

STRESS ANALYSIS OF THE MACHINING PROCESS THROUGH THE FINITE ELEMENT METHOD (FEM): THE EFFECT OF A SINGLE MnS INCLUSION.

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Abstract. *The influence of the microstructure on the mechanical behavior of materials is widely known and is usually evaluated through tensile tests at low strain rates, when the yield and the ultimate strength are measured. On the other hand, manufacturing processes such as machining are carried out by using very high strain rates, when compared to those in tensile tests. The mechanical behavior of the material changes according to the cutting speed in the machining, i.e, the strain rate. Therefore, the machinability of a metallic material is related to its chemical composition, microstructure and strength but also to cutting parameters such as: feed, cutting speed, cutting depth and cutting fluid. In this work, an evaluation on the effect of cutting speeds in two different steels with the same nominal composition was carried out. The results showed the influence of both the cutting speed and the manganese sulfide morphology in the cutting forces. A stress analysis through the finite element method (FEM) was also carried out to analyze the cutting mechanisms resulting from the machining process. The resulting stresses during turning were simulated using FEM, based on the relationship between cutting forces and feed forces. The evaluation of stress distribution in the FEM analysis took into account the microstructure of the steel, mainly the morphology of the manganese sulfide inclusions. No dynamic effect was considered in the model. Nevertheless, a relationship between the FEM model and the experimental results was observed which shows that the machinability is improved by longer MnS inclusions.*
Keywords: *Machining, Finite Elements Method, Steel, MnS Inclusions.*

1. INTRODUCTION

The influence of the microstructure on mechanical behavior of materials is widely known and is usually evaluated through tensile tests at low strain rates, when the yield and the ultimate strength are measured. On the other hand, manufacturing processes such as machining are carried out by using very high strain rates, when compared to those in tensile tests. The mechanical behavior of the material changes according to the cutting speed in the machining, i.e., the strain rate.

The steels machinability is an important characteristic and it can be related to the mechanical properties of the material. The machinability of a metallic material is also related to its chemical composition, microstructure, strength and cutting parameters such as: feed, cutting speed, cutting depth and cutting fluid.

Based on the orthogonal cutting model (Shaw, 1984), the cutting process, during turning, involves three regions. The first region is alongside the shear plane, the second one is the region between the chip and the tool and the last one is the contact between the tool and the turned surface. Therefore, most of the machining processes involve high plastic strain, which occurs in the chip formation. The more easily the chips are formed the cheaper the machining of the component is.

Sulfur addition in steels propitiates the formation of manganese sulfide inclusions that make chip breaking easier. However, the sulfur addition causes losses in the mechanical properties. Models relating cutting force, among other machining parameters, to morphology, size, shape and distribution of inclusions have been proposed in literature (Jiang et al. 1986; metals handbook, 1989; Vignal et al. 2003). These models are both experimental and analytical (Jiang et al. 1986; Vignal et al. 2003). However, the conditions analyzed were markedly different from ones the carried out in industry. The evaluation of cutting forces during machining can also be used to study the cutting mechanisms and the effect of microstructural components during machining, as well as their mechanical properties. The cutting forces are related to the cutting parameters; hence to make use of it, as a comparative parameter, it is convenient to transform the cutting force into a specific cutting pressure, namely *ks* (N/mm^2). This relationship is calculated by dividing the cutting force (*Fc*) by the multiplication product of cutting depth (a_p) and feed (f) (Ferraresi, 1995).

The main objective of this work is to establish a relationship between the cutting forces and the microstructure. Thus, a simplified numeric model was developed by using the finite element method. The stress analysis was simulated by a homogeneous matrix of ABNT 1045 steel containing manganese sulfide inclusions. Therefore, the effect of manganese sulfide inclusions morphology on the matrix stress field during cutting process was analyzed.

2. MATERIAL, EXPERIMENTAL AND FEM ANALYSIS PROCEDURE

2.1. Material

The materials used in this study were ABNT 1045 steels obtained from different batch. The nominal composition of the steels studied is shown in Table 1.

Table 1. Nominal composition of the steel studied.

%C	%Si	%Mn	%P	%S	%Cr	%Ni	%Mo
0.43-0.5	0.15-0.35	0.6-0.9	0.04 max	0.05 max	0-0.2	0-0.25	0.06

The materials used in this study were obtained from rolling bars of 50 mm in diameter, cut into samples approximately 100mm long in order to be tested.

2.2. Microstructural characterization

The metallographic sample preparation of the longitudinal section of each bar was carried by grinding and polishing. After metallographic preparation the samples were observed by using optical microscopy. No etching was carried out.

