Machinability of inclusion engineered free cutting steel under built-up edge conditions

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MACHINABILITY OF INCLUSION ENGINEERED FREE CUTTING STEEL UNDER BUILT-UP EDGE CONDITIONS

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ABSTRACT: Inclusion engineered free cutting steels exhibit outstanding machinability behaviour at elevated machining speeds. Therefore they are promising candidates to replace toxic leaded steels. In the present work an inclusion engineered steel developed by Swiss Steel was investigated at low cutting speeds taking into account air cooling and oil spraying. The material flow during machining and the resulting surface integrity of the inclusion engineered steel were studied and compared with leaded steel, bismuth alloyed steel and tin bearing steel. Under the investigated conditions evidence of in-situ lubrication and of liquid metal embrittlement could only be provided for lead and bismuth containing steels. For this reason inclusion engineered steel can not be considered as a substitute for leaded steels machining at low cutting speeds.

1 INTRODUCTION

In the past decade intensive efforts were made to replace leaded free cutting steels by more environmental friendly steels. In spite of this work and of the increasing political pressure on toxic additives the world wide annually production of leaded steels still exceeds 2 million tons. The prolonged success of these steels lies in the low melting point of lead. This guarantees steel inherent lubrication and liquid metal embrittlement (LME) at low machining speeds preventing built-up edge formation (BUE).

The functional replacement of lead will have to address two important questions: (i) how can the tool-chip interface be lubricated during machining, and (ii) how can BUE formation be suppressed effectively?

Focusing only on the steel composition itself different material concepts were proposed. Already in the early eighties Inland Steel published the beneficial machinability of bismuth-containing free cutting steels [1,2]. The melting point of bismuth is even lower than the melting point of lead resulting in excellent in-situ lubrication during machining. Nevertheless: bismuth has severe disadvantages. The few worldwide sources of bismuth makes it not a real economic lead alternative. The hot rollability gets worse by adding bismuth resulting in high rolling temperatures and modest wire surface quality. It is also very questionable whether bismuth alloyed steels would be less toxic than leaded steels.

A more environmental friendly steel concept was developed by Nippon Steel [3]. Graphite inclusions were generated in the steel to obtain a lubricating effect during machining. In this case an expensive thermal treatment must be used to get the right size of inclusions. The resulting steel differs in strength level and toughness from conventional free cutting steels. Published data [4] show excellent machinability at elevated machining speeds. Studies under

BUE conditions are not known. Nevertheless the outstanding and usually undesired brittleness of the steel could be an advantage in preventing BUE formation.

Bismuth and graphite steels clearly drop out because of economic reasons. Other alternative steel concepts have therefore become more popular. Recently tin has been proposed to replace lead [5]. The low melting point of tin makes it a promising candidate. Nevertheless the solubility of tin and its precipitation behaviour differ clearly from lead. The improvement of machinability due to tin has not been clearly demonstrated yet. Under some particular conditions satisfying machinability was stated [6,7]. In general it must be taken into account that tin causes hot shortness problems during rolling. For this reason tin enriched scrap is undesirable. Large production of tin bearing steels would affect the quality of all scrap-based steels on a longer time scale.

Another metallurgical concept that found broad interest is oxide inclusion engineering. Well designed soft glassy oxide inclusions in free cutting steels can clearly improve tool lifetimes at elevated cutting speeds in comparison to conventional leaded steel grades (Figure 1). This idea has been applied by some European [8,9,10] and Asian steel making companies [11] developing different metallurgical steel production processes to gain optimum oxide inclusions in their steels. Due to the quite high softening points of the designed oxides it is unclear whether these inclusions are able to lubricate the tool-chip interface. Also their influence on BUE formation has not been investigated yet.

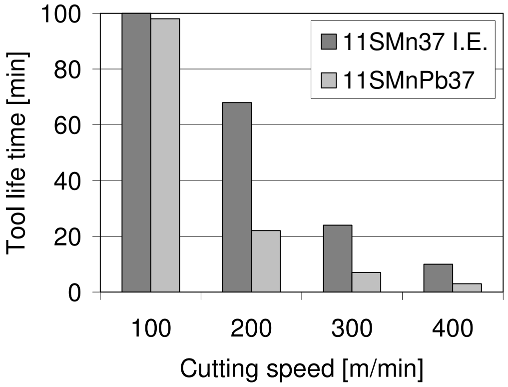


FIGURE 1. Tool lifetime of inclusion engineered steel in comparison to standard 11SMnPb37 [12]

The present study intended to investigate the behaviour of inclusion engineered steel 11SMn37 I.E. at low cutting speeds. Material flow and tool-chip lubrication thereby should be positively influenced applying air cooling and external spraying to come as close as possible to the machinability of standard leaded steel 11SMnPb37. Other potential candidates to replace leaded steel like tin steel or bismuth steel were also taken into consideration. A methodology was looked for to get fast reliable information about material flow (LME), in-situ lubrication and BUE formation.

