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QUANTITATIVE ANALYSIS OF SULPHIDE INCLUSIONS IN FREE CUTTING STEELS AND THEIR INFLUENCE ON MACHINABILITY

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ABSTRACT

Free cutting steels are intended for the fabrication of parts on automated machine tools. Free cutting steels have to meet the requirements set by automated parts production such as: longest possible tool life, highest material removal per unit time, chip breakability and workpiece surface quality. In describing the nature of non - metallic inclusions reference is mostly made only to the assessment of the banded structure of the inclusion. In plastic deformation soft manganese sulphide inclusions get thinner and longer while the autonomy of individual particles is retained. Plastic deformation is less efficient if the hardness of the inclusions is higher, which can be achieved by different metallurgical or chemical effects by the formation of oxide-sulphide inclusions. The shape of non-metalic inclusions can be described in various way. One of the simple ways is to describe it by the ratio of inclusion length to inclusion width. The machinability index varies with the ratio of inclusion shape, from 200 to 100%, which means that it is desirable that the manganese sulphide inclusions in steel must be as globoidal as possible. Detailed analysis of inclusions is possible only if we use highly developed, up-to-date equipment.

Key words: Free cutting steel, sulphide inclusions, machinability.

INTRODUCTION

The economic incentive to achieve higher rates of metal removal and longer tool life, has led to the development of a range of free cutting steels, the main feature of which is high sulphur content, but which are improved for certain purposes by the addition of lead (Leskovar and Grum, 1984). Tellurium has been added to steel as a replacement for sulphur and evidence has been given for machining qualities. However, it has certain toxic properties, which involve a hazard for steel manufacturers and the use of tellurium steels is not likely to become widespread. The manganese content of these steels must be high enough to ensure that all the sulphur is present in the form of manganese sulphide, and steel manufacturers pay attention not only to the amount but also to the distribution of this constituent in the steel microstructure (Baker, et al., 1976). Control of the mangan sulphide particle shape, size and distribution is achieved during the steel making. It is influenced both by deoxidation process of the molten steel before casting the ingots and by the hot rolling process (Gove and Charles, 1974). Lead additions are, usually, about 0.15 - 0.35 percent. Lead is insoluble in molten steel, or nearly so, and good distribution is difficult to achieve. In order to disperse the lead in the shape of fine particles throughout the steel, it is added to the steel as this is tapped from the ladle into the ingots molds (Van Vlack, 1953).

BASIC CONCEPTION OF INVESTIGATION

The aim of this investigation was to determine the characteristics of wear on the cutting edge of cemented carbide tools in the cutting of free-cutting steels at different machining conditions (Leskovar and Grum, 1983; Leskovar et al., 1981). Table 1 presents the data on particular steel qualities, their chemical composition and mechanical properties, while table 2 gives a comparison of some steels of Slovene production with some foreign standards.

Table 1: *Chemical composition and mechanical properties of free cutting steels.*

FREE CUTTING STEEL		CHEMICAL COMPOSITION					MECHANICAL PROPERTIES				
		C	Mn	Si	P	S	Pb	R_m	$R_{p\,0,2}$	δ_5	HB
SLOVENE STANDARD	DESIGNATION AISI	%	%	%	%	%	%	N/mm^2	N/mm^2	%	-
Č.3990	STEEL WITH HIGH 1213	0.10	0.05	0.06	0.09	0.30	-	500	310	9	155
ATJ 100 Pb	MACHINABILITY INDEX 12 L 14	0.12	1.06	0.05	0.08	0.30	0.24	585	310	9	175
ATJ 50 C	CEMENTATION STEEL C 11 L17	0.15	1.31	0.30	0.02	0.11	0.21	622	290	17	175

Table 2: *Comparison of analysed free cutting steels to some foreign standards.*

STEEL DESIGNATION				
SLOVENE STANDARD	DIN 1651 1974	ISO DR	AISI	Alpine
Č. 3990	9 S Mn 28 K	2	12 13	ZS
ATJ 100Pb	9 S Mn Pb 28 K	2 Pb	12 L 14	ZS Pb
ATJ 50 C	-	-	C 11 L 17	-

