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Tool wear and machinability of HIPed P/M and conventional cast duplex stainless steels

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Abstract

In this study, active wear and failure mechanisms of TiN-coated cemented carbide tools with internal coolant supply when drilling of HIPed P/M Duplok 27 and conventionally-produced duplex stainless steel ASTM A8190 1A have been investigated. Stainless steels are often considered as poorly machinable materials. In P/M-produced duplex stainless steels, there are more hard oxide particles causing machining difficulties from the wear point of view. High strength and work hardening rate cause also difficulties from the machining point of view. In this study, drilling tests carried out by using a machining centre and optical microscope are presented. Chips were analysed by SEM electron microscopy and EDS-analysis. The machinability of duplex stainless steels is examined based on tool life and cutting speed presented by v–T-diagrams. The effect of cutting speed and the differences between powder metallurgically and conventionally-produced duplex stainless steels are also analysed by chip formation and tool wear mechanisms. Based on the cutting tests, cutting speeds of 20–100 m/min, feed rate of 0.15–0.25 mm and solid carbide drills, diameter of 8.6 mm, can be applied from machinability point of view. P/M duplex stainless steels with hard oxides decrease machinability. Tool wear criterion, VB-value of 0.3 mm, is reached after drilling time of 10 min, when 50 m/min cutting speed and 0.2 mm/r feed rate are utilised. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Drilling; Machinability; Stainless steels; Tool wear

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 corrosion resistance equivalent (PRE)-value representing the alloying content of the stainless steel.

Modern duplex stainless steel grades tend to be difficult to machine, by virtue of their higher austenite and nitrogen contents and with increasing alloy content, the machinability decreases rapidly [1].

Stainless steels are normally recognized as difficult materials to machine because of their high toughness, low thermal conductivity and high degree of work hardening. Stainless steels can be regarded as poorly machinable materials, because of their

- high tensile strength leading to high cutting forces and severe tool wear;
- high work hardening rates, especially for austenitic grades, and low thermal conductivity leading to high cutting temperatures and hence accelerated tool wear;
- high fracture toughness resulting in high temperatures, poor chip breakability and poor surface finish;
- abrasive carbide particles present in the high alloyed stainless steels causing tool wear;
- tendency to the BUE formation, which contrary to that in conventional steels, is present even at high cutting speeds due to the high fracture toughness and work hardening coefficient of these steels; the presence of the BUE impairs markedly the surface finish.

Due to the presence of porosity and structure of sintered powder metallurgy (P/M) steels, the machinability of such materials often bears a little resemblance to materials of similar composition of cast or wrought origin. It is generally accepted that the porosity causes a constantly interrupted cutting, which causes tool chatter and accelerates tool wear [2]. The porosity causes also a decrease in the thermal conductivity [2,3], which leads to an increase in the cutting temperature with a corresponding decrease in tool life. In hot isostatic pressed (HIP) P/M steels no porosity is expected to be present, but due to an increased oxygen content, large

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Table 1
Chemical compositions of the studied stainless steels (wt.%)

Code	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	Al	N	O
Duplok 27	0.03	0.2	0.7	0.02	0.001	2.3	26.5	7.0	3.0	–	–	0.3	–
A890 1A	0.03	0.74	0.63	0.026	0.006	3.01	25.0	5.54	2.03	–	–	–	–

amounts of hard oxide inclusions are present causing increased wear of tools.

New generation solid carbide drills with internal coolant supply providing efficiency in drilling operations are often utilised when hard to cut new high-strength stainless steels are to be machined. There is a need to understand materials aspects affecting tool wear and tool life of cemented carbide drills, when the high alloy austenitic and duplex stainless steels are machined. The differences in machinability between HIPed P/M stainless steel with hard oxide particles and cast stainless steel are studied to find tool wear behaviour.

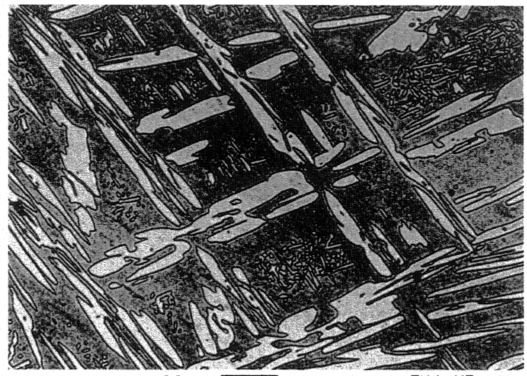


Fig. 2. The microstructure of cast A890 1A stainless steel.