2 EXPERIMENTAL

Commercially available steels were cold drawn and peeled. The chemical compositions of the investigated steels are given in Table 1. The difference in sulphur content as well as in the sulphide distribution of these steels is expected to play a role, but this effect was considered to be minor.

TABLE 1. Chemical compositions

	C	S	Mn	P	Si	Pb	Bi	Sn
11SMn37I.E.	0.09	0.38	1.47	0.01	0.16	-	-	-
11SMnPb37	0.07	0.39	1.39	0.05	-	0.25	-	-
Bismuth steel	0.09	0.31	1.03	0.06	-	-	0.08	-
SAE12T14	0.09	0.30	1.13	0.06	-	-	-	0.05

Single point turning tests were performed on a standard turning machine (Schaublin 42L) equipped with a conventional force platform (Kistler type 9121). Steels samples of 500 mm in length and 31 mm in diameter were turned applying three cuts of 2 mm in depth. The tin and the bismuth steel samples were obtained by peeling drawn bars from 35 mm to 31 mm. The other steel samples were directly cold drawn. To eliminate the influence of the outer skin the first 2 mm deep cut was not used for analysis. Every test was performed three times.

In order to hit the regime of BUE formation a variation of cutting speeds (v_c = 10, 20, 30, 40, 50, 60, 80 und 100 m/min) at fixed feed rate f = 0.2 mm/rev and cut depth a_p = 2mm were chosen.

A standard HM insert was used in one uncoated version and with two different coatings (CNMG 120408-GN IC28, CNMG 120408-GN IC9015, CNMG 120408-GN IC8048). The outer coating layer was “none”, TiN and Al_2O_3, rake angle $\gamma = 1°$ and clearance angle $\alpha = 6$.

To vary cooling conditions air cooling (6bar) and spraying with a commercial minimum quantity lubricant were applied during the machining. The lubricant, based on synthetic ester oil, contained 1.8% S and 0.3% P and was fed to the air stream (6 bar) at a rate of 20 ml/h.

Additionally to the machining forces chip thickness and piece surface roughness were determined. Chip thicknesses were used to characterize the material flow. After each test six arbitrarily chosen chips were sized manually using a sliding calliper. Surface roughness R_z was measured as indicator for BUE formation using a standard Talysurf instrument.

3 RESULTS

To reduce the number of investigations a fixed tool coating was chosen based on preliminary studies with 11SMn37 I.E. In a second step chip compression behaviour of the four steels was analysed considering the relationship between steel deformation (chip thickness h_{ch}) and applied force (cutting force F) under air cooling and oil spraying. This gives some indications about material flow and in-situ lubrication. The BUE phenomenon however is difficult to isolate from force measurement data. In a last investigation an attempt was made to study the BUE formation in more detail looking at the surface quality of the resulting work piece.

3.1 COMPARISON OF TOOL COATINGS

Standard HM tools with two different multilayer coatings were compared with the uncoated tool of the same geometry. The outer layer of the coating influences the adherence between steel and tool, i.e. tool-chip lubrication as well as BUE formation. In the present investigation the outer layers were TiN and Al_2O_3 respectively. TiN is expected to give best results due to its low adhesion force with the ferrite phase and its high affinity to sulfide [12].

In principal, friction forces would be the resultant of tool-chip interaction. However in the calculation of the true friction force some assumptions about the tool edge ploughing force must be made. This is not trivial particularly in case of BUE occurrence. For this reason the cutting force was preferred in this work. Main contributions to the cutting force come from material deformation and tool-chip interaction. Modifications in lubrication affect the tool-chip interaction and therefore should be reflected in the cutting force signal. BUE formation on the other hand changes the material flow conditions at the cutting edge resulting in cutting force changes. Cutting force measurements therefore should be sensitive to both, lubrication of the tool-chip lubrication and to BUE formation.

