Tool life and surface integrity in hard milling of hot work tool steels

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Abstract: Machinability enhancement of hot work tool steels can be achieved intrinsically through tailoring of alloying elements and steel processing route but also externally through the use of adequate tooling. The aim of the present investigation was to identify the limitations in hard milling of AISI H13 (50HRC) with respect to different strategies for microstructure control. Accordingly, tool life tests in face and cavity milling were performed using modern PVD-coated carbide inserts where subsequent investigation of tool wear mechanisms and surface integrity were carried out. A modified tool life model derived from Taylor's approach was employed for the assessment of tool life. The results indicate that traditional improvement in machinability through additives and inclusion control appears not always adequate and the role of primary carbides distribution needs also to be considered. Surface integrity studies, namely residual stress, indicate the predominance of compressive residual stress in the machined surfaces.

Keywords:, Machinability, Hot work tool steel, Microstructure control, Tool life, Surface integrity.

1. INTRODUCTION

The advent of mass production demanded good machinability, and this was achieved by the steel makers through alloying modifications (addition of Pb and S), process control (ESR-Electro-Slag Remelting) and special treatments (Ca-Si treatment etc.). Now machining in the hardened state (300~600HV), is an attractive alternative in both component as well as die and tool making and the field is a rapidly expanding [Tönshoff et al., 2000, Elbestawi et al., 1997]**.** All the links in this chain, namely the work material, cutting tools and the machining system have to be optimised. The cutting tool makers and machine tool builders are ready with technical solutions but the synergetic improvement is best achieved when steel design and processing is also tailored towards this [Chandrasekaran et al., 2005]. The positive effects of high Si and S levels as well as Ca treatment on machinability in hard milling has been reported [Poulachon et al., 2001, Fuji et al., 2003, Umino et al., 2004] and the effects of material microstructure on machinability is reported in [Poulachon, G. et al., 2003]. Motivated by the need for appropriate steel design strategies, one class of steels were investigated by us in detail, including traditional machinability tests (Taylor's equation), which indicated large difference between materials arising possibly from steel processing. Along with the state of the art in steel making practice, advanced structure analysis and close attention to tool wear mechanisms based on SEM were the other two critical features in these investigations. One group of tool steels that are often milled, namely AISI H13 type hot working steel were investigated.

2. WORK MATERIALS AND EXPERIMENTAL METHODS

2.1. Material characterization

A standard hot working tool steel AISI H13 (identified hereafter as Std) and three additional variants were chosen to evaluate the effect of traditional (S+Ca) inclusion treatment, novel additive (Bi) and special steel processing method (ESR) on machinability in hard milling. These alloyed steels were heat treated to obtain a nominal hardness of 50HRc resulting in a tempered martensite structure. They contain along with primary carbides varying levels of oxy-sulphide inclusions and both these features were mapped using EPMA [Chandrasekaran et al., 2005], from a field of 800 x 800 μm. Inclusion mapping (Table 1) shows that both H13-ESR and H13-Si+Ca to contain a greater number of finer inclusions unlike H13.

Steel	Number n	Mean size d (μm)	Surface area a (μm^2)	Area fracion R=a/A (%)
H13-Std	23	6.7	805	0.125
H13-ESR	546	1.7	1261	0.2
H13-S+Ca	846	1.9	2377	0.4
H13-Bi	17	8.7	1010	0.16

Table 1: Inclusion mapping of the different tool steels

Moreover, H13-ESR contained large number of more rounded sulphide inclusions, while H13-Si+Ca and H13-Bi contained even many non-sulphide inclusions, which was found to have serious implications on machinability. Quantitative SEM analysis of the primary carbides in the four H13 variants also revealed clear differences. H13-ESR contained practically no primary carbides > 0.8 μm unlike the other three grades. The area fraction of primary carbides controlled by alloy content did not differ between the materials much, but the largest carbides in H13, H13-Si+Ca and H13- Bi were almost 2 to 3 times the size of those in H13-ESR (Figure 1).

Addtionally, TEM study of the different tools steels (Figure 2) revealed the precipitation of a fine structure of secondary carbide in H13-ESR while a coarser structure was encountered in H13-S+Ca. The H13 variant displayed more secondary carbide precipitation at the grain boundaries and the precipitates had the same appearance as for H13-ESR and H13-S+Ca. H13-Bi displayed a cloud like structure of secondary carbide surrounding the primary carbides.

