The behaviour of graphitized steels in machining processes

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Abstract. Graphitized steels are claimed to perform excellent in machining processes. They therefore can be considered as environmental friendly alternatives to widely used Pb-alloyed steels. Due to liquid metal embrittlement and in-situ lubrication Pb improves machinability in a narrow tool-chip interface temperature window corresponding to low machining speeds. Although graphite inclusions are also supposed to generate in-situ lubrication, the mechanism and the corresponding optimum working zone is not very clear. The present work applies a new test methodology (including in-situ tribology, analysis of material flow and chip formation, optimum working zone analysis) to investigate the effect of graphite inclusions in turning and drilling operations. Pb-alloyed low carbon free-cutting steel and Pb-alloyed case hardening steel were used as reference steels.

Introduction

Using free cutting steels in mass production machining performance is the most important property. It is the main factor influencing part production costs. Widely spread low carbon free cutting steels like 11SMn30 exhibit low hardness resulting in low machining forces. Addition of sulphur leads to the formation of manganese sulphides, which protect the machining tool by in-situ layer formation and reduces friction forces in the chip-tool interface. As a consequence high productivity and long tool lifetimes are reached. However the ferrite matrix of such steels is soft and tends to stick on the tool surface if cutting speeds are low. This so called built-up edge formation (BUE) can be a severe problem producing small parts or in machining operations with partially low speeds like cutting-off or drilling. BUE formation can be efficiently suppressed by adding lead to the steel. Liquid lead then acts as lubricant in the chip-tool interface. Due to its low melting point this effect already occurs at low machining speeds. At higher speeds this benefit disappears (which might be caused by a change in viscosity). As a rule of thumb considering all kind of machining conditions productivity of leaded steel 11SMnPb30 is estimated to be 20% higher comparing to non-leaded steel 11SMn30. This explains the popularity if this steel which is consumed in large quantities in machining workshops all over the world.

The other side of the coin is the toxicity of heavy metal lead. Facing a tendency to more stringent environmental laws it becomes more and more probable that leaded steels will disappear. It is a question of economic importance that other steel concepts can be found to fill in this gap. In the past silicon-rich ferritic steels with graphite precipitates have been discussed as environmental-friendly substitutes for leaded steels by several authors. Iwamoto et al. [1] investigated graphitic steel 53SiB5 in turning tests. At cutting speeds of 200 and 250 m/min the tool lifetime of a sintered carbide tool was significantly increased in comparison to leaded steel SAE12L14. Similar results were obtained by Katayama et al. [2] performing turning as well as drilling tests. The authors found that the tool lifetime of high speed steel drills was 2.2 times that of lead-free machining steel and the tool life of cemented carbide insert used for lathe turning was 3 to 7 times.

Although these former studies certainly showed the beneficial behaviour of graphitic steels in machining operations, the underlying physical mechanism and corresponding optimum working zones are not very clear. Graphite is known as solid lubricant. It is therefore reasonable to believe that graphite inclusions might lubricate the chip-tool interface under certain conditions. It is however unknown whether graphite inclusions are able to suppress BUE formation in a similar way lead inclusions do. Additional investigations are therefore needed to bring more light into the machining behaviour of graphitic steels.

In the present work different questions concerning the machinability of graphitic steel 50SiB8 were formulated. To give some answers a combination of four tests was chosen:

- Turning test: Related with lower friction forces and liquid metal embrittlement low carbon leaded steels show a characteristic minimum of the cutting force at low cutting speeds [3,4]. The addition of manganese sulphides also generates a similar positive but less pronounced effect. How does graphitic steel 50SiB8 behave?
- In-situ-measurement of friction coefficient: Can lubrication due to graphite been verified?
- Quick-stop drilling test: Leaded steels are expected to form thin chips resulting in a low torsional moment, good chip breakage and easing the transport of chips out of the drilling hole. What would the chip formation of graphitic steel 50SiB8 looks like?
- Optimum working zone (V_c,f) in drilling: This industrial standard test procedure is applied to determine optimum cutting parameters for various steels. It has been shown that the addition of lead opens the optimum working zone. This means that leaded steels are machined well within a large range of cutting parameters indicating the “robustness” against process variations. Can graphite steel 50SiB8 be machined well in a narrow or in a wide range of cutting parameters?