For the investigation three qualities of free-cutting steels have been chosen, two of them having a high machinability index (12 13 and 12 L 14) and the third a cementation steel (C 11 L 17). The steels with a high machinability index show differences in the composition at the second and third decimal place, steel 12 L 14 contains 0.24 % Pb while steel 12 13 contains no lead. Steel C 11 L 17 differs more in terms of composition, containing a higher percentage of carbon, manganese and silicon, and a lower percentage of phosphorus. The higher percentage of carbon and manganese increases the strength and hardness of this steel quality and in this way worsen machinability. However the essential decrease in the machinability of steel C 11 L 17 is due to a smaller percentage of sulphur while containing almost the same quantity of lead as steel 12 L 14.

The mechanical properties of these steel qualities (Table 1), are such as are to be expected from their chemical composition, of course under the assumption that the presence of lead in steel does not have any effect which has been proven in work (Razinger 1981) on samples of free-cutting steels of Slovene production.

The following machining conditions have been selected for the investigation:
cutting speed:
$v_1 = 250$ m/min; $v_2 = 375$ m/min; $v_3 = 500$ m/min.

feed rate:
$f_1 = 0.132$ mm/rev; $f_2 = 0.222$ mm/rev

depth of cut:
a = 2 mm
tool material: quality P10, cemented carbide produced by the firm SINTAL (Zagreb, Croatia), designated SPUN-SV08,

tool geometry (Figure 1):
clearance angle $\alpha = 5°$; rake angle $\gamma = 6°$; inclination angle $\lambda = 0°$; setting angle $\kappa = 75°$; tip angle $\varepsilon = 90°$, tip radius r = 0.8 mm.

The measured set-up for the determination of machinability and wear mechanisms on the tool consists of elements which make possible an analysis of the characteristics of the tool, workpiece and chip during and after the machining process .

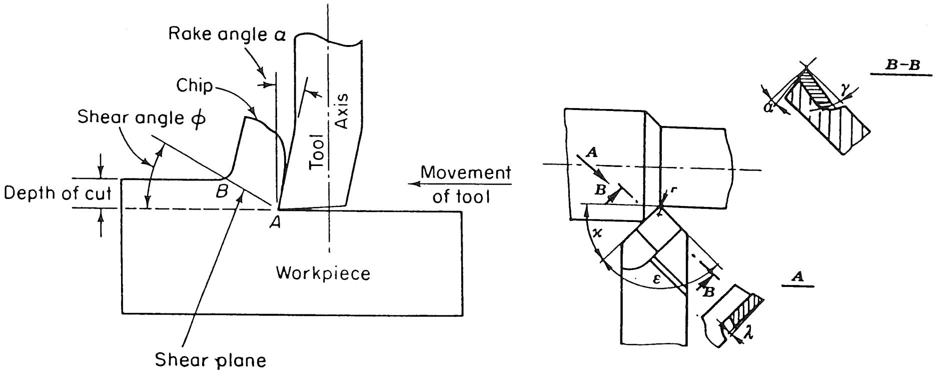

Figure 1: *Cutting tool action and tool geometry.*

ANALYSIS OF SHAPE AND ORIENTATION OF INCLUSIONS IN FREE CUTTING STEELS

Detailed analysis of inclusions in possible only if using highly developed, up-to-date equipment. Therefore we upgraded the existing system for computer aided morphometric analysis of microstructure components. The system consists of the conventional equipment for the preparation of metallographic specimens and a metallographic microscope METALLOPLAN (Leitz) to which the following hardware and software were added:

- a machine for automatic mechanical preparation of specimens (ABRAMIN-Struers)
- CCD TV camera and monitor for image transmission from the microscope
- PC 386 SX ARCHE
- video-processing extension card ME IIC (DIGITHURST)
- image processing software MS IIC (DIGITHURST)
- Program packages for transmission (WS), logical processing (dBASE) and statistical processing (UNISTAT III), and
- color printer PAINTJET (HP).