The volumetric fraction of the sulfide manganese inclusions was observed and quantified through the use of optical microscopy with image analyzer equipment and software.

2.3. Machining

A universal lathe (ROMI 30) was used in the steel samples turning. The tests were carried out by monitoring the cutting forces in different cutting speeds (15, 50, 110 and 190 m/min). The following cutting parameters were kept constant in all cases: feed of 0.2 mm/rotation, cutting depth of 1 mm and the same type of cutting tool, which maintained the plane strain conditions (Shaw, 1984). In order to measure the forces developed during the machining tests, the cutting and feed forces were obtained by using a load cell located on the tool-holder and connected to a data acquisition board. The samples were fixed in by three-jaw chuc*ks* without using a tailstock. The tool utilized was TCMT160304 type. The side cutting edge angle utilized was 0º, the rake angle +4º and relief angle 7º. No cutting fluid was used.

2.4. Finite element procedure

Finite element simulations were carried out by using the ABAQUS commercial software. First, a homogeneous mesh of quadrilateral elements with linear integration was prepared for simulating the stress field in a homogeneous material and for evaluating and calibrating the model for later simulations.

Next, the effect of the MnS inclusions in the stress field in the steel microstructure was simulated (Fig 1). Triangular elements with linear integration were used for analyzing the microstructures under plane strain conditions (Altintas, 2000). Both the isotropic and homogeneous behavior were adopted for the MnS inclusions and the steel matrix; the ferritic-perlitic microstructure was not considered in the simulation. A coherent interface between inclusions and metallic matrix was also adopted, simplifying the numerical analysis. The occurrence of fracture was not taken into account and a coherent interface was assumed.

The Finite Element mesh was refined in some areas (mainly along the interfaces between sulfide inclusions and the steel matrix) to avoid convergence problems resulting from the nature of the elements selected (Abaqus manual, 2006).

For the simulations, the mechanical properties of MnS inclusions were obtained based on nano-indentation testing and compared with those in literature (Vignal et al. 2003). In this case only the elastic behavior was considered and the selected values were 160 GPa for the elastic modulus and 0.3 for the Poisson ratio. The mechanical properties of the steel matrix were obtained from the literature (Matweb, for 1045 hot rolled steel). The elastic properties were 200 GPa for the elastic modulus and 0.3 for the Poisson ratio, and the plastic behavior characterized by 310 MPa for the yielding stress and 565 MPa for the ultimate stress with a corresponding rupture strain of 16%.

The input forces in the simulation were in the range between the yield and the ultimate stresses to ensure plastic behavior of the metal matrix in the numeric model. Two main forces, namely *ks* and *ka*, were used in the simulations. *ks* is the specific cutting pressure, which can be calculated based on cutting force, whereas *ka* is based on feed force. These forces are the most representative ones during the cutting process. However, *ka* cannot be not calculated. So, it was estimated based on the relationship the between cutting and feed forces obtained during the tests. The value of *ka* is approximately half the *ks*. The value adopted for *ks* was 1250 MPa and, as a result the *ka* adopted was 625 MPa. Figure 1 shows the region studied and also shows an example of the MnS inclusions morphology.

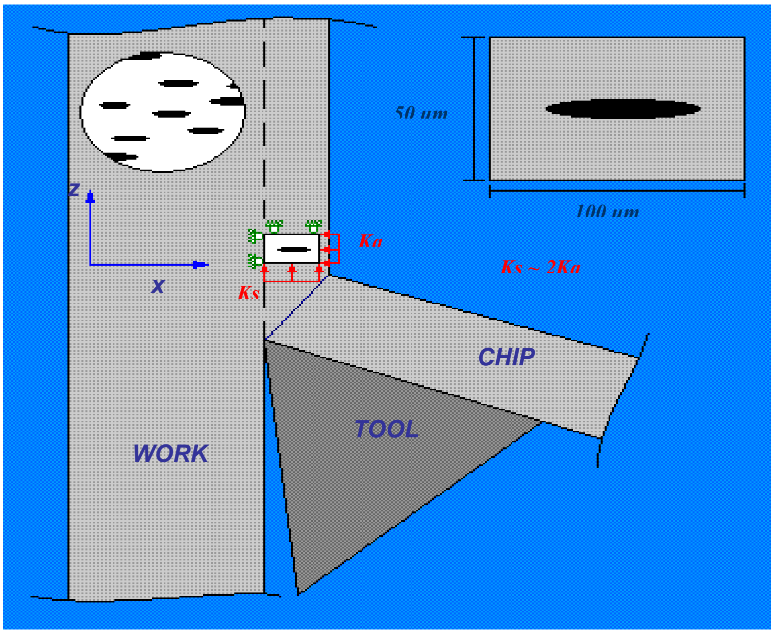

Figure 1. Schematic representation of an orthogonal cutting process showing the analyzed region. Applied pressures (*ks* and *ka*) and the orientation of MnS inclusions.