2. Experimental details

2.1. Test materials

The workpiece materials were HIPed P/M super duplex Duplok 27 and conventionally-produced A8910 1A stainless steels. The chemical compositions are given in Table 1. The microstructures of the steels are shown in Figs. 1 and 2, respectively.

The microstructure of Duplok 27 stainless steel consists of lighter austenite phase and darker ferrite phase. The microstructure of A890 1A stainless steel consists of oriented dendritic austenite and ferrite phases.

2.2. Tool life testing and analyses

Drilling tests were carried out with a machining centre. Solid carbide drills were clamped on a high accuracy collet holder. Cutting speeds of 20–100 m/min, feed rate of 0.15–0.25 mm and solid carbide drills, diameter of 8.6 mm were used. Tool wear criterion applied was VB-value of 0.3 mm. The measurements were carried out by an optical microscope without releasing the drill from the tool holder. Drills and chips were analysed by SEM electron microscopy.

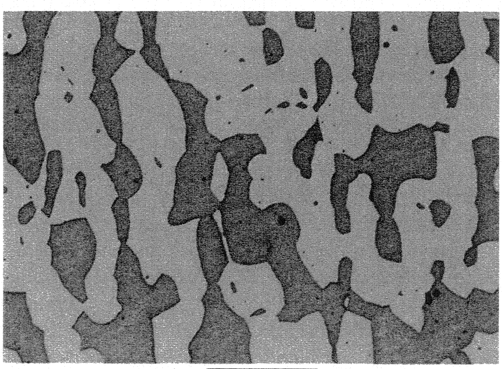


Fig. 1. The microstructure of HIPed P/M Duplok 27 stainless steel.

3. Results

3.1. Tool life testing

Tool life v–T-curves of Duplok 27 and A890 1A steels are presented in Fig. 3. In the drilling of Duplok 27 steel with the cutting speed of 40 m/min, the drilling length was 4.4 m. Increasing the cutting speed to 60 m/min, the drilling length decreased to 1.9 m. Tool life shortened from 10 to 5 min. In the drilling of A890 1A steel with the cutting speed of 40 m/min, the drilling length was 6.4 m. Increasing the cutting speed to 60 m/min, the drilling length decreased to 2.5 m. Tool life shortened from 20 to 6 min. Comparing conventionally-produced stainless steel A890 1A to HIPed P/M Duplok 27 stainless steel, tool life and drilled hole length increased 50%.

3.2. Tool wear mechanisms

Tool wear proceeded continuously, firstly flute tip was rounded and after a few holes, the cutting edge was affected

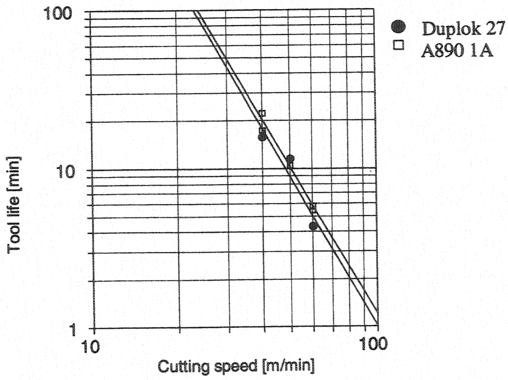


Fig. 3. Drilling of Duplok 27 and A890 1A stainless steels by Titex Alpha4 + DX45 Ø 8.5 mm P40; feed rate 0.2 mm/r.

by the formation of BUE. Due to presence of built-up edge in rake and flank face, there is possibility to adhesion wear of both surfaces near cutting edge. Because of internal cutting, fluid supply lowering the cutting temperature, the amount of oxidation and diffusion wear is supposed to be limited.

There was a higher tendency to built-up edge formation in A8910 1A stainless steel than in HIPed P/M super duplex Duplok 27 stainless steel. The formation of built-up edge in the drilling of A890 1A stainless steel with cutting speed of 40 m/min and feed rate of 0.2 mm/r with solid carbide drill Titex Alpha4 + DX45 is shown in Fig. 4.

The increase of cutting speed increased the BUE formation on the rake face. Compared to Duplok 27, no breaking of chisel edge corner existed in drilling of A890 1A steel. The formation of built-up edge into rake face has also altered tool geometry causing chipping of cutting edge, shown in Fig. 5.