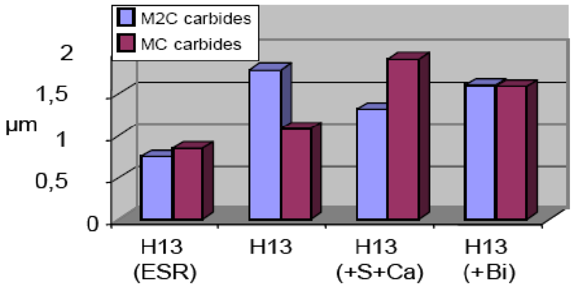

Figure 1: Mean size of primary carbides in H13 steels

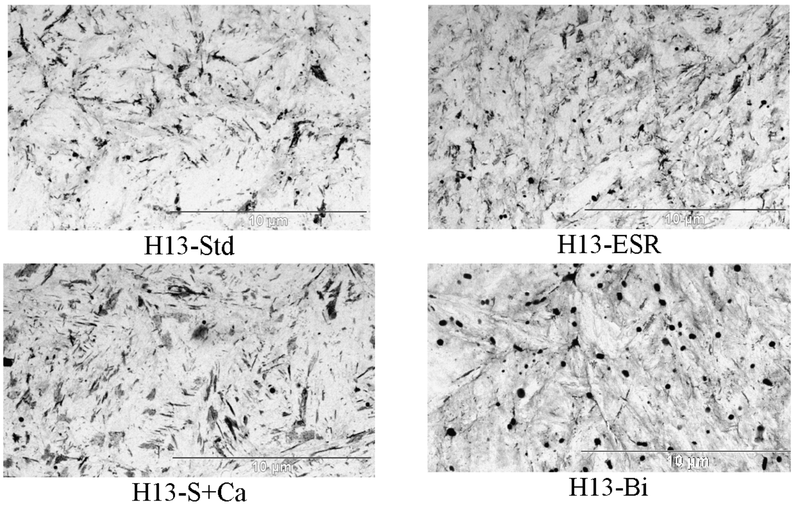

Figure 2: TEM-Secondary carbide structure in the in the different steels

2.2. Machining tests

For the purpose of investigating tool wear mechanisms and modelling tool life, dry face milling tests were carried out for a range of semi-finish milling conditions using single octogonal carbide insert with PVD coating (TiCN-TiAlN-TiN –Seco grade F30M -D18 geometry). The cutting conditions were chosen accordingly to achieve an economical tool life and varied in the following range: vc= 55; 80 m/min, fz= 0.15; 0.25 mm/tooth, ap= 0.3; 1mm and ae= 20; 45 mm.

2.3. Surface integrity studies

Surface integrity studies included measurement of average surface roughness using standard perthometer as well as determination of the residual stress state in the machined affected layers. In the latter, residual stress was determined using the X-ray diffraction method with a Set-X equipment, supplied with a linear detector. A surface area of about 5 mm^2 was irradiated with Cr-Kα radiation, filtered in return with a vanadium filter. The peak displacement of Fe-α {211} diffracting planes was analyzed for 27 ψ, during 45s for each peak acquisition. The residual stresses were calculated using the $\sin^2\psi$ method. The full residual stresses tensor was determined at the sample's surface and in-depth, in the X direction (direction of the feed motion), in the Y direction (direction normal to the feed direction) and in the Z direction (direction normal to the sample surface). In order to determine the in-depth residual stresses, successive layers of material were removed by electropolishing. Further corrections to residual stress data were made due to the volume of material removed.

3. RESULTS AND DISCUSSION

3.1. Tool wear and related mechanisms

Flank wear results from dry face milling tests at a reference cutting conditions of vc= 80 m/min, f = 0.15 mm/rev, ae = 45 mm, ap = 0.3 mm for the four H13 steel variants are shown in Figure 3. The results indicates that machinability between the best (H13-ESR) and the worst (H13-Bi) variants differ by almost 5 times. Nor did the H13-S+Ca variant exhibit any improved in machinability.
It should be pointed that the optimal face milling conditions for each material could be different but our aim here with the single tooth milling tests had been to observe the influence of material behaviour on wear mode and related mechanisms.