The tool coatings were tested under three different cooling conditions. “Dry machining” means without any coolant. “Air cooling (6 bar)” represents a cooling without any lubrication agent. Adding 20ml/h of lubricant gives the condition “with lubricant”.

In Figure 2a the results obtained under dry machining conditions are shown. At 100 m/min cutting where no BUE formation occurs the lubrication effect of the tool coatings can clearly be seen. No significant difference between TiN and Al_2O_3 could be found. Below about 50 m/min a steep drop in the force curve was observed for the dry machining condition (indicated by the arrow). In literature this behaviour is ascribed to BUE formation [14]. This behaviour is not obviously seen in case of coated tools. This is an indication that coated tools suppress BUE formation.

Changes in the cutting force are related with changes in chip thickness. In Figure 2b the relationships between cutting force and chip thickness are given for the uncoated tool and the TiN coated tool respectively. From this plot it becomes obvious that the steep drop in Figure 2a (“uncoated tool”) must be due to the occurrence of thinner chips.

The cooling conditions “air cooling” (Figure 3a) and “with lubricant” (Figure 3b) gives rather similar results. It is not quite clear how effective the cooling in the vicinity of the tool edge really was. However in case of cooling the occurrence of BUE formation should be shifted to higher cutting speeds which seem to happen (arrows in Figure 3a and 3b). Nevertheless underlying geometrical effects (for example stronger curling of chips) could also play a role.

Uncoated tools are highly sensitive to changes of cutting parameters. This is a severe disadvantage under practical production circumstances. Machining with coated tools, however, behave significantly more stable. In this work the TiN coating was favoured due to the somewhat lower cutting force in comparison to the tests with the Al_2O_3 layered tool. Further investigations were therefore done with the TiN coated tool.

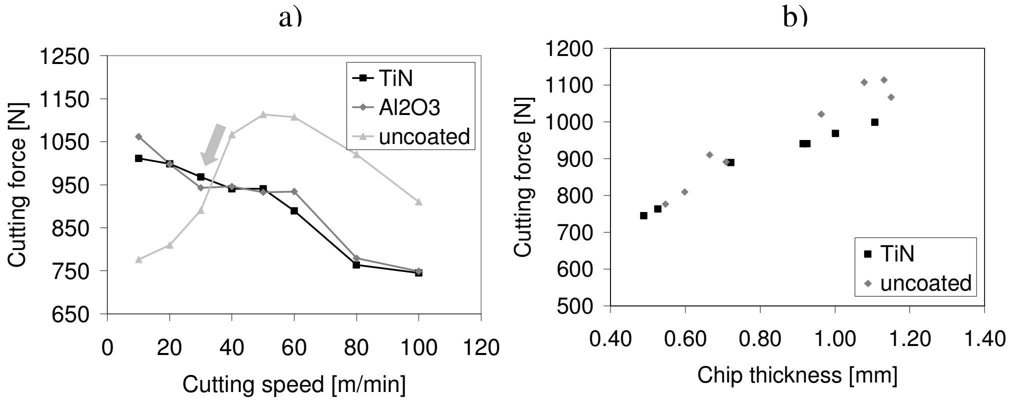


FIGURE 2. (a) Cutting forces of 11SMn37 I.E. under dry machining conditions and (b) dependence of cutting force on the chip thickness h_{ch}

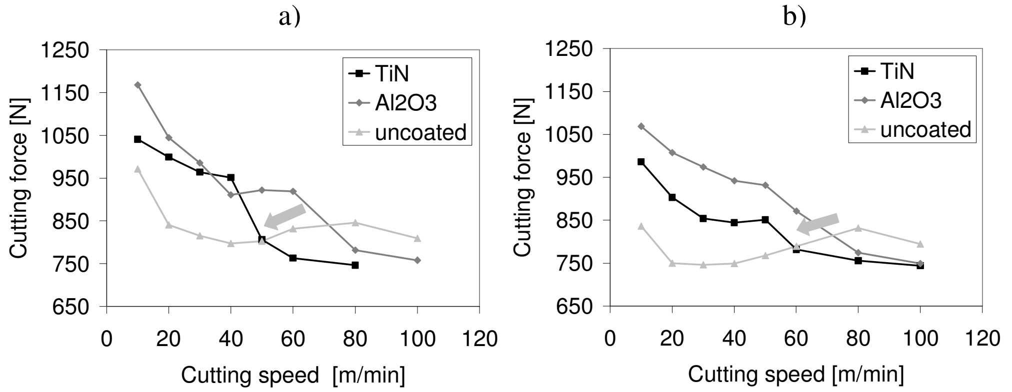


FIGURE 3. Cutting forces of 11SMn37 I.E. under (a) air cooling conditions and (b) under the condition "with lubricant"