To analyse tool wear from cemented carbide drills, SEM was used. BSE-images of rake surfaces of drills from drilling tests of HIPed P/M Duplok 27 stainless steel and cast A890 1A steel are presented in Figs. 5 and 6.

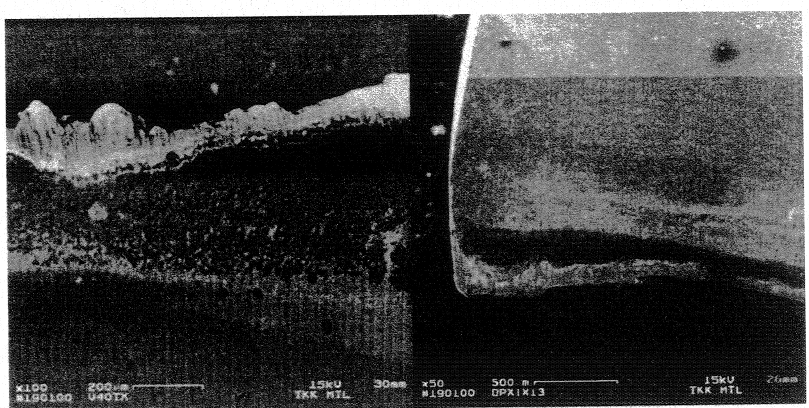
3.3. Chip morphology

To analyse chip morphology, SEM was used for both Duplok 27 and A890 1A steels with cutting speeds of 40, 50 and 60 m/min. The chips from HIPed P/M Duplok 27 steel are presented in Figs. 7 and 8 and the chips from cast A890 1A in Figs. 9 and 10. Convex and concave surfaces of the chips are presented. Tool wear increased, when cutting speed was increased from 40 to 60 m/min. There was a higher tendency to built-up edge formation in A8910 1A stainless steel than in super duplex HIPed P/M Duplok 27 stainless steel. The microstructure of A890 1A stainless steel is typical cast structure, shown in Fig. 2.

Fig. 7 presents the effect of cutting speed into the surface texture of Duplok 27 chips. There are grooves formed in the interaction between chip and rake face. The concave side of chips presented in Fig. 8 shows the change of chip lamella thickness when the cutting speed is increased.

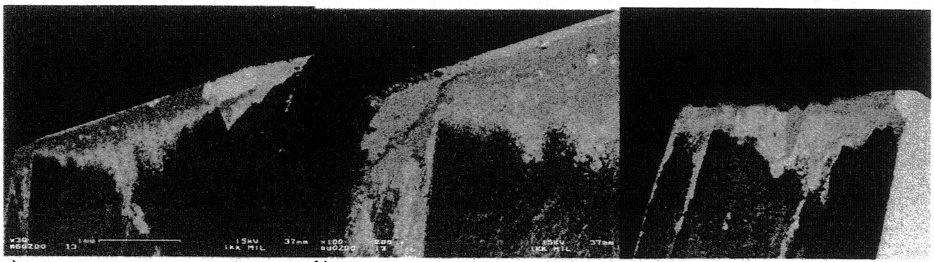
Higher tendency to BUE formation of cast A890 1A steel chips in Figs. 9 and 10 can be compared to smoother Duplok 27 steel chips in Figs. 7 and 8. The decrease of machinability comparing A890 1A to Duplok 27 steel can be observed from the strongly serrated chip when comparing chips presented from the convex chip surfaces in Figs. 7 and 9.

In Fig. 9, is presented the bottom of A890 1A chip. Compared to Duplok 27 chips, there are burrs and grooves. The chip formation is affected by the instabilites of cast structure. Compared to Duplok 27 steel chips, the increased presence of built-up edge in the drilling of A890 1A stainless steel is shown by convex surface of chips in Fig. 9.



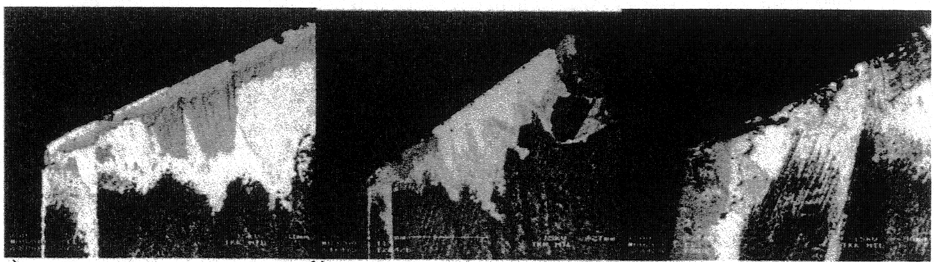
a) b)

Fig. 4. The formation of built-up edge in drilling of cast A890 1A stainless steel with cutting speed of 40 m/min and feed rate of 0.2 mm/r. Solid carbide drill Titex Alpha4 + DX45 was used.