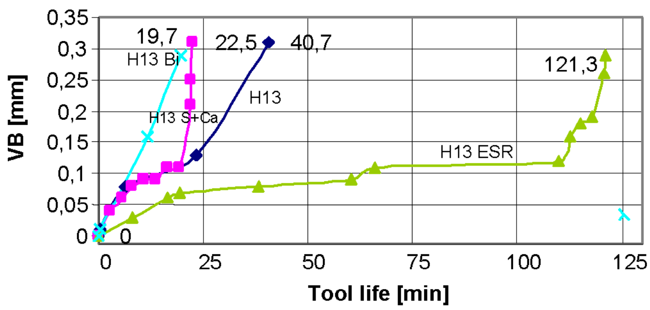

Figure 3: Typical tool life result from single tooth face milling test

Figure 4 displays typical progression of tool wear for the H13-Std steel and Figure 5 (a-d) shows results from SEM-EDS study of some of the worn tools from face milling tests involving four variants of tool steel H13 at mid-tool life. Except in the case of H13-ESR exhibiting a very long tool life, the appearance of the other tools towards the end of tool life was similar.
In the case of H13-ESR a stable wear mechanism based on fine abrasion seems to have been established (Figure 5b), while in other cases this was not so. Obviously this was feasible due to the right type of inclusions and fine carbide structure in H13-ESR. Fine carbide alone with unsuitable (for the cutting conditions used) inclusion content does not result in machinability improvement. The same may be said about the efficacy of special additives such as Bismuth (Figure 5d).

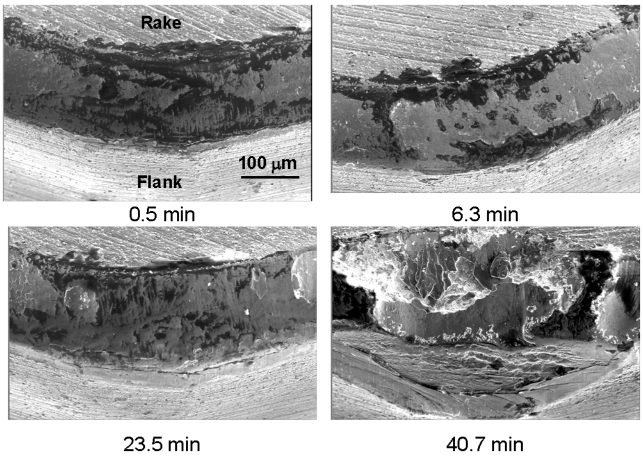

Figure 4: Progress of tool wear with cutting time (H13 Std steel)

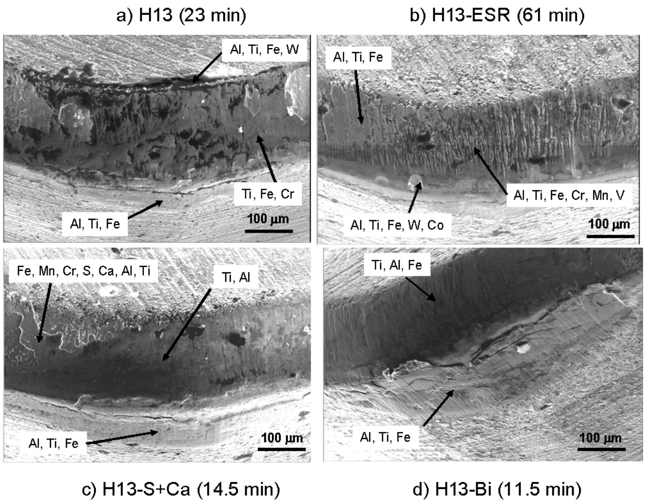

Figure 5: Tool wear (flank region) at mid-tool life (H13 steels)

EDS analysis of the worn inserts (Figure 5) revealed the presence of chemical elements from work material (Fe, Mn, Cr) indicative of adhesion at tool-chip and tool-work contact. In the presence of both inclusions and carbides as in some tool steels tested, features such as the type, size and percentage area fraction of inclusions interact with the carbides in affecting the machinability. Thus even in hardmilling of H13, it is not the amount, but type of inclusions that is critical to reduce tool wear. Moreover, unlike continuous machining operation like turning, hard milling is characterised by intermittent thermo-mechanical loading at the tool-chip contact. Protective inclusion layer may not be sustainable under these circumstances [Chandrasekaran et al., 2005], and the presence of large primary carbides in the work material, affect the outcome even more negatively. The resulting increase in the flank wear and localised heating results in high chip adhesion and the erosion of this portion of the tool and terminating tool life. If the primary carbides are small (< 0.8 µm as in the H13ESR grade) progress of flank wear is stable and resulting machinability is improved substantially. There is also some evidence that adhesive affinity could be reduced through Si content [Fuji et al., 2003]. The above scenario is often valid under conditions of semi-finish milling. However, it was also observed that at higher metal removal rates through feed and or depth of cut rather than cutting speed, the situation could change and other steel variants with traditional treatment could display better machinabilty. As the industry tends towards near net shape manufacture, emphasis on effective performance in finish milling is going to be critical, and hence the need for correct steel development strategy.

