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The influence of microstructure and non-metallic inclusions on the machinability of clean steels

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Abstract

This study focused on the evaluation of the machinability of different carburising steel grades by using a cemented carbide cutting tool during semi finishing of steel. The effect of the steel composition, microstructure and inclusion characteristics on the cutting tool wear in the soft part turning was evaluated for a reference steel R (0.028% S, 0.0009% O), a clean C steel (0.003% S, 0.0005% O), and an UC ultra clean steel (0.002% S, 0.0004% O). An improved cutting tool life of about 10-25% was obtained when machining the reference steel R. The favorable machining performance of this steel was attributed to its higher content of non-metallic inclusions, larger grain size and lower micro hardness than that of the clean steels.

1. Introduction

The level of a steels' cleanliness can be defined by its content of harmful elements i.e. the oxygen, sulfur, nitrogen, carbon, phosphorus and hydrogen contents.^[1] Holappa et al. reported that advances in steel manufacturing since the 1970's have resulted in new clean steel grades that contain less than 10 ppm of impurities and that have an excellent mechanical strength and an excellent corrosion resistance.^[1,2] The driving force behind these advances comes partly from the automotive sector and partly from the oil and gas industry. Specifically they have demanded steel grades that can tolerate a high mechanical load or an aggressive and corrosive environment, respectively. In contrast to the excellent mechanical properties and/or corrosive resistance of ultra-clean steels, they are typically considered to be difficult to machine, which will result in a reduced cutting tool life. Therefore, the challenge of future steel technology is to produce high performance steel grades with an improved combined mechanical strength and machinability.^[3]

Machinability itself is a wide and complex concept that indicates the overall machining performance of a workpiece. A machinability index is a general measure of a number of parameters, such as the power consumption, generated surface roughness of the machined workpiece, the ability to form chips, a cutting tool wear and an environmental impact.^[4] Therefore, the machinability index depends on the characteristics of the workpiece material, the cutting tool and the machining process.^[5]

Carburising steel grades which are composed of about 0.2% carbon are common in automotive production. They are easy to machine for a soft condition (about 150-200 HB) and they offer a combination of a high mechanical strength and a high wear resistance for a hard condition (58-63 HRC). In addition, the characteristics of these steel grades can be modified by using a heat treatment operation, such as annealing, aging, quenching and tempering.^[6]

Spheroidisation is a soft annealing process that occurs at an elevated temperature of about 950 K, where the lamellar cementite (Fe_3C) in the hard and brittle pearlite structure breaks into smaller fragments of a spherical shape, and moves to the softer ferrite phase.^[7] The purpose of a spheroidisation is to increase the formability and to reduce the hardness of the workpiece.^[7,8] Thus, a heat treatment operation is suitable to obtain an improved machinability of a carburising steel grade for a soft condition. Carburising itself gives a hard outer layer of about 1-1.5 mm thickness and a hardness of 60 ± 2 HRC which is necessary in industrial applications where the contact fatigue is a challenge such as in transmission components.

A comparison of the machinability between a standard carburising steel grade (R, 0.041%S), a clean and an ultra-clean steel (C and UC, 0.001-0.004%S) showed that the cutting tool life in hard part turning of the R steel was about 30% higher in comparison to the clean steels.^[9] However, no clear correlations between the machinability ratings of the standard and ultra-clean carburising steel grades and their content of non-metallic inclusions have yet been established for soft machining operations. Therefore, this study aims at clarifying the influence of steel cleanliness, inclusion characteristics and microstructure of spheroidised carburising steels on tool wear for soft part turning.

2. Experimental

2.1. Workpiece material

Three carburising steels provided by Ovako Hofors were investigated in this work. Their batch compositions, the corresponding ISO codes and the designations used in this study are presented in **Table 1**.

Table 1. Chemical composition of carburising steels used for the material analysis and machining tests (in wt-%).

Steel grade	ISO	C	Si	Mn	Cr	Ni	Mo	S	O	Ca
R	20NiCrMo2-2	0.21	0.24	0.88	0.56	0.50	0.21	0.028	0.0009	0.0002
C	20NiCrMo7	0.20	0.24	0.60	0.53	1.69	0.24	0.003	0.0005	0.0002
UC*	16NiCr6-4 F	0.17	0.32	0.78	1.13	1.35	0.09	0.002	0.0004	0.0010

*Ca-treated to 10 ppm.