Experimental

Turning test

Tests were performed on a turning machine Schaublin 42L under dry cutting conditions. An TiAlN-coated carbide tool CCGW09T304FN was used. Cut of depth and feed rate were fixed: ap = 1.5mm, f = 0.25mm/rev. Cutting speeds were varied between 10 and 200 m/min to cover the expected range of BUE formation.

In-situ measurement of friction coefficient

A new in-process tribometer was developed [5] to measure friction during orthogonal turning on a lathe as demonstated in Fig. 1. The tribometer consists of a spring preloaded tungsten carbide pin (TiAlN coated) with a 3mm spherical tip mounted behind the cutting edge and rubs on the freshly generated work piece surface. The pin is placed 14mm behind the orthogonal cutting contact zone. Previous cutting force measurements were used to set the pin preload F_n by a spring, which corresponds to the feed force at same cutting conditions. The friction forces on the pin are measured by a 3D-Dynamometer Kistler 9047C. Experiments were carried out at cutting speeds between 50 and 300m/min with a feed rate of 0.1mm/rev and a 3mm depth of cut. Although the tribometer has the option of supplying lubrication, dry cutting conditions were used.

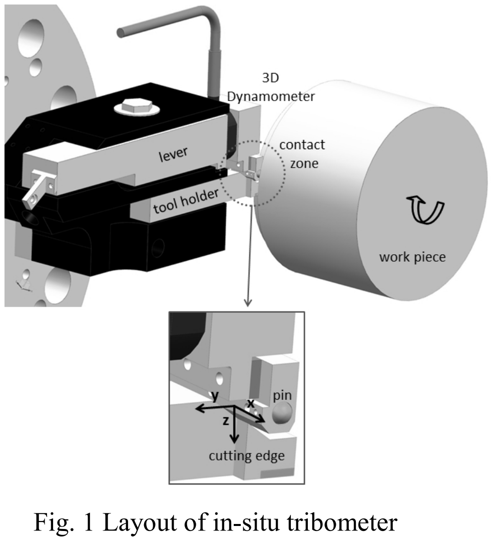

Fig. 1 Layout of in-situ tribometer

Quick-stop drilling test

Small samples of Ø8 mm x 10 mm were machined with an Ø6 mm TiAlN coated tungsten carbide twist drill. After a drilling depth of 6-7 mm the light-weight sample is abruptly released from the clamping jaw. The geometry and weight of the samples were adjusted in previous tests to guarantee that the sample immediately moves together with the tool after releasing. After carefully removing the tool from the sample stable chip roots could be obtained at 60 and 150 m/min cutting speeds. The real chip roots were reconstructed from computer-tomography generated data and given out as .stl-files, which could further be analyzed with CAD-Software. As a result the chip thickness as function of drill tool radius-coordinate is obtained.

Optimum working zone (V_c,f) in drilling

In this test Ø4mm holes with a depth of 16 mm were machined with a HSS drill of type Tivoly N 6-5-2. Cutting speed Vc and feed rate f were varied. The optimum working zone (OWZ) is defined by the (Vc,f)-range where 1'140 holes can be drilled without any problem. This corresponds to a total cutting length of 18 m. Outside OWZ only a small number of holes can be machined before tool breakage.

Results

An 80 tons heat of 50SiB8 was produced under regular industrial conditions at Swiss Steel AG. The steel was molten from scrap in an electric arc furnace and continuously cast into 150x150 mm^2 billets. In the rolling mill billets were reheated to 1200°C and hot rolled into Ø65mm bars. The graphitisation was done in a continuous furnace at Deutsche Edelstahlwerke at a temperature of 700°C. Fig. 2 shows the resulting microstructure which consists of a ferritic matrix with spheroidized carbide inclusions and graphite precipitates. The mechanical properties of all tested steel variants are given in table 1. Due to the needed large amount of silicon (destabilisation of cementite) the ultimate tensile strength of 50SiB8 is significantly larger comparing with low carbon free cutting steels like 11SMnPb30. For this reason leaded case hardening steel 16MnCrS5Pb with a normalized ferritic-pearlitic microstructure was used as second reference steel.