The thus improved and upgraded system enables simultaneous image transmission from the microscope into the computer, image processing and analysis, and outprint or storage on the disk. The repeatability in specimen preparation (grinding and polishing) is achieved through automated preparation on the ABRAMIN machine, on which it is possible to preset the speed, time, forces and intervals of adding abrasives during machining operation.

Image acquisition system

The TK870E (JVC) TV camera with a CCD image sensor with the effective raster 500 x 582 pixels gives a composite or RGB signal of PAL standard. The signal al (also from a TV or video source) can be guided into the video-processing ME II C extension card, which captures the image and digitalizes it in real time (1/25 sec). The heart of the card consists of three Intel graphic processors 82786. Each has 1 MB RAM memory for image, graphics and text storage. During the analysis they store two images of a resolution 650 x 550 pixels and 24 byte depth (255 levels for each colour). Besides a screenwidth colour image taking 1 MG of space, we can speed up the work by limitting the image scope and selecting windows. This kind of images can be processed, stored and retrieved. The system for image acquisition and processing is shown in Figure 2.

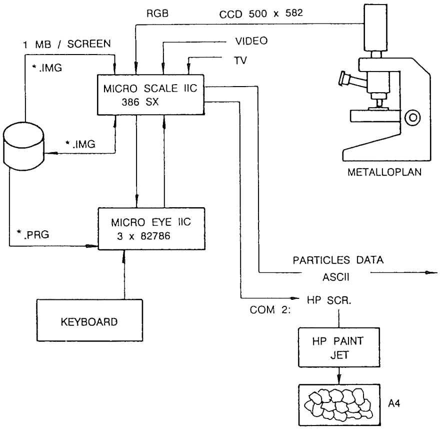

Figure 2: *System for image acquisition and processing.*

Image processing system

The image processing system consists of a PC 386 SX and extension card MicroEye II C and program package MicroScale II C. The ME II C card receives video signals through a RGB input. By means of three A/D converters the image is transmitted through a video controller and three D/A converters onto the control screen. During the display of either live or processed image we can start the image acquisition, which means image digitalization and image loading into another RAM-frame of the three co-processors 82786. On the basis of the inputted commands and possible comparisons with the image in the third storage frame (subtraction and mix), image processing is carried out. Through a two-way image data bus and a video interface a simultaneous display is possible on the control screen and the display of the results of the processing on the computer screen. The processing of the full screen takes up to 10 seconds (area measurement) and up to 150 sec in scanning up to the full number of particles (356). Through a PC AT bus the image can be transferred onto the disk or printer.

The program package MS II C performs the tasks from the reception of the RGB signal at the input of the extension card through processings and analysis to image storing on the disk or printer.

The key to any image processing is the distinction of the part of the image that is of interest the rest from of it. The point of the current interest can be set by moving the lower or upper level (0-255) for each colour separately. We can work in the absolute of relative mode.

The measuring routines included:

- area measurement; counting points of current interest
- circumference measurement; the number of points between the area of interest and the rest of the image
- ERODE; reducing the current area by the boundary layer
- DILATE; extending the current layer by the boundary layer
- EDIT: changing the area from that of current interest into the rest and vice versa.

In the scope of object-oriented routines, we can treat the points we are currently interested in as a closed particle of field. Within the boundaries and windows, particles can be scanned to see if their area conforms to the criteria of minimum and maximum area set. By scanning we define the position of the particle on the screen, its area, perimeter, largest and smallest diameter and the twisting angle of the particle′s largest diameter (particle′s axis) to the horizontal axis.

Secondary routines enable the definition or loading of the suitablescale, definition, and plotting the colour saturation histogram for the screen (window) or line histogram (10-line wide band).

All the measurement results can be sent to the disk. Likewise also the virgin and processed images. For on-line statistical processing, the basic statistical functions have been built into the program.

