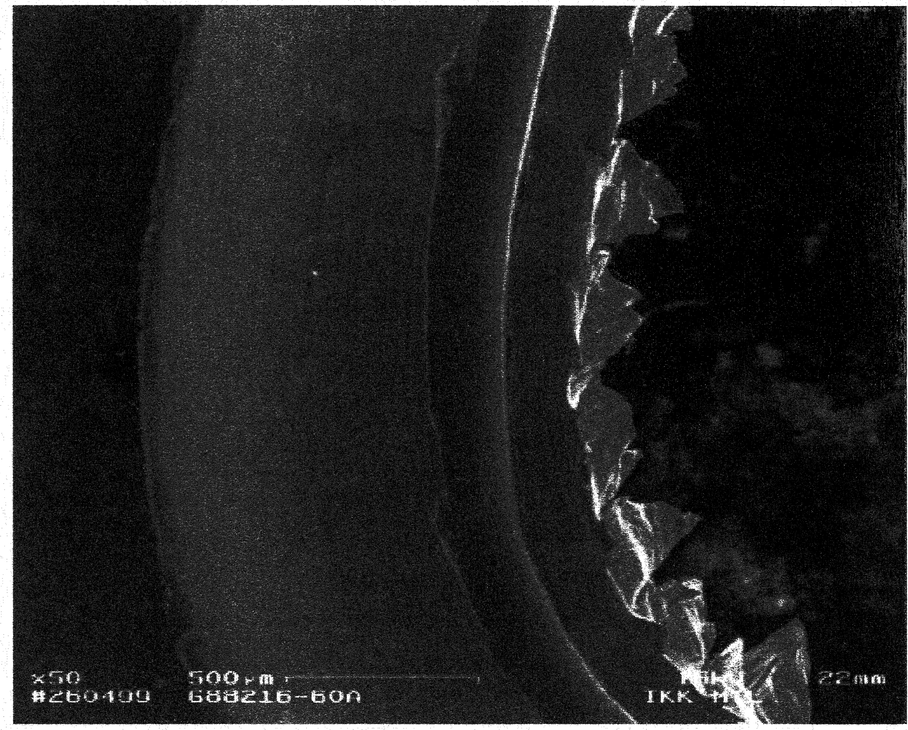


Fig. 9. SEM-image in the direction towards the workpiece. Chip from X5 CrMnN 18 18 trial material with 0.57 wt.% N. Cutting speed $v_c = 65\,\mathrm{m/min}$, depth of cut $a = 1.6\,\mathrm{mm}$ and feed rate $v_f = 0.24\,\mathrm{mm/r}$.

strongly deformed chip is observed. Serrated structure having width of 0.2 mm is seen.

2.6. *Cutting forces*

Cutting forces of X5 CrMnN 18 18 trial materials are presented in Tables 3 and 4. There was a difference in cutting forces when machining X5 CrMnN 18 18 trial material with 0.57 wt.% N.

Table 3
Cutting force components of X5 CrMnN 18 18 trial material with 0.91 wt.% N

v_c (m/min)	F_y (kN)	F_x (kN)	F_z (kN)
60	2.4–2.9	1.2–1.5	0.7
65	2.4–3.0	1.2–1.6	0.7–0.8
70	2.5–3.5	1.3–2.9	0.7–1.2
100	2.3–3.5	1.2–2.5	0.7–1.0

Table 4
Cutting force components of X5 CrMnN 18 18 trial material with 0.57 wt.% N

v_c (m/min)	F_y (kN)	F_x (kN)	F_z (kN)
60	2.2	1.0	0.6
65	2.2	1.0	0.6
70	2.2	1.0	0.6
100	1.8	0.8	0.5

3. Discussion

Rapid tool wear and tendency to chipping was studied on major cutting edge. In turning tests of X5 CrMnN 18 18 trial material with 0.91 wt.% N using cutting speed $v_c = 60\,\mathrm{m/min}$, tool life of about $T = 31\,\mathrm{min}$ was achieved. Tool life decreased to $T = 25\,\mathrm{min}$ at cutting speed of 65 m/min. By increasing cutting speed chip formation difficulties are caused and chipping of tool material and catastrophic failure of tool was often occurring.