3.2 CHIP COMPRESSION BEHAVIOUR OS STEELS

Material deformation gives the dominant contribution to the cutting force. Cutting force (F) and chip thickness (h_{ch}) are therefore expected to correlate (see Figure 2b). Considering machining with a TiN-coated tool corresponding F-h_{ch}-plots are shown for 11SMn37 I.E. (Figure 4a), the tin bearing steel (Figure 4b), 11SMnPb37 (Figure 5a) and the bismuth steel (Figure 5b) respectively.

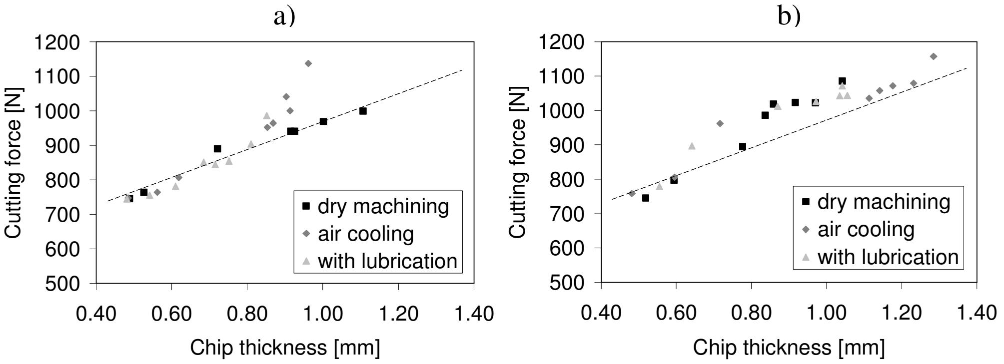


FIGURE 4. F-h_{ch}-plot of (a) 11SMn37 I.E. and of (b) tin steel machined (both with a TiN-coated tool)

Under dry machining conditions the cutting force increases linearly with the chip thickness for 11SMn37 I.E. (dashed line as guide to the eyes). Using a coolant the cutting force should increase as soon as the cooling is effective in the zones of deformation (dominantly in the primary shear zone). This seems to be the case if the cutting speed is low enough (and thick chips occur). However the effect is modest.

The tin bearing steel behaves very similar to 11SMn37 I.E. (the dashed line out of Figure 4a is given as reference). A small shift to higher cutting forces could be due to differences in the chemical composition (lower sulphur content).

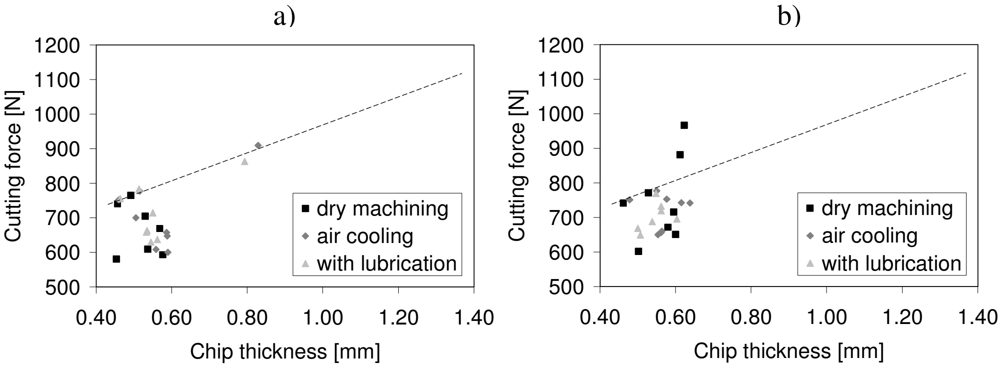


FIGURE 5. F-h_{ch}-plot of (a) 11SMnPb37 of (b) bismuth steel (both with a TiN-coated tool)