The reference steel grade R is a common quality of carburising steel (280 ppm S, 9 ppm O) in automotive applications, like transmission components of a gearbox. Steel grades C and UC correspond to a clean steel (30 ppm S, 5 ppm O) and high performance and ultra clean steel (20 ppm S, 4 ppm O), respectively. The grades C and UC are designed for elevated levels of fatigue strength in gears and bearings whilst the grade R is easier to machine as it contains a larger amount of MnS inclusions. Also, MnS inclusions elongate during hot-working in the rolling direction acting as stress raisers in the steel matrix. Thus, MnS inclusions reduces the transverse fatigue strength of the reference steel. These test bars with a 90 mm diameter and a 500 mm

length from all steel grades were soft annealed (spheroidised) at 945 K for 15 hours.

2.2 Characterisation of steels

The microstructure analysis of the investigated steel grades was conducted by using samples which were cut out at the position of a half radius of the steel bars. The cross-section of each sample was wet ground, polished and etched with a 2% nital solution. Thereafter, a light optical microscope (LOM) and a LEO SUPRA 35 field emission gun (FEG) scanning electron microscope (SEM) equipped with an electron backscatter diffraction (EBSD) camera detector were used for further microstructure evaluation. The grain size and orientation of the microstructures were identified by using EBSD and using an inverse pole figure (IPF) mapping. In the IPF, the crystal planes are indexed and coloured on the basis of their position in the stereographic triangle. In addition, an extra high tension (EHT) of 5 kV, an aperture of 60 μm , a step size 0.5 μm (1000x), 0.05 μm (10000x) and 4x4 binning were used. Also, hardness profiles of steel bars were obtained by using a standardised measurement (Vickers method) on the transverse section of the cut out pieces of the rolled bars.

The equivalent carbon content (CE) was estimated by using the formula provided by IIW:

$$CE = \%C + \left(\frac{\%Mn}{6}\right) + \left(\frac{\%Cr + \%Mo + \%V}{5}\right) + \left(\frac{\%Ni + \%Cu}{15}\right) \quad (1)$$

where $\%C$, $\%Mn$, $\%Cr$, $\%Mo$, $\%V$, $\%Ni$ and $\%Cu$ represents a steel grade's content of carbon, manganese, chromium, molybdenum, vanadium, nickel and copper, respectively, given in wt-%.^[10] The equivalent carbon content is a parameter which is often used to predict the physical property of a steel grade such as the hardenability and weldability, when alloying elements other than carbon are used. The idea is to convert the content of these alloying elements to their equivalent carbon percentage.

Non-metallic inclusions were studied in three dimensions (3D) after an electrolytic extraction (EE) and filtration of soft-annealed steel specimens. The steel specimens (15x10x4 mm) were cut out from the half radius of the steel bars in the longitudinal direction. The electrolytic extraction was conducted by using a 10% AA electrolyte and an electrical current of 40-60 mA. Furthermore, the extracted non-metallic inclusions were collected during filtration on a polycarbonate filter with an open pore size of 0.4 μm . Then, the inclusions on the filter surface were investigated by using a SEM equipped with energy dispersive X-ray spectroscopy (EDS). The total amount of the analysed particles was 207, 119, and 70 for the grades R, C and UC, respectively. The characteristics of the observed inclusions were quantified with respect to length (L), width (W), shape (aspect ratio $AR = L/W$), calculated equivalent diameter (d_{eq}), number of inclusions per unit volume of steel (N_V) and volume fraction of inclusions (f_V). The d_{eq} values were calculated by using the following equations:

$$d_{eq} = \frac{L_{max} + W_{max}}{2} \quad (2)$$

$$N_V = n \cdot \frac{A_f}{A_{obs}} \cdot \frac{\rho_m}{W_{dis}} \quad (3)$$

where L_{max} and W_{max} are the maximum length and maximum width of the analysed inclusion, respectively. The parameter n is the number of observed inclusions in the selected size range, A_f is the area of film filter with inclusions after filtration and A_{obs} is the total observed area. ρ_m corresponds to the density of the sample metal matrix (equal to $\sim 0.0078 \text{ g}\cdot\text{mm}^{-3}$) and W_{dis} is the dissolved weight of steel during the extraction process.

2.3 Machinability evaluation

A commercial cemented carbide (CC) cutting tool of grade Sandvik GC4325 was used for the machinability tests of the steel bars. The cutting tool were positively shaped, had a nose angle equal to 80° and a nose radius equal to 0.8 mm (CNMG120408PM). The tool life tests in the turning operation were performed by using the Walter C3-PCLNL-22040-12 holder and using a Castrol Syntilo 9913 coolant consisting of a 5% emulsion (injected with a flow rate of $2.4 \text{ L}\cdot\text{min}^{-1}$).^[11] The main parameters used in the machining tests are given in **Table 2**.