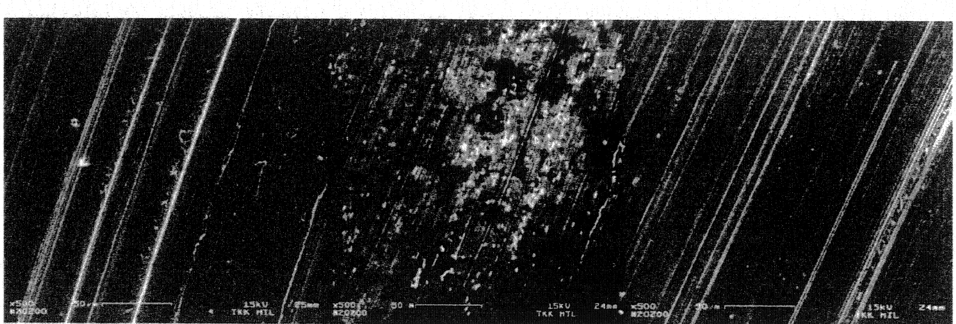
a) b) c)

Fig. 5. SEM (BSE)-images of drills from drilling tests of HIPed P/M Duplok 27 stainless steel. Cutting speeds of $v_c = 40$ (a), 50 (b) and 60 m/min (c) and feed rate $v_f = 0.20$ mm/r were used.



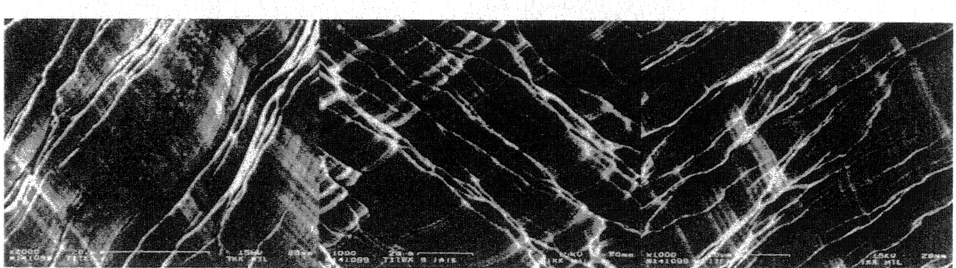
a) b) c)

Fig. 6. SEM (BSE)-images of drills from drilling tests of cast A890 1A steel. Cutting speeds of $v_c = 40$ (a), 50 (b) and 60 m/min (c) and feed rate $v_f = 0.20$ mm/r were used.



a) b) c)

Fig. 7. SEM-images of HIPed P/M Duplok 27 steel chips from the convex side. Cutting speeds of $v_c = 40$ (a), 50 (b) and 60 m/min (c) and feed rate $v_f = 0.20$ mm/r were used.



a) b) c)

Fig. 8. SEM-images of HIPed P/M Duplok 27 steel chips from the concave side. Cutting speeds of $v_c = 40$ (a), 50 (b) and 60 m/min (c) and feed rate $v_f = 0.20$ mm/r were used.

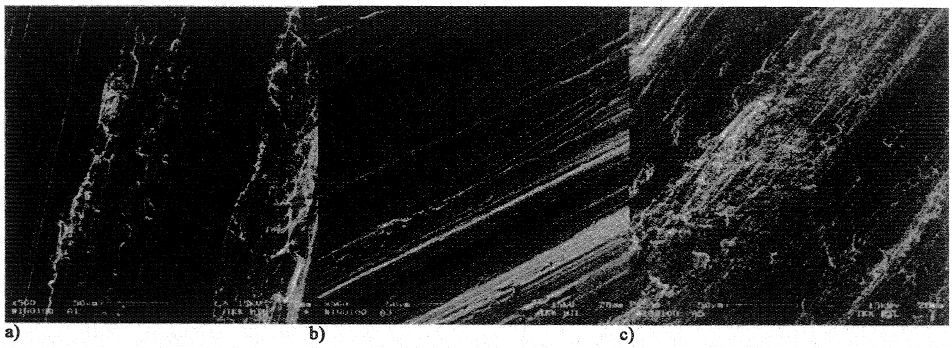


Fig. 9. SEM-images of chips from the convex side of chips of cast A890 1A steel. Cutting speeds of $v_c = 40$ (a), 50 (b) and 60 m/min (c) and feed rate $v_f = 0.20$ mm/r were used.