The purpose of the FEM analysis was to study the influence of the morphology of MnS inclusions on the stress field developed along the steel matrix under the action of both *ks* and *ka*. During the analysis, different combinations of morphologies of a single inclusion (named thickness, *a*, and length, *b*) were tested, as indicated in Fig. 2.

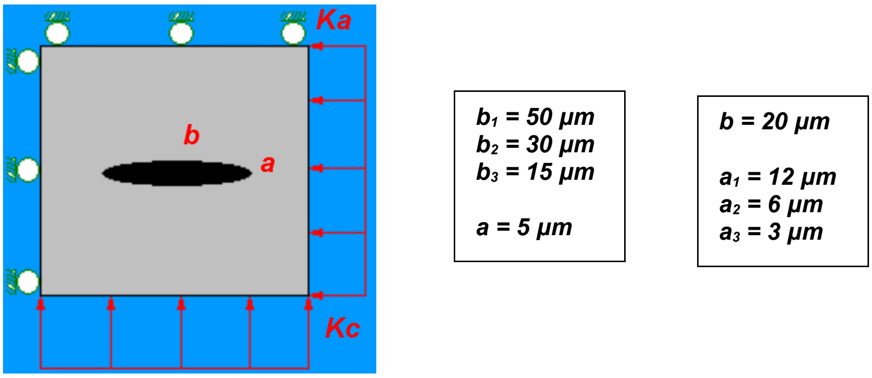

Figure 2. Inclusion thickness and length simulated during the FEM analysis: Schematic representation the dimensions evaluated by using FE analysis, evaluating the effect of the length (b) and the thickness (a).

The inclusion dimensions (length and thickness) selected for the FEM analysis were similar to those measured by using optical microscopy. The output variable analyzed was the Von Misses stress, since it presents a good correlation between the experimental results and the plastic strain phenomenon (Hertzberg, 1996). As mentioned before, the model does not take into account the high strain rate involved in the cutting process.

3. RESULTS AND DISCUSSION

3.1. Experimental results.

The studied steels were microstructurally characterized and turned to measure the cutting forces. The results of machining tests were correlated to the morphology, size of manganese sulfide inclusions. Figure 3 depicts an ordinary microstructure and distribution of manganese sulfide inclusions in the ABNT 1045 steel. Figure 4 shows the length distribution of MnS inclusions in the two different steels analyzed with the same nominal chemical composition. The steel indicated with green presented shorter inclusions than that with blue. Figure 5 shows the thickness distribution of inclusions in the two different steels. The steel indicated with green presented thinner inclusions than that with blue.

Figure 6 depicts the relationship between the specific cutting pressure (*ks*) and the cutting speed for the steels studied. Both steels presented almost the same chemical composition although different results for *ks* (N/mm^2) at different cutting speeds were obtained (except for 110 m/min). Results indicated that the smaller the inclusion the higher the specific cutting pressure. The results showed in Figs. 4 and 5 are an average of 5 (five) tests for each condition. Although close, specific pressure values for the steel with long inclusions (blue) was systematically lower than those for the other steel.

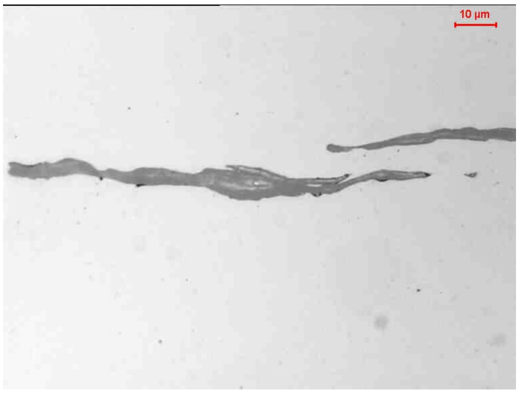

Figure 3. Longitudinal section of an ABNT 1045 steel bar. Black areas correspond to MnS inclusions alongside the section analyzed. Optical microscopy.

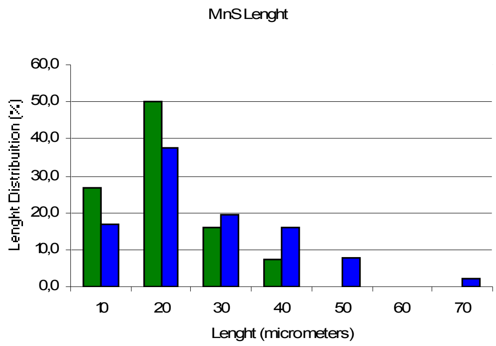

Figure 4. Length distribution of MnS inclusions in the two different steels analyzed. The steel indicated in green presented shorter inclusions than the one indicated in blue.