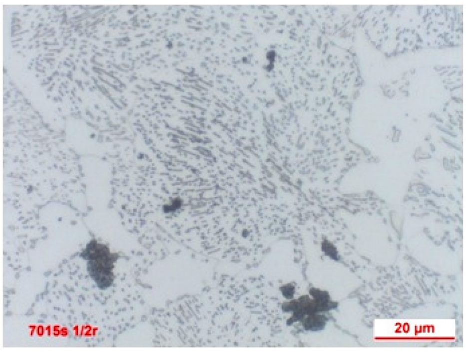

Fig.2 Microstructure

	test	Diameter mm	Rm MPa
50SiB8	all	Ø65 mm	633
11SMnPb30	friction	Ø65 mm	428
11SMnPb30	OWZ	Ø64 mm	445
16MnCrS5Pb	all	Ø62 mm	597

Table 1 Diameter and ultimate tensile strength

Whereas steel grade 11SMnPb30 was investigated in the as cold drawn condition, steels 50SiB8 and 16MnCrS5Pb were only hot rolled, heat treated and machined. An additional cold drawing would lead to much higher ultimate tensile strength values making a comparison more difficult.

Turning test

Mean values of cutting forces (out of three measurements) were plotted in Fig. 3. The different levels reflect the differences in ultimate tensile strength. The cutting force of 11SMnPb30 is about 150N lower in comparison to 50SiB8 and 16MnCrS5Pb. Both leaded steels show the expected tough in cutting force at cutting speeds below 75m/min. No similar effect can be found for graphitic steel 50SiB8. Decreasing cutting speed the curve of 50SiB8 is increasing continuously and much faster in comparison to the reference steels. Higher forces are thought to be related with the formation of thicker chips.

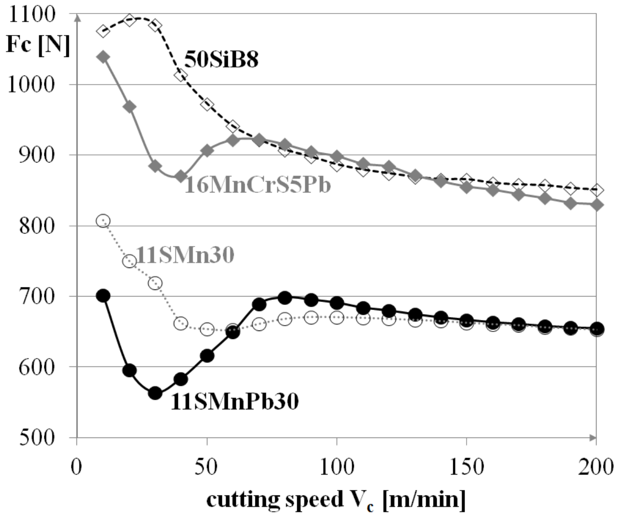

Fig. 3 Cutting forces in turning

This result is a strong indication that steel 50SiB8 is more susceptible for BUE formation and will form thicker chips than the leaded reference steels if cutting speeds are below ~75 m/min.

In-situ measurement of friction coefficient

Fig. 4 gives an overview of the frictional behaviour of the investigated materials at different cutting speeds on freshly generated metallic surfaces. The preload F_n was set by a spring at 430N. Previous examinations show that F_n has a negligible influence on the friction coefficient. The average uncertainty in friction measurements is maximum ±4%. Over all cutting velocities, friction coefficients μ can vary significantly (i.e. from 0.2 to about 0.6). Increasing the cutting speed these differences are getting smaller and the curves approach a value of 0.2 in dry conditions, which corresponds to a semi-solid frictional regime as assumed by Neugebauer et al. [6] and Rech et al. [7].