In contrast to these results the leaded steel grade 11SMnPb37 behaves completely different (Figure 5a). Only few data follow the dashed line (obtained with 11SMn37 I.E). These singular dots belong to cutting speeds below 20 m/min or above 80 m/min. Between these cutting speeds the chip thicknesses are almost constant. This phenomenon can be explained by LME. In a temperature range of 300 – 400°C the lead inclusions in the steel become liquid. Under this condition the possible strain accumulation of the steel before fracture is severely reduced. Only thin chips (here 0.5 – 0.6 mm) can be formed. Most cutting forces lie clearly below the reference line. This is remarkable because there is no indication that the chip formation energy of 11SMnPb37 is lower than in case if 11SMn37 I.E. (outside the LME regime the results lie on the dashed line). Therefore an in-situ lubrication due to liquid lead is the most probable explanation for this effect. Lowest cutting forces were obtained at 30 and 40 m/min cutting speed.

In spite of the much lower bismuth content (0.08%) in comparison to the lead addition (0.25%) bismuth steel behaves very similar to leaded steels (Figure 5b). Due to the lower melting point of bismuth the trough in the cutting force curve is shifted to lower cutting speeds (Figure 6) compared with the leaded steel. For this reason bismuth is expected to be a more effective machinability agent than lead as soon as machining operation at very low machining speeds are considered.

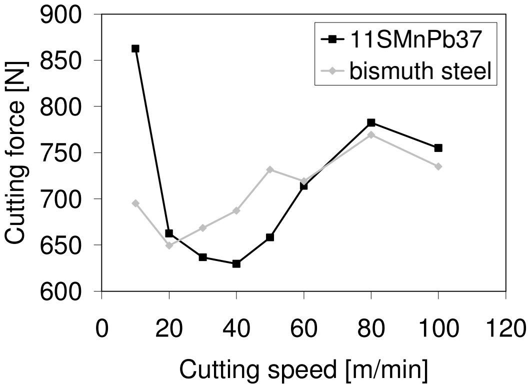
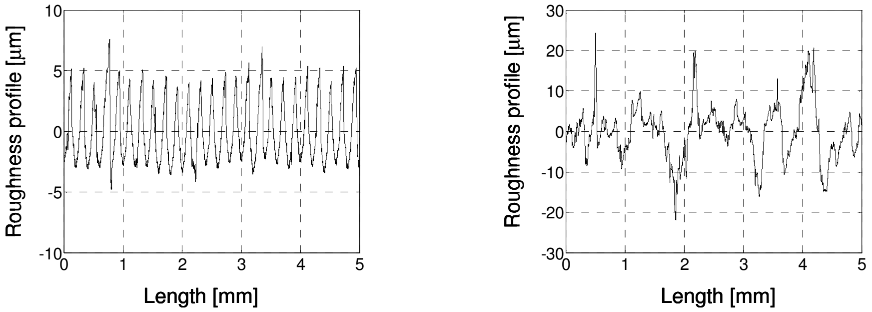


FIGURE 6. Cutting forces of bismuth steel compared to leaded steel machined with lubricant and a TiN-coated tool

3.3 SURFACE QUALITY OF WORK PIECE

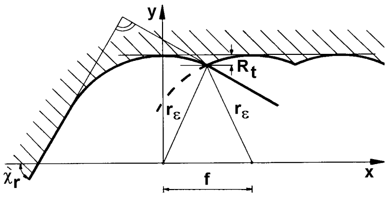
Using TiN coated tools no clear indication for BUE formation could be recognized from cutting force or chip thickness measurements. BUE formation happens very locally as a result of bad material flow conditions at the vicinity of the cutting tool edge. Beside cases of severe BUE it is difficult to observe BUE formation looking at the machining process itself. On the other hand the work piece surface quality should change very sensitively as soon as BUE formation occurs.

Ideally the shape of cutting tool edge and the plasticity of work piece material determine the surface quality after machining. The microscopic surface roughness then is a copy of the tool trace on the work piece.



a) v_c = 100 [m/min]

b) v_c = 20 [m/min]



f = 0.2 mm

r_ε = 0.8 mm

$R_t = f^2/8 * r_\varepsilon$

R_t = 6.75 mm

FIGURE 7. Examples of surface roughness profiles of 11SMn37 I.E. machined with uncoated tools under dry conditions

As soon as a piece of BUE disturbs the surface quality the periodicity of the surface profile (Figure 7a) is getting lost (temporarily, Figure 7b). The occurrence of single events affecting the surface roughness might be best quantified by the difference in height between maximum and minimum position in the roughness profile. This value is called R_t. Theoretically R_t is expressed as a function of tool edge radius and feed rate (Figure 7). With a tool edge radius of 0.8 mm and a feed rate of 0.2 mm/rev the value of R_t should be 6.75 µm. In the present investigations the lowest measured value of R_t was 8.98 µm for the 11SMnPb37 machined with a TiN coated tool at 100 m/min cutting speed. This value can be interpreted as reference for an ideal tool geometry (without BUE).