Results processing

In each automated image analysis we have to decide between the image resolution restrictions and suitable representativity of the sample. The former forces us, for the sake of measurement accuracy, to acquire images at highest enlargement, and the latter to choose smaller enlargements and thus smaller number of particles. Using the existing equipment, the only solution is to use higher enlargements, repeating the analyses on several places (screens) thus increasing the number of the analyzed particles. MS II C software does not support this kind of work. The write-out of the results into the file, as a matter of fact, always includes a head containing the data on the number of the analyzed particles and some mean values (however it does not contain the more wanted data on the specimen). Only later follow the data on the position, area, perimeter minimum and maximum grain diameter and angle, separated by commas. The files are, otherwise, in pure ASCII form. This kind of organisation of the recording does not make it suitable for direct use in the statistical package UNISTAT II or database d BASE III +.

In principle, we are forced to work through the file in the editor, removing the introductory data and blank lines at the beginning and end of one screen. Because of matrix restriction in UNISTAT III program (only 15 000 data can be processed simultaneously), files were also split up into several smaller ones in this step. These records have to be in pure ASCII form too (Figure 3).

Since in image analysis, a most complete spectrum possible of the microstructure components was taken, we make all further analysis from the original (full) files. From these we prepare the analysis for different groups of particles (large, spherical, oval ...). Grouping particles into characteristic groups, and applying additional conditions (e.g. "angle" is greater than 30 degrees) by using the statistical program is a rather time-consuming operation. Thus we carried out all the file processing linked to sorting out and setting conditions etc. in the dBASE program package for data processing. The file was inputted as an ASCII (SET DELIMITER) series, processed as a database. dbf and written on disk in ASCII form (SET ALTERNATE).

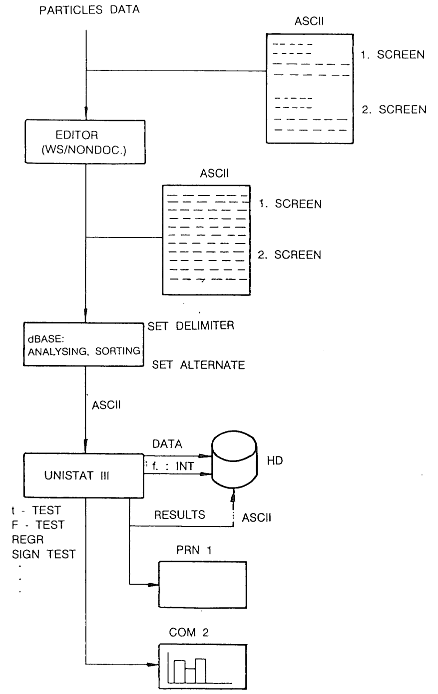

Figure 3: *Data processing in computer-aided morphometric analysis of microstructural components.*

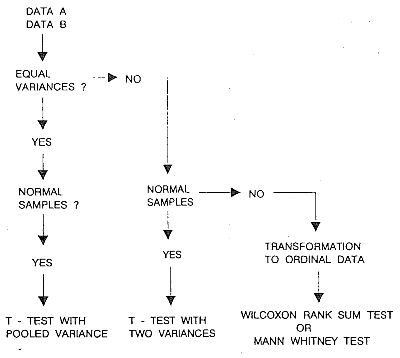

Figure 4: *Comparative statistics of two independently chosen steel qualities.*

Only the thus prepared files were statistically processed in UNISTAT III. Besides the elementary statistical evaluations we carried out also the comparative analysis of the shapes of inclusions in the particular steel qualities. In the case of diverse steel qualities we used the scheme shown in Figure 4. In the analysis we collected particles using such data as "average particle diameter at which the D_{min}/D_{max} ratio >3". The particles populations treated in the analysis of one steel quality ranged between 100 and 6500.