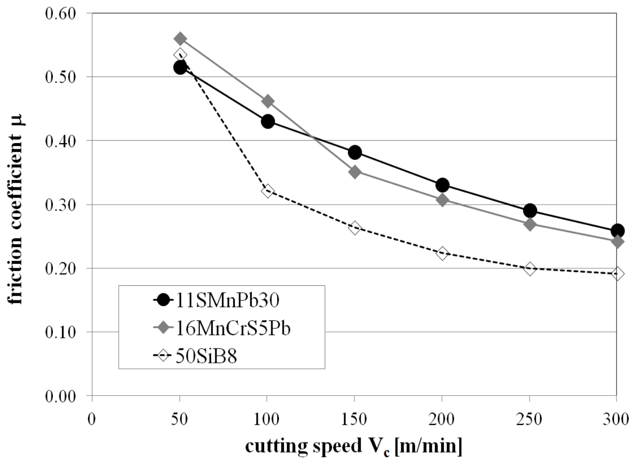

Fig. 4 Measured friction coefficients

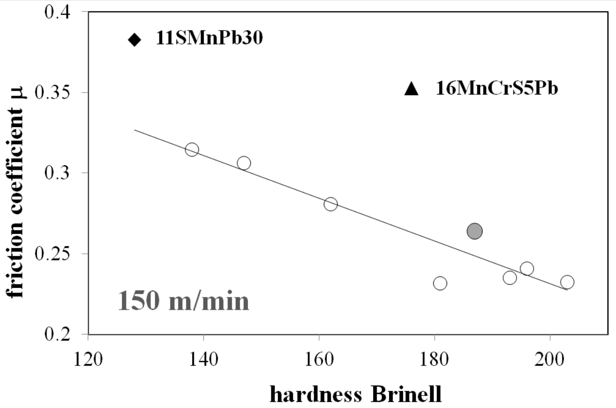

Fig. 5 Friction coefficient in dependence of hardness

Steel 50SiB8 exhibits a lower friction coefficient than 11SmnPb30 at cutting speeds above 100m/min. Because friction behaviour depends on material hardness the hardness effect must be ruled out to verify whether graphite really lubricates the workpiece-tool interface. To do this various labcast heats were produced (vaying for example silicon) and different heat treatments were applied to get Brinell hardness values between 130 and 210. Fig. 5 shows the results for a cutting speed of 150 m/min. The grey dot at a hardness of 187HB belongs to the Ø65 mm bar of the present investigation (Fig. 4). In the considered interval a linear relationship between friction coefficient and hardness was found.

After separating out the contribution of hardness 11SMnPb30 and 16MnCrS5Pb still have significantly larger friction coefficients comparing to 50SiB8 confirming the lubrication by graphite. Below 100m/min, where built-up edge formation is likely to occur, the sequential order changes and lead starts to become a similar or more efficient lubricant. These results make clear that graphite is not supposed to be a one to one substitute for lead.

Quick-stop drilling test

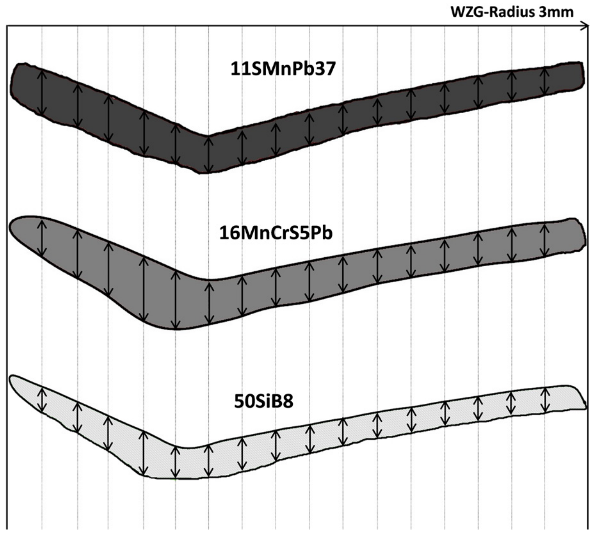

Fig. 6 Chip thickness perpendicular to the cutting edge Vc = 60 m/min, f = 0.35 mm/rev

Analyzing the chip roots in X-ray tomography the whole 3-dimensional information about the chip is obtained and chip thickness (perpendicular to the cutting edge) as a function of drill tool radius-coordinates can be deduced. Fig. 6 shows a comparison between 11SMnPb37, 16MnCrS5Pb and 50SiB8 at a drilling speed of 60m/min. The machining speed then varies from zero at the centre of the hole to 60m/min at the outer radius covering the expected BUE regime.

Based on turning tests and friction coefficient measurements graphitic steel 50SiB8 might be supposed to generate thicker chips than leaded steels. This could not be confirmed. No indication for the occurrence of BUE problems was found. Material flow obviously differs from material flow in turning and excellent results were obtained with 50SiB8.