Table 2. Main parameters for the machinability tests.

Machining test	Machining operation	Cutting speed, v_c ($\text{m}\cdot\text{min}^{-1}$)	Feed rate, f_n ($\text{mm}\cdot\text{rev}^{-1}$)	Depth of cut, a_p (mm)
Tool life	Face turning	300, 360 and 450	0.3	2-3

The test was considered ended when the cutting tool reached a maximum flank wear value (VB_{max}) $\geq 0.3 \text{ mm}$ or when it became damaged by an edge fracture, a chipping, a plastic deformation or a nose wear. The maximum flank wear (VB_{max}) of the cutting tools was measured at predetermined intervals by using LOM. Also, the tool wear analysis of the cutting tools was undertaken by using a JEOL JSM 7000F FEG-SEM equipped with a back-scatter (BS) detector.

3. Results and Discussion

3.1. The effect of microstructure and hardness of steels on cutting tool life

Based on the evaluation of the microstructure, it was found that the steel grades has a ferritic-pearlitic structure which contains spheroidised cementite along the ferrite grain boundaries (GB). Typical SEM-EBSD images of grains in the investigated steel grades after soft annealing are shown in **Figure 1**. In addition, the main characteristics of the investigated steel grades are given in **Table 3**.

Figure 1. Orientation of grains in the investigated steel grades (a) R, (b), C (c) and UC.

Table 3. The microstructural characteristics of the investigated steel grades.

Steel	Carbon content (Wt-%)	Microstructure	Carbon equivalent, CE (wt-%)	Average grain size, D_G (μm)	Hardness at $\frac{1}{2}$ radius, $HV_{0.5R}$ (HV5)
R	0.21	Ferrite-pearlite	0.54	11.0 ± 0.3	149 ± 4
C	0.20	Ferrite-pearlite	0.57	9.4 ± 0.5	165 ± 6
UC	0.17	Ferrite-pearlite	0.63	8.2 ± 0.3	171 ± 1

It is apparent that though the carbon content in the given steel grades decreases slightly, the carbon equivalent (CE) and the average hardness of the steel bars ($HV_{0.5R}$) increases significantly. Also, the average grain size (D_G) decreased in order from steel grade R to UC. Moreover, the relationships between the CE , $HV_{0.5R}$ and D_G values are shown in **Figure 2a**. The relative changes of the investigated characteristics of steel R, C and UC were evaluated by using the following equation:

$$K(P_i) = (P_i)/(P_R) \quad (4)$$

where $K(P_i)$ is the coefficient of relative change of parameter value (P_i) for the C or UC steel grade in comparison to that for the reference R steel grade (P_R). The obtained relationships between the values of $K(CE)$ and $K(P_i)$ are shown in **Figure 2b** for different steel grades. The parameter of N_{A-G} in this figure corresponds to the number of grains per unit area observed on the surface of a metal sample. It can be seen that as the CE value increased from 0.54 to 0.63 wt-% (on 17%) the $HV_{0.5R}$ (on 15%) and N_{A-G} (on 97%) values increased whilst the D_G value decreased (on 25%). It is interesting to point out that a change of the CE value has a larger effect on the N_{A-G} and D_G values than on the $HV_{0.5R}$ value. It means that the number of grains and the grain size of the investigated steel grades are strongly linked to the carbon equivalent.

At the same time, the number of grains and the grain size of a steel grade are directly correlated to the surface area of grain boundaries. Consequently, the carbon equivalent has an influence on the surface area of grain boundaries within the steel matrix.

Figure 2. Relationships (a) between the CE , $HV_{0.5R}$ and D_G values and (b) between the coefficients of the relative change of the same parameters for the investigated steel grades.

It is known that a steel grade that has a higher equivalent carbon content has an improved hardenability, which corresponds to a higher hardness of the workpiece and, as a result, a reduced machinability.^[12] Furthermore, a steel grade that is characterised by a small average grain size has a high yield strength (σ_y), as is explained by the widely established Hall-Petch relation:

$$\sigma_y = \sigma_0 + k_y D_G^{-\frac{1}{2}} \quad (5)$$

where σ_0 represents the contribution of friction-free stress from grain boundaries and k_y is a material dependent constant whilst D_G is the average grain size of the steel grade. As a result, steel grades with low D_G values are expected to have a relatively poor machinability. It can be explained by the grain boundary strengthening, where the movement of the dislocations are hindered by the presence of grain boundaries. It results in a reduced mobility of the dislocations within the lattice structure and a higher onset point for plasticity. Thus, a higher critical stress is required to cause dislocation slip or a grain fracture.^[13-16] Moreover, steel grades with a small grain size have a larger area of grain boundaries. Therefore, they require a higher power consumption in metal cutting operations than steel grades with larger grains. These expectations were supported by the obtained tool life values of the steel grades R, C and UC at the different cutting speeds, which are shown in **Figure 3**. It should be pointed out that the largest effect of the metal matrix characteristics (such as CE , $HV_{0.5R}$, D_G and N_{A-G}) on the cutting tool life was obtained at the lower cutting speed. More specifically, the TL value was increased with 24% at the cutting speed of 300 m/min and only by 9% at a speed of 450 m/min.

Figure 3. Cutting tool life of different carburising steel grades depending on the equivalent carbon content (a) and the average grain size (b).

3.2. Inclusion characteristics of soft annealed carburising steels

A comparison of the particle size distribution demonstrated differences between the steel grades (see **Figure 4**). The reference steel grade R contained a larger number of non-metallic inclusions than the clean steels C and UC. Grade R also contained the longest non-metallic inclusions. The majority of the non-metallic inclusions in this steel were elongated MnS with lengths of up to 145 μm . Also, a small amount of complex oxy-sulfides and oxides (Al,Mg)O were found. Still, most of the non-metallic inclusions were not longer than 20 μm . A significantly smaller amount of non-metallic inclusions were found in the C and UC steel samples. Similarly to R, the steel grade C contained mostly MnS-rich inclusions and oxy-sulfides, even though a small number of pure oxides were found. On the contrary, the vast majority of the non-metallic inclusions in the ultra-clean steel (grade UC) consisted of CaS and complex oxy-sulfides. A small count of pure oxides was detected. The particles in grade UC were much smaller in size (<10 μm) and more globular in shape. The main characteristics of non-metallic inclusions observed in steel samples from grade R, C and UC, after electrolytic extraction are given in **Table 4**.

Figure 4. Particle size distributions (a) and the compositions of the non-metallic inclusions (b) observed in R, C and UC steel grades.

Table 4. Characteristics of all non-metallic inclusions observed in different steel grades after EE*.

Steel grade	S (wt-%)	O (wt-%)	L (μm)	AR	d_{eq} (μm)	N_V (count·mm ⁻³)	f_V
R	0.028	0.0009	19±17 [2~145]	10±7 [2~33]	5±3 [1~23]	3.10·10 ⁴	3.60·10 ⁻³
C	0.003	0.0005	15±40 [1~371]	8±11 [2~86]	4±3 [1~29]	0.26·10 ⁴	0.46·10 ⁻³
UC	0.002	0.0004	2±1 [1~9]	1±0.2 [1~2]	2±1 [1~8]	1.20·10 ⁴	0.16·10 ⁻³

*: [] – the minimum and maximum values of parameter.

Typical SEM images of non-metallic inclusions observed in different steel grades are shown in **Figure 5**. The elongated MnS inclusions, the complex oxy-sulfides (contained (Al,Mg)O core and MnS or (Mn,Ca)S outer layer) and globular CaS inclusions were observed in the samples.

Figure 5. Typical SEM images of non-metallic inclusions observed in the R, C and UC steel grades after completed electrolytic extraction and filtration.

Figure 6. Cutting tool life (TL) in soft part turning at different cutting speeds depending on (a) volume fraction (f_v) and (b) aspect ratio (AR) of non-metallic inclusions in the given steel grades.

It can be seen in **Figure 6** that the cutting tool life (TL) in soft part turning depends on the volume fraction (f_v) and aspect ratio ($AR=L/W$) of non-metallic inclusions, and especially of MnS-rich inclusions. More specifically, the larger values of f_v and AR of sulfide-rich inclusions promote an improved chip formation process and a reduced cutting tool wear. It can be explained by a significant increase of the surface area between the steel matrix and the non-metallic inclusions. It is believed that a larger surface area can cause an easy exfoliation of the steel matrix along this interfacial surface. It should be pointed out that the aspect ratio of inclusions (AR), which corresponds to their morphology, correlates to the surface area of inclusions in the steel. However, the volume fraction of inclusions (f_v) characterizes the amount of non-metallic inclusions in the steel. Therefore, the effect of f_v and AR parameters on the tool

life is shown in Figure 6 separately. Moreover, MnS inclusions are softer at machining temperatures than oxide inclusions.^[5, 17-18] Therefore, MnS inclusions are less detrimental to the flank wear of a cutting tool. In addition, MnS inclusions promote the formation of protective slag deposits (often rich in calcium) on the cutting tool surface, which can reduce the flank and crater wear rate.^[9, 18-22]