In Figures 8a, 8b and 9, the measured R_t values are given for the conditions “dry machining”, “air cooling” and “with lubricant” respectively. At cutting speeds between 40 and 100 m/min there is no significant difference between all these machining conditions. Decreasing the cutting speed R_t is continuously increasing to about 20 µm.

The improved surface quality at elevated cutting speeds could be due to higher stiffness of the work piece material or to higher velocity of chips moving out of the vicinity of the cutting edge (preventing the chips from scratching on the work piece surface).

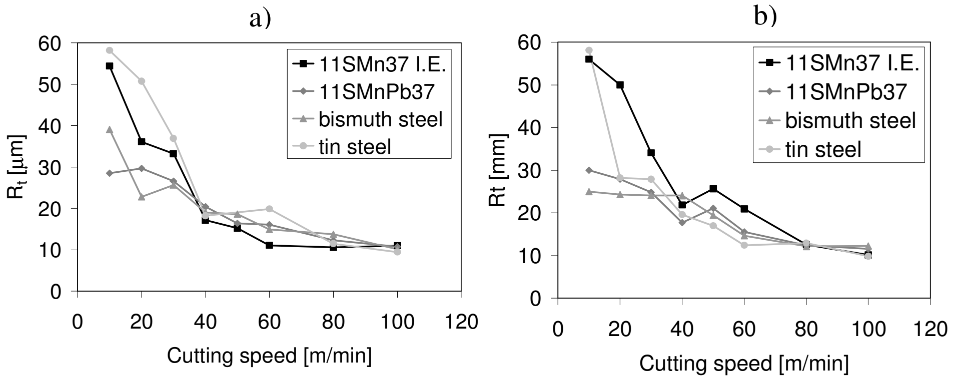


FIGURE 8. Surface roughness R_t after (a) dry machining and (b) machining with air cooling (both with a TiN-coated tool)

At low cutting speeds BUE formation is expected to appear and to affect the surface quality negatively. Indeed below 40 m/min a characteristic change in the R_t-curve can be observed. Whereas air cooling does not significantly affect this behaviour the use of a small amount of lubricant improves surface quality clearly. Earlier investigations show that the lubricant does not suppress the BUE formation itself but it avoids the deposit of parts of the BUE on the work piece [15]. This effect can be seen for all four steels.

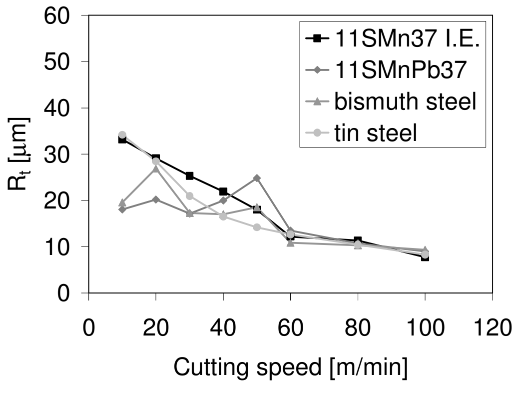


FIGURE 9. Surface roughness R_t after machining with lubricant and a TiN-coated tool

Within the scattering of data the 11SMnPb37 and the bismuth steel are not distinguishable. Both steels show a better surface finish than 11SMn37 I.E. and tin steel. Using a lubricant the differences between the steels are significantly reduced.

4 CONCLUSIONS

F-h_{ch}-plots can be used to investigate the occurrence of LME as well as the effectiveness of in-situ lubrication under real machining conditions

- In spite of the outstanding machinability of inclusion engineered steels at elevated cutting speeds no beneficial effect (in sense of LME or in-situ lubrication) could be demonstrated at cutting speeds below 100 m/min. LME behaviour and in-situ lubrication were only found for the leaded steel and the bismuth alloyed steel, not for the tin bearing steel.

- The use of a lubricant improves part surface quality if machining takes place under BUE conditions (below 40 m/min).

5 ACKNOWLEDGEMENTS

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