When two interdependent samples were compared, e.g. the steel prior and subsequent to heat treatment or the steel on the circumference of the bar to that in the core, we applied the analytical procedures as shown in Figure 5.

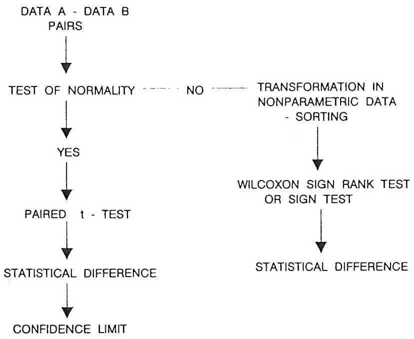

Figure 5: *Comparative statistical analysis of two interdependent steel qualities.*

STATISTICAL ANALYSIS OF MANGANESE SULPHIDE

As it has been recalled in the introduction, the effect of manganese sulphide is strongly dependent on the inclusions size, shape and distribution in the matrix. In steels 12 13, 12 L 14 and C 11 L 17, the matrix microstructure is predominantly ferrite, whereas in steel C 11 L 17 it is half-pearlite, half ferrite (AISI standard). What will be the size and distribution of manganese sulphide inclusions depends on the casting process quality whereas their shape depends on the temperature of forming, and strength or hardness of non-metallic inclusions. In Table 3 are collected the following standard data:

- areas of the manganese sulphide inclusions,
- perimeters of the manganese sulphide inclusions,
- minimum size of the manganese inclusions,
- centre of gravity line in the traverse direction,
- maximum size of the manganese sulphide inclusions defined by its length in the longitudinal direction.

In the analyzed free cutting steels we chose from 18 to 20 fields of measurements in the microscope counting from 443 up to even 757 manganese sulphide inclusions. Regardless of the number of fields of measurements, we can see that the chosen sample of each steel is extremely large and that it gives significant results. In free cutting steel 11 L 17 (AISI) 21 fields of measurements were analyzed counting 573 manganese sulphide inclusions. The average area of an inclusion was 85.7 µm^2. From these data it is obvious that in the analysis we were able to perceive an inclusion of size equal or higher than 2 µm x 3 µm=6 µm^2, the minimum length passing the centre of gravity was 3.5 µm and the maximum also passing through this point was 19.22 µm. Similar results can be noted also in the other two steels 12 L 14 and C 11 L 17 in which the size and shape of the particles was almost the same.

Table 3: *Statistics of manganese sulphide inclusions in 11 L 17 and C 11 L l17 (AISI standard) free cutting steels.*

STEEL	**STATISTICS OF MANGANESE SULPHIDE INCLUSIONS**							
11 L 17	**N/21**	**AVG**	**STD**	**VAR**	**SUM**	**SSQ**	**MIN**	**MAX**
Area	573	85.7	161.02	25927	49090	1. 90E+07	10.67	2542
Perimeter	573	47.6	54.02	2918	27284	2968328	9.28	466
Min diam	573	3.5	1.88	3.5	2023	9177	0.87	17
Max diam	573	19.22	22.65	513	11015	505128	3.31	202

STEEL	**STATISTICS OF MANGANESE SULPHIDE INCLUSIONS**							
12 L 14	**N/18**	**AVG**	**STD**	**VAR**	**SUM**	**SSO**	**MIN**	**MAX**
Area	645	90.2	157.57	24828	58167	2.12E+07	10.67	1854
Perimeter	645	50.2	61.00	3721	32362	4020410	9.13	479
Min diam	645	3.7	2.03	4.1	2362	11295	0.87	20
Max diam	645	20.2	25.71	661	13043	689570	3.19	215

The data in the Table 3 represent the following parameters:
N ... number of fields of measurements in metallographic microscope
AVG ... average value of the area,
STD ... standard deviation,
VAR ... variance,
SUM ... calculated sum,
MIN ... minimum size on the inclusion ' s centre of gravity line,
MAX ... maximum size on the inclusion ' s centre of gravity line.