Optimum working zone (V_c,f) in drilling

This test focuses on the (Vc,f)-transition zone between good (>1'140 holes) and bad (few holes) machinability. In Fig. 7 this zone is marked by a white line. The boxes (with number of reached holes) represent measurements. The dark area is the OWZ. Drilling of holes is almost infeasible outside the OWZ.

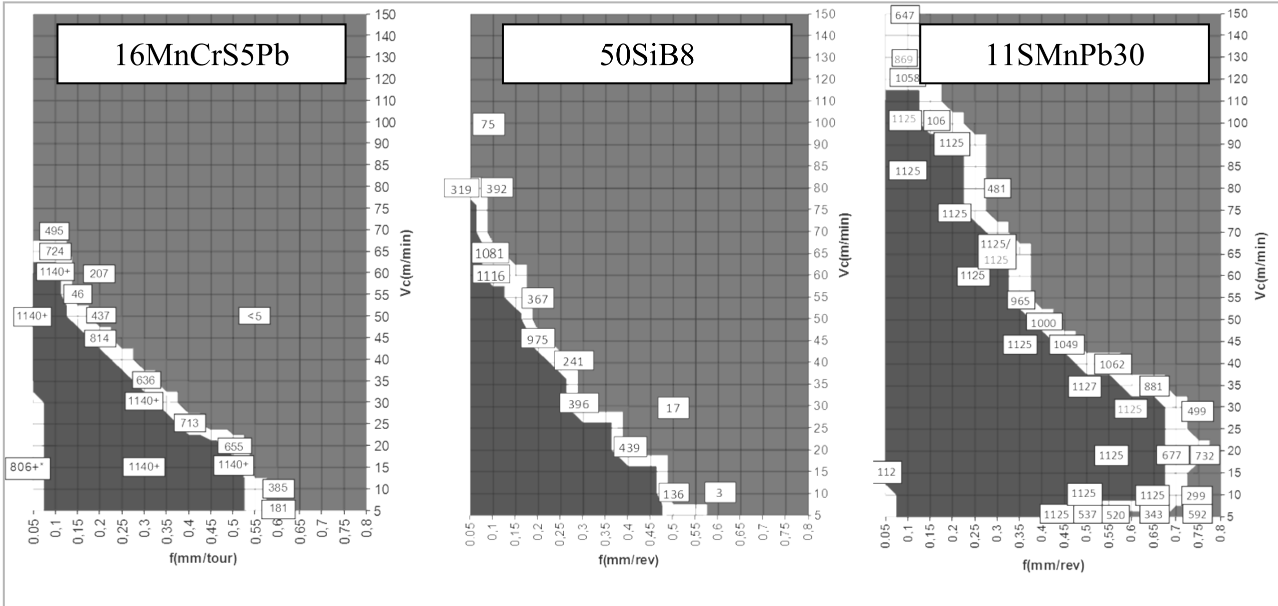

Fig. 7 OWZ diagrams of 16MnCrS5Pb, 50SiB8 and 11SMnPb30

Whereas the OWZ of 16MnCrS5Pb and 50SiB8 are almost identical, the OWZ of 11SMnPb30 is significantly larger. This is in particular true for low cutting forces (<40 m/min)

Conclusions

- In-situ lubrication due to graphite inclusions was verified at turning speeds ≥ 100 m/min

- The friction coefficient of the system "graphite steel-tungsten carbide tool" increases from ~0.2 at 300 m/min to ~0.55 at 50 m/min. At 50m/min the friction coefficient of 11SMnPb30 was found to be lower than that of 50SiB8.

- As a consequence of internal lubrication and "brittle" material flow characteristics graphitic steel 50SiB8 as well as leaded steels 11SMnPb30 and 16MnCrS5 exhibit comparable thin chips in drilling.

- Varying the machining speed from 5 to 150 m/min in drilling with HSS tools, low carbon free-cutting steel 11SMnPb30 shows an outstanding large optimum working zone.
  The performance of graphitic steel 50SiB8 is less excellent but matches well with the optimum working zone of leaded steel 16MnCrS5Pb with comparable hardness

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