3.2. Tool life model

Considering, the cutting speed (vc), tooth feed (f_z), axial and radial depths of cut (*a*p and a_e respectively) and the cutter diameter (D_f) as the main cutting parameters, for a given tool grade and geometry and work material, the classical Taylor equation could be expressed as in eq (1) below.

$$a_p^{\,F}\left(\frac{a_e}{D_f}\right)^D f_z^{\,E}\, T^G\, vc = C \qquad (1)$$

where C, D, E, F, G, H are constants.

However even for a 2 level test with 5 unknown constants $2^5 = 32$ tests are required. If material and/or tool variants have to be considered then the number of tests become unrealistic. One approach to overcome the situation is to use the concept of Tool-Material Pair TMP [AFNOR, 1997]. Based on a half-fractional design of experiments, this model takes into account material variation, as well as cutting parameter interactions. The basic inputs come from milling tests using the Material-Tool pair to establish the limiting values of vc and fz through their relation to specific cutting power taking also into account other end requirements, such as surface finish, chatter free working etc. This facilitates to identify the effective cutting domain. This approach has been successfully in [Rech et al 2004], to study the machinabilty of plastform steels, wherein the method is also described.

The model T-(VB) expresses the tool machining time versus the flank wear level at the end of the tool-life (from VB > 0.20 mm):

$$\log(T) = A_0 + \sum_{i=1}^{6} B_i X_i + \sum_{i=1}^{5}\sum_{j>i}^{6} C_{ij} X_i X_j \qquad (2)$$

The A_0 coefficients are constant values. B_i are coefficients of the main effect of variables, and C_{ij} coefficients express the second order interactions between variables.

The above approach and test procedure were used to compare the four hot working tool steels in this study.

Figure 6 illustrate the reliability of the present tool life model when compared to standard Taylor approach indicating a more accurate a prediction of tool life when mutual interaction of process variables are considered.

The coefficients of Eq. (2) describe the relationship between tool life and the different parameters. For instance when comparing H13 ESR over H13+S+Ca with D18 geometry, the tool life equation obtained is (sign - => decrease the tool life; sign + => increase the tool life):

$$\text{Log } T = 1.562 - 0.328 X_{vc} - 0.3 X_{ae/Df} - 0.239 X_{ap} - 0.178 X_{fz} - 0.157 X_{material} + 0.054 X_{VB} - 0.058 X_{vc}X_{ae}$$

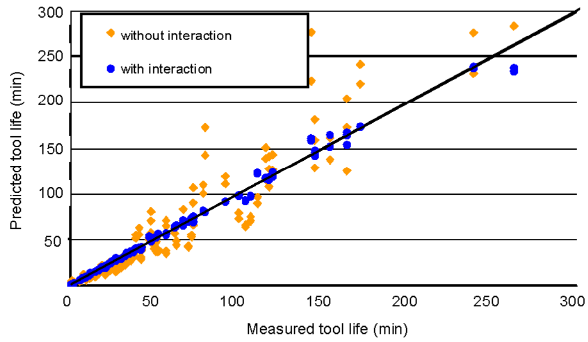

Figure 6: Reliability of models for D18 geometry in face milling operation

Statistical analysis of the results have shown that if only one criterion is considered, the influence of work material and the action of sulphide inclusions can be neglected. This can be explained by the high error rate in a machining operation and the measurement acquisition method. But if 64 points are considered, this rate decreases and the influence of material parameter (like sulphur or bismuth) become significant with a significant variation in tool-life, and sometimes a strong interaction between the feed rate per tooth and the work material is detected.

Effect of material is really coupled with the feed rate in several cases. This means that in the milling process of these variants, it's preferable to use large feed rates than large cutting speeds to have a "material effect" on tool life.

On the one hand, relative to face milling operation with D18 geometry, the combination of resulphurized steel with the highest feed rate improves the tool-life by 22 % ($10^{(2\times(-0.02+0.064))}$ = 1.22 if we consider the Model H13/H13+S+Ca : Material= -0,02 / fz-material = +0.064 / fz-ap = -0.064 /Vc-ap = -0.06 *ae-ap* = -0.060 / *Vc-ae* = -0.056)

On the other hand, the combination of H13 material with the highest feed rate improves the tool-life by 33 % =>$10^{(2\times(-0.015+0.077))}$ = 1.33.