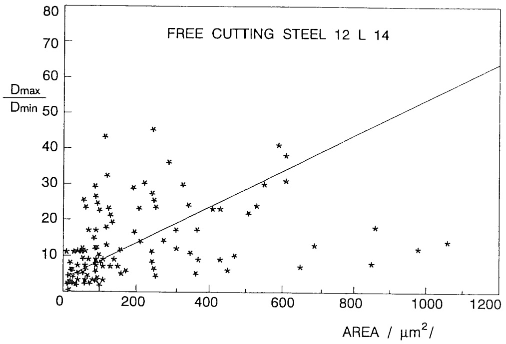

Figure 6: *Interdependence of D_{max}/D_{min} with respect to mangaese sulphide inclusion area.*

ANALYSIS OF EXPERIMENTAL RESULTS

Statistical analysis of manganese sulphide

Figure 6 presents the relation between the D_{max}/D_{min} ratio and the area of the manganese sulphide inclusions. A prevailing trend is the ratios $D_{max}/D_{min} = 1...10$, then the values disperse strongly with the area being larger than 100 μm^2. In the case of larger areas, the majority of manganese sulphide inclusions are narrowed substantially, but there are also other not so markedly narrowed, having smaller values of D_{max}/D_{min}. The tendency of the results is shown by the regression line revealing that at high area values of the manganese sulphide inclusions, higher D_{max}/D_{min} ratios, can also be expected (Grum and Ferlan, 1993).

Figure 7 presents the distribution of the area values of manganese sulphide inclusions in 12 L 14 steel. The figure presents four separate graphs presenting different magnitudes of the area. The first one presents the area up to 150 μm^2. The majority of the inclusions fall into the first class and then decrease rapidly so that only a few particles can be found with an area around 700 μm^2. In the second graph, the magnitude of the area was lowered to 30 μm^2. Observing the distribution of the inclusions in the first class, we see that the vast majority of the inclusions have a size of up to 30 μm^2, only some of them being larger. In the next two graphs, the magnitude class was lowered further and that to 15 μm^2 or 2 μm^2. From the discussed graphs it can be noted that the majority of the inclusions are relatively small, which is also expected of free cutting steels for successful metal cutting.

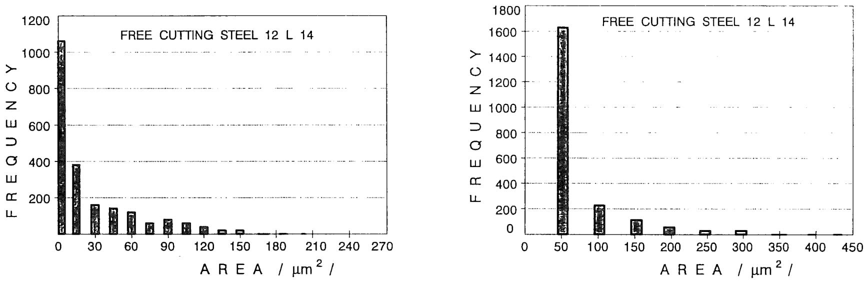

Figure 7: *Distribution of manganese sulphide inclusion in free cutting steel 12 L 14 (AIS1 standard).*

Characteristic wear parameters

Very interesting result are shown by the simultaneously following of wear on the clearance face VB and the increase of crater depth KT at the same speed "v_1" and feed rates f_1 and f_2. Crater depth increases fastest for steel quality 1213 which contains only sulphur as alloying element, whereas in the other two steel qualities the crater increases somewhat faster at the feed rate f_2 than at the feed rate f_1. Steel qualities 12 L 14 and C11 L 17 show, as expected, despite different content of the alloying elements (sulphur and lead), a highly similar increase of crater depth KT. The latter is somewhat bigger at steel quality C 11 L17.