Conclusions

The influence of the characteristics of metal matrix and non-metallic inclusions in steels on the tool wear for soft part turning of different spheroidised carburising steels (R – common steel grade, 0.028%S; C – clean steel, 0.003%S and UC – ultra-clean steel, 0.002%S) was investigated. Based on the results in the study, the following conclusions can be drawn:

1. An increased carbon equivalent (CE) from 0.54 wt-% in the R steel to 0.63 wt-% in the UC steel promoted an increased average hardness by 15% at a half radius position of steel bars ($HV_{0.5R}$). In addition, when the number of grains per unit area observed on the surface of a metal sample (N_{A-G}) increased by 97%, the average grain size (D_G) decreased by 25%.
2. The cutting tool life (TL) increased with decreased CE , $HV_{0.5R}$ and N_{A-G} values and with increased D_G values in the steel.
3. The largest effect of the metal matrix characteristics (such as CE , $HV_{0.5R}$, D_G and N_{A-G}) on the cutting tool life was obtained at the lower cutting speed. More specifically, the TL value can be increased by 24% at a cutting speed of 300 m/min and only by 9% at a speed of 450 m/min.
4. The soft part machinability of clean carburising steels (C and UC) is significantly improved by a resulfurisation (reference R). The superior machinability of the standard steel grade R is partly linked to its high content of sulfur (0.028 wt % S), which results in an increased amount of MnS inclusions in the steel matrix. The MnS inclusions act as stress raisers in the primary shear zone during machining. As a result, they improve the chip formation process and prolong the cutting tool life.

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References

- [1] L.E.K. Holappa, A.S. Helle, *J. Mater. Process. Technol.* **1995**, 36, 177.
- [2] R.V. Väinölä, L.E.K. Holappa, P.H.J. Karvonen, *J. Mater. Process. Technol.* **1995**, 53, 453.
- [3] N. Ånmark, *Licentiate Thesis*, KTH Royal Institute of Technology, Stockholm, Sweden, May, **2015**.
- [4] J.-E. Ståhl, *Metal cutting – theories and models*, Lund University, Lund, Sweden **2012**.
- [5] N. Ånmark, A. Karasev, P. Jönsson, *Mater.* **2015**, 8, 751.
- [6] T. Holm, P. Olsson, E. Troell, *Steel and its Heat treatment*, Swerea IVF, Gothenburg, Sweden **2012**.
- [7] N. Gupta, S.K. Sen, *Def. Sci. J.* **2006**, 56, 665.
- [8] D. Hauserova, J. Dlouhy, Z. Novy, *Arch. Metall. Mater.* **2014**, 59, 1199.
- [9] N. Ånmark, T. Björk, A. Ganea, P. Ölund, S. Hogmark, A. Karasev, P.G. Jönsson, *Wear.* **2015**, 334-335, 13.
- [10] J.F. Lancaster, *Metallurgy of welding*, Abington Publishing, Cambridge, UK **1999**.
- [11] SIS, SS-ISO 3685 Tool life testing with single-point turning tools. **1994**.
- [12] J.P. Davim, *Machinability of Advanced Materials*, Wiley, Somerset, USA **2014**.
- [13] A. Iza-Mendia, I. Gutiérrez, *Mater. Sci. Eng. A.* **2013**, 561, 40.
- [14] E.O. Hall, *Phys. Soc. Sec. B.* **1951**, 64, 747.
- [15] N.J. Petch, *Acta Metall.* **1987**, 35, 2027.
- [16] M.-Y. Seok et al. *Scripta. Mater.* **2014**, 87, 49.
- [17] C.-H. Leung, L. Van Vlack, *J. Am. Cer. Soc.* **1979**, 62, 613.
- [18] C.-H. Leung, L. Van Vlack, *Metall. Trans. A.* **1981**, 12A, 987.
- [19] D. Lou, K. Cui, Y. Jiang, *J. Mater. Eng. Perform.* **1997**, 6, 215.
- [20] L. Jiang, K. Cui, H. Hänninen, *J. Mater. Process. Tech.* **1996**, 58, 160.
- [21] E. Harju, S. Kivivuori, A.S. Korhonen, *Surf. Coat. Tech.* **1999**, 112, 98.
- [22] J.M. Brion, B. Sander, G. Pierson, *Wear*, **1992**, 154, 225.