It should be noted that contrary to previous studies [Poulachon et al., 2001], low interaction between sulphur and cutting speed was found in our investigation. In earlier work, lower hardness of P20 type mold steels (300 HB) used enabled higher cutting speeds and hence sufficiently high temperature necessary to trigger a beneficial effect of sulphide inclusions. This was not the case in our investigation due to higher material hardness that limited the cutting speed range (<100 m/min) that were employed for achieving an economic tool life. Some interactions are also shown as important such as the one between cutting speed and radial engagement (Vc/ae) or between feed rate per tooth and axial engagement (fz/ap).

The results show that the most influential parameter is the cutting speed, followed by the parameters a_e, a_p and f_z. These models highlight that few interactions can't be neglected as the generalised Taylor's model assumes, especially the interaction Vc/ap,

vc/a_e, a_e/a_p and f_z/a_p. Thus Primary important information can be observed with this kind of statistical treatment.

3.3. Surface integrity results

Figure 7 displays the results concerning the average roughness value, Ra, of each machined steel surface as a function of tool wear for vc=80 m/min, fz= 0.15 mm/tooth, ap=0.3 mm and ae=45 mm. Ra was determined in two directions: longitudinal direction (x), coincident with the feed direction as well as in the transversal direction (y), perpendicular to x.

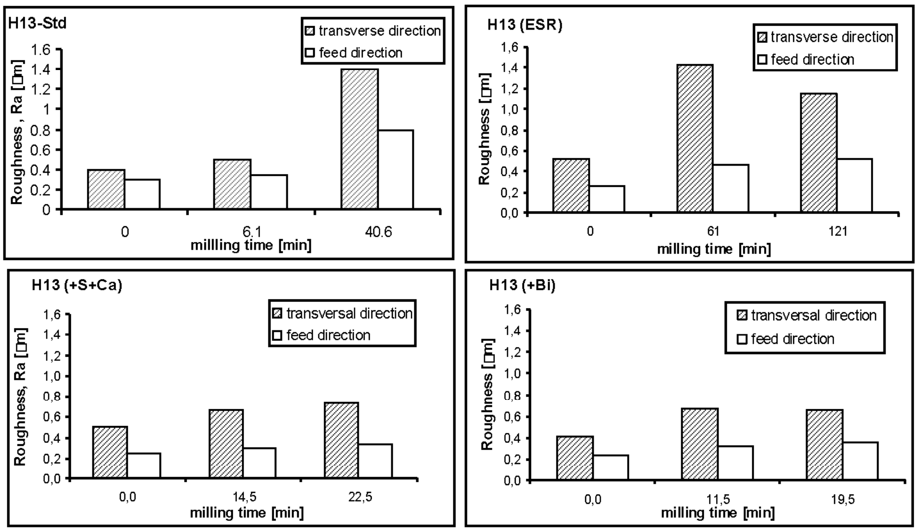

Figure 7: Average roughness of the machined H13 variants with new and worn tool

Roughness generally increases with tool wear and this is more pronounced in the transversal direction y to the feed motion. The Ra values are almost similar for all steels when machining with a new tool (0.4-0.5 µm in the transversal direction and 0.2 µm in the longitudinal one). When machining with worn tool, Ra values varied only marginally for H13-S+Ca and H13-Bi steels, while substantial increase was noticeable H13 Std and H13-ESR variants. In the latter it should be pointed that higher milling time were used to reach the tool life criterion of VB=0.3 mm.

The corresponding residual stresses profiles measured in the *x* and *y* directions of the machined surfaces are shown in Figure 8 and Figure 9 for new and worn tool respectively. The residual stresses increases in compression as the distance from the machined surface increases, reaching a maximum compressive value, then these increases again stabilising at a value corresponding to work material stress state before machining. When machining with a new tool (Figure 8), only small differences are seen between the different work materials with peak compressive stresses values ranging from -400 to -500 MPa. The thickness of the affected layers seems to be independent from the steel variant, about 100-120 µm.

Figure 9 indicate that higher compressive stresses are generated when a worn tool is used (-800 to -1200 MPa) as well as larger compressive stress layer thickness, about

600 µm for H13 Std and 300 to 400 µm for the other steels. The compressive residual stresses seem also to become larger in the x direction when compared to y direction.
It should be pointed that tensile stresses were also observed at the surface in some cases. However these very small (100 MPa) in comparison to work material yield strength (1500 MPa) and tensile strength (1800 MPa). Furthermore, a polishing step is often required on the hot work die steel after machining which would remove the tensile layer, leaving a surface in compression.