A better understanding of the behaviour of particular steel qualities at machining is possible by analysing Figure 8 which again shows the behaviour at machining with the smallest cutting speed v_1 and both feed rates f_1 and f_2 for all three steel qualities. Here the wear on the clearance face is almost independent on the feed rate, but the difference in crater depth after cutting time T=15 min of cutting is more visible. The crater depth is very distinct for steel quality 12 13 and is about four times larger than for the other two qualities. The main cutting force F_z remains within the expected limits, and for qualities 12 13 and C 11 L 17 it depends on the feed rate, while for quality 12 L 14 Pb it is equal for the two feed rates (Grum, 1986).

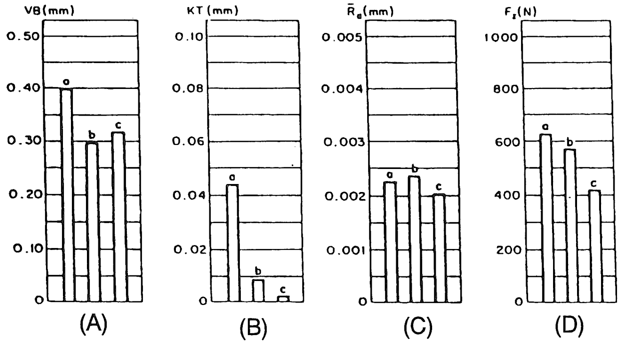

Figure 8: *(A) Wear on the clearance face V; (B) crater depth on the rake face KT; (C) magnitude of the main cutting force F_z; and (D) surface roughness of the workpiece R_a after 15 min of turning. Workpiece material: a-12 13, b-C 11 L 17, c-12 L 14. Cutting conditions: cutting time T=15 min, v_1=250 m/min, f_1=0.132 mm/rev, a=2 mm.*

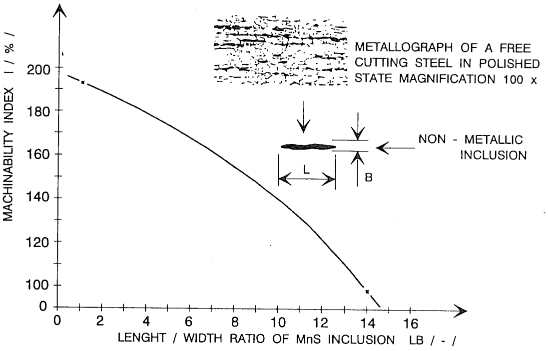

Figure 9: *Machinability index in dependence on the shape of MnS in free cutting steels.*

Figure 9 shows the effects of the shape of manganese sulphide inclusions on machinability index. With the ratio Dm/min = 1 ... 14 the machinability index varies from I=200 ... 100 per cent, which means that manganese sulphide inclusions in free cutting steels should be as much circular (globoid) as possible (Van Vlack, 1953). Such geometric conditions are however very difficult to achieve mostly because of the unavoidable hot working of steel until the semi-product. It has namely been found out that with some inclusion such as: tellurium, boron and selenium in free cutting steels alloyed by sulphur the ratio D_{max}/D_{min} = 2...4 can be achieved. Such a ratio of course ensures better machinability (Leskovar and Grum, 1983).

In figure 10 the conditions in the tool-workpiece-chip cross section are illustrated. At lower or mild machining conditions the protective layer does not occur and the inclusions, e.g. MnS. remain isolated even after cutting. At increasing machining conditions the MnS from the chip or workpiece material is softened and extruded and starts depositing on the tool rake face.

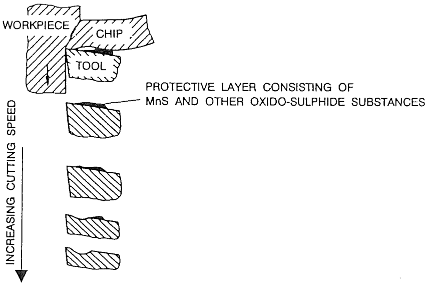

Figure 10: *Influence of cutting speed on tribological conditions between the tool and chip with special emphasis on the effects of non-metallic inclusions.*

The conclusions to be drawn from the above mentioned research are that limiting cutting speeds play a very important role and depend mainly on the deoxidizing agents. The formation of a built-up edge on the rake face depends on the speed of cutting and on the feed-rate. The increase of the cutting speed shifts the generation of the built-up edge to the lower feed rates. This confirms the hypothesis on the influence of temperature in the contact zone on the formation of the built-up edge.