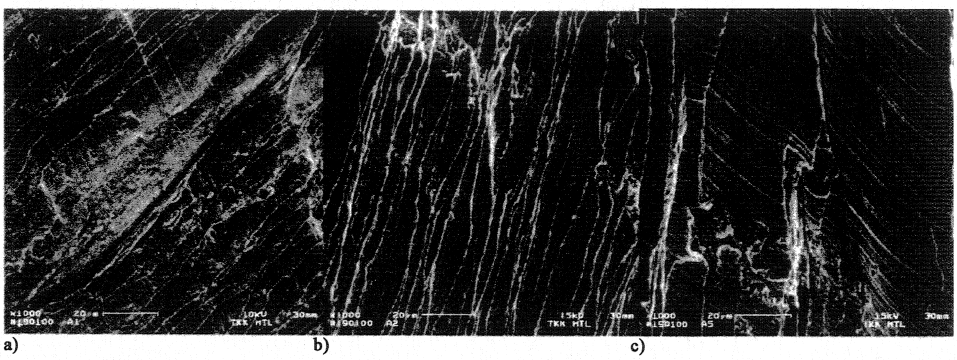


Fig. 10. SEM-images from the concave side of chips of cast A890 1A steel. Cutting speeds of $v_c = 40$ (a), 50 (b) and 60 m/min (c) and feed rate $v_f = 0.20$ mm/r were used.

4. Discussion

Machinability of stainless steels is often compared to the pitting resistance equivalent, PRE-value representing the alloying content of the steel. The pitting resistance equivalent (PRE) index, PRE = wt.% Cr + 3.3 × wt.% Mo + 13 × wt.% N, together with the tool life of Titex Alpha4 + DX45 for the drilling of test materials with cutting speed of $v_c =$ 40 m/min and feed rate $f = 0.2$ mm/r are presented in Table 2. The PRE of HIPed P/M Duplok 27 stainless steel is 25% higher than the PRE-value of cast A890 1A stainless steel. Tool life decreases 40% when HIPed P/M Duplok 27 stainless steel is machined compared to cast A890 1A stainless steel.

Table 2
Pitting resistance equivalent (PRE) index, PRE = wt.% Cr + 3.3 × wt.% Mo+13× wt.% N, together with the tool life of Titex Alpha4+DX45 in drilling of test materials with cutting speed of $v_c = 40$ m/min and feed rate $f = 0.2$ mm/r

Test material	PRE index	Tool life (min)
Duplok 27	39.4	4.4
A890 1A	31.7	6.4

Tool wear proceeded continuously in drilling of both materials by solid carbide drills with internal coolant supply. Compared to that at fast cutting speeds, plastic deformation of the tool takes place, in combination with flaking of the insert coating and frittering [1], the tool wear is affected by formation BUE and flaking of coating.

Stainless steels undergo marked work hardening during machining. Work hardening of stainless steels during machining can be observed from the microhardness values of the chip bottom, because the chip bottom can be considered to be the most highly deformed zone of the chips. From the drilling tests with $v_c = 50$ m/min, A890 1A steel chips show microhardness values; austenite 452 HV (20 g) and ferrite 372 HV (20 g) and if measured from chip bottom; austenite 505 HV (20 g) and ferrite 445 HV (20 g). Duplok 27 chips are more strongly deformed than A890 1A chips; the chip bottom of austenite in Duplok 27 605 HV (20 g) (original microhardness 370 HV (20 g)) versus austenite phase of A890 1A steel 505 HV (20 g).

5. Conclusions

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

1. The machinability of Duplok 27 and A890 1A stainless steels is affected by the formation of BUE. There is a higher tendency to formation of BUE in A890 1A than in Duplok 27 steel.
2. The tool life when using solid carbide drills with internal coolant supply is between 5 and 12 min in machining of Duplok 27 stainless steel.
3. The tool life when using solid carbide drills with internal coolant supply is between 7 and 20 min in machining of A890 1A stainless steel.
4. The formation of BUE causing adhesion wear is supposed to be the dominant failure mechanism of solid carbide drills when drilling Duplok 27 and A890 1A stainless steels.

Acknowledgements

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