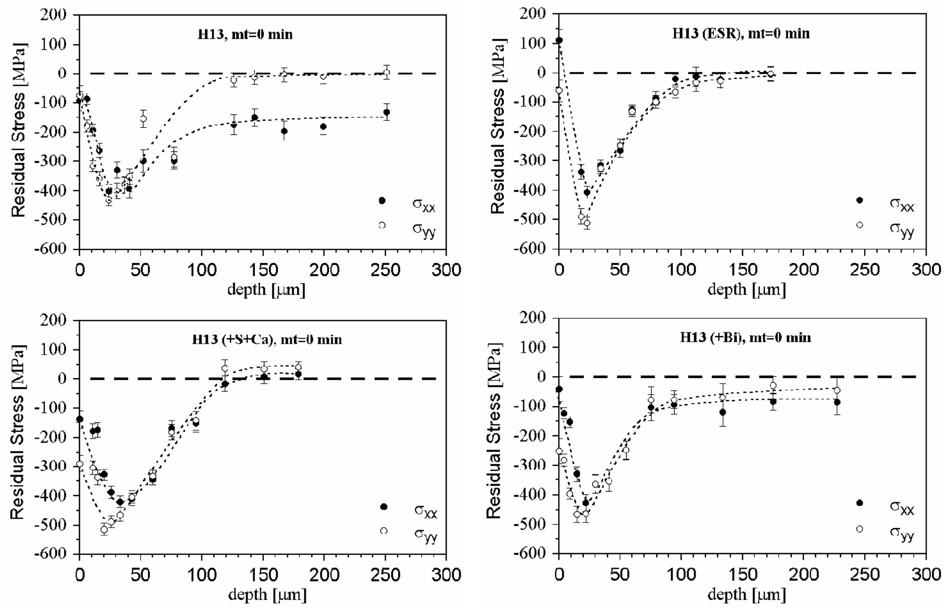

Figure 8: In-depth residual stress profiles, for H13 steels machined with new tool

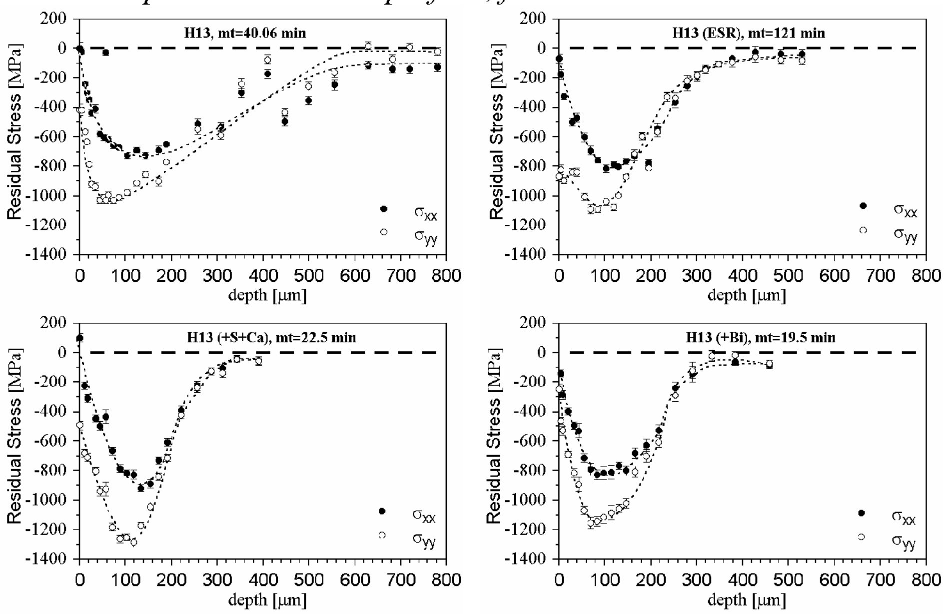

Figure 9: In-depth residual stress profiles, for H13 steels machined with worn tools.

4. CONCLUSION

The results from the present investigation indicate that traditional improvement in machinability in hard milling through additives and inclusion control appears not always adequate and the role of primary carbides distribution needs also to be considered. In the case H13 hardened tool steel a combination of primary carbide size control through ESR treatment in combination with high population of suitable inclusions results in order of magnitude improvement in machinability. Surface integrity studies, namely residual stress, indicate the predominance of compressive residual stress in the machined surfaces.

5. ACKNOWLEDGEMENT

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