On the basis of knowledge that non-metallic inclusions occurring in steel because of the effect of deoxidizing agents can be either a soft, hard, plastic, or brittle substance, these different substances can leave more or less distinct effects on the development of wear. Substances which are enough plastic at given machining conditions can deposit between the chip and the tool during the cutting process. They can inhibit abrasive wear and diffusion processes. This means that the function of a protective layer can be expected at different machining conditions in dependence on the substance composition and concentration.

In this way, it obtained a linear dependence between the areas where protective substances (built up-edge) appear and disappear from the tool rake face. A given feed rate and depth of cut is followed by a lower cutting speed when non-metallic substances appear and stick to the rake face. With increasing speed the amount of these substances at first grows steadily due to their plasticity, then, at higher and higher speed rates the extrusion of these substances begins. The cutting speed at which all the substances become extruded from the rake face is called the upper cutting speed. Thus, we can talk of the lower cutting speed at which the protective layer starts appearing and the upper cutting speed at which the chip normally extrudes the substances from the rake face. We also talk of the limiting cutting speeds at a given feed rate and depth of cut at which we can expect the most favourable wear and diffusion conditions on the rake face and thus also the longest tool life. Besides non-metallic inclusions, the limiting cutting speeds, at which a protective layer on the rake face appears, are affected also by tool material. Thus, the findings about the protective layer appearance at the lower limiting speed are not the same for the case of high speed steel tools as for the case of cemented carbide tools etc.

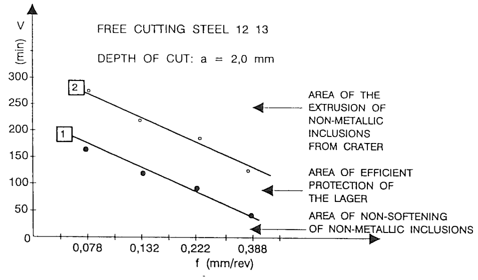

Figure 11: *The effect of machining conditions on the development of the protective layer.*

Figure 11 shows the functional dependence of machining conditions and the development of the protective layer from non-metallic substances on the rake face of a cemented carbide tool. Inside the lines 1 and 2 the machining conditions are such that they enable, due to the pressures on the rake face, the softening and retaining of the protective layer. In the area under line 2 the machining conditions do not enable the softening of non-metallic substances and thus do not enable the development of the protective layer - so this is the area of intensive wear. The area of machining conditions above line 2 assures however an extreme softening and owing to high pressures also the extrusion of non-metallic substances from crater wear area on the rake face. Thus, it is the area between lines 2 and 2 that enables the development of an efficient protective layer of non-metallic inclusions.

CONCLUSION

Free cutting steels should be fabricated so that the best possible machinability is achieved. The term machinability means that it is possible to machine the material at very high speeds, consuming least energy and that friction between the tool and the workpiece or chip is lowest. High cutting speeds are made possible mostly by chip breaking and to a smaller extent by reducing friction in the cutting process. Friction conditions between the chip and tool are described by tool wear on the rake face and flank and are known as tool life time. Tool life time should be as long as possible and should enable machining at high cutting speeds. The fabrication of steel is in and by itself very important, as influences are exerted on the quality of free cutting steels by choosing the type and amount of deoxidizing agents. This had been pointed out decades ago by a number of researchers making reference to the influence of other components in steel on tool wear. In conclusion, we can say that turning conditions can be changed most significantly by the size, distribution and shape of manganese sulphide inclusions. For this purpose we decided to make a statistical analysis of the distribution of the areas, shape factors and D_{max}/D_{min} ratios of these particles.

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