Machining the material X5 CrMnN 18 18 trial material with 0.57 wt.% N the tool life was $T = 10\,\mathrm{min}$. Tool life was increased when turning test material of higher nitrogen content. By cutting speed of $v_c = 60\,\mathrm{m}$ tool life of $T = 22\,\mathrm{min}$ was achieved. Cutting speeds of $v_c = 65$ and $v_c = 75\,\mathrm{m/min}$ caused about 7 min tool life.

BUE formation decreased surface roughness. In analysing the samples with microhardness measurements, the presence of BUE was found. There were protuberance-like material formations on turned surfaces. Additionally there were microcracks. The evidence of BUE was focused on surfaces

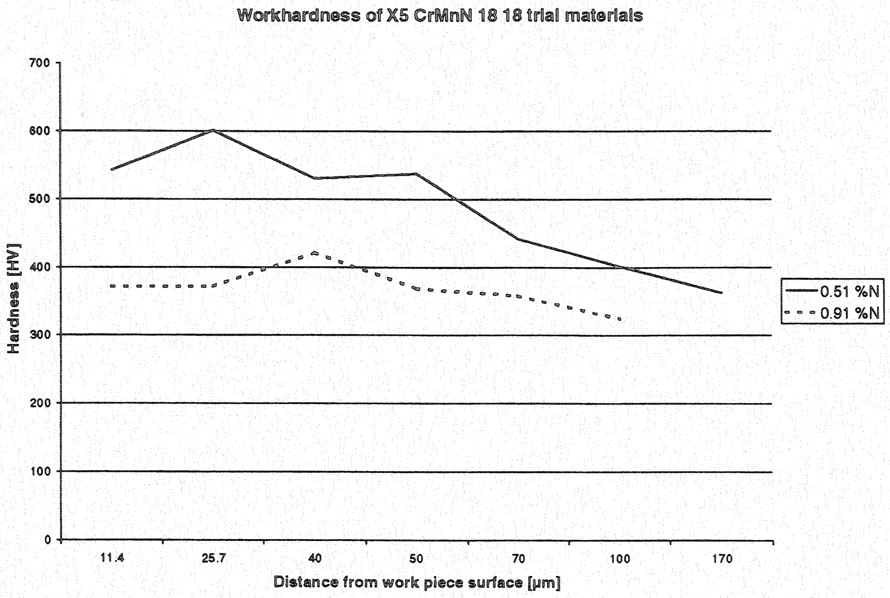


Fig. 10. Microhardness (20g) values of X5 CrMnN 18 18 trial material surfaces.

of X5 CrMnN 18 18 trial material with 0.57 wt.% N. Small amounts of trial material were also found from cracked edge areas. Workpiece surfaces were measured by microhardness testing device with video camera system. Results from the measurements are presented in Fig. 10.

The maximum microhardness value measured from X5 CrMnN 18 18 trial material with 0.57 wt.% N was approximately 600 HV. The microhardness curves show descending trend if measured in the direction of the surface normal. The other trial material with 0.91 wt.% N shows hardness values just below 400 HV. Comparing these two materials in Fig. 10 a work hardened surface of 0.1 mm thickness can be found from the trial material with 0.57 wt.% N.

4. Conclusions

From the results obtained in the present work the following conclusions may be drawn:

1. In the turning tests of X5 CrMnN 18 18 trial materials wear mechanisms were catastrophic failure of tool nose due to high cutting forces and sharp edge chipping.
2. The presence of BUE was decreasing the machinability of X5 CrMnN 18 18 trial materials.
3. There was a difference in machinability between X5 CrMnN 18 18 trial materials. Tool life T when machining the trial material with 0.91 wt.% N was 30 min and decreased to 10 min when the trial material with 0.57 wt.% N was applied with depth of cut, $a = 1.6\,\text{mm}$ and $v_f = 0.24\,\text{mm/r}$.
4. Increasing the cutting speed from $v_c = 60$ to 70 m/min, the tool life of X5 CrMnN 18 18 trial material with 0.57 wt.% N decreased rapidly from 10 to 5 min.
5. There is a difference in cutting force between X5 CrMnN 18 18 trial materials. In turning X5 CrMnN 18 18 trial material with 0.91 wt.% N tangential force $F_y = 2.4$–$3.5\,\text{kN}$ and when turning X5 CrMnN 18 18 trial material with 0.57 wt.% N tangential force $F_y = 1.8$–$2.2\,\text{kN}$ was achieved, respectively.

Acknowledgements

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