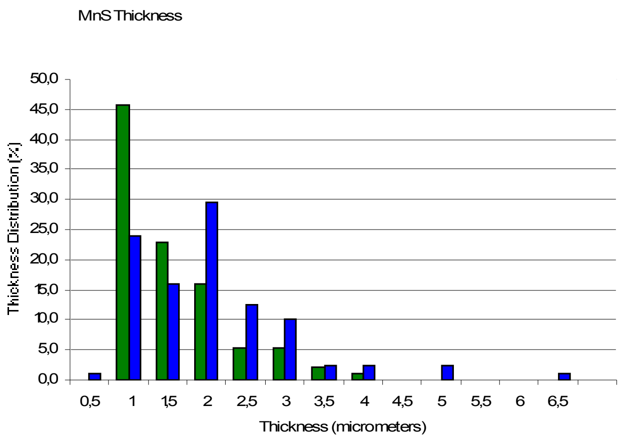

Figure 5. Thickness distribution of MnS inclusions in the two different steels analyzed. The steel indicated in green presented thinner inclusions than the one indicated in blue.

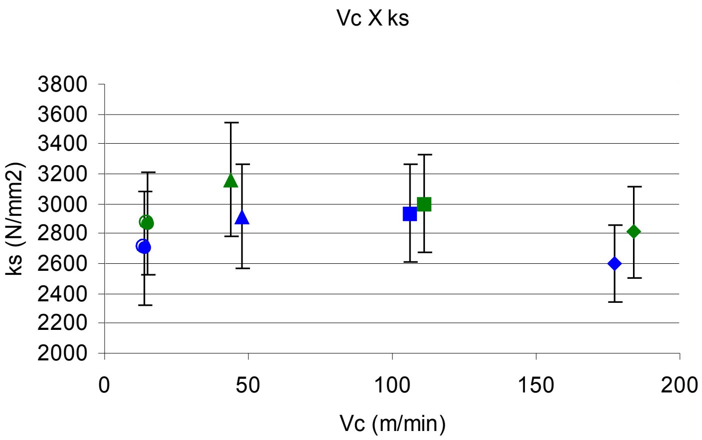

Figure 6. Relationship between the specific cutting pressure (*ks*) and the cutting speed for the studied steels.

3.2. FEM Analysis

In this work different MnS inclusion morphologies were analyzed. The first analysis carried out was related to length of the sulfide manganese inclusions in the steel matrix (Fig. 7) and the second was related to their thickness (Fig. 8).

Figure 7 shows the stress concentration simulated in the steel matrix due to three different lengths of inclusions. From Fig. 7 it can be concluded that the regions close to the tip are more critical than those located in the "flat" region of the same inclusion. This could be an indication that, even in the presence of different inclusion lengths, a stress concentration is generated at their tip. Hence, the plastic strain at the matrix will probably initiate at the tip region, improving the metal removal process during cutting.

Regarding time, it can also be verified in Fig. 7 that, for a given time, the stress field increase with the length of the inclusions. Therefore, the longer the inclusions the easier the metal removal will be. This can also be observed in Fig. 4 and Fig. 6, which show the results of length distribution and specific cutting pressure, respectively. The "blue" steel presents a lesser cutting force than the "green" one, which presents a concentration of higher inclusions (around 80% of inclusions in the "blue" steel have a length equal or bigger than 20 μm). It is also important to note that in all three cases showed in Fig. 7, an X shaped area of stress relief was formed. The stress relief area emerged from the longer (flat) surfaces of the inclusions, which indicates that these regions have the opposite effect of the tip parts.

Simulations varying the inclusion thickness were also conducted in order to evaluate the effect of the stress field in the matrix during the cutting process. As shown in Fig. 8, no significant changes were observed, in the stress matrix distribution, as a result of the increase in the inclusion thickness.

The observation of the stress distribution in Figs. 7 and 8 also allow for some comments. The stress fields were not expected to be symmetrical. The explanation for those non-symmetries arises from the boundary conditions and the forces imposed on the model. The boundary conditions applied both the upper and left regions of the numeric model (Figs. 7 and 8) allow for two different displacements of the material, as such: 1. in the horizontal direction in the case of the elements located in the upper side of the boundary and; 2. in the vertical direction in the case of the elements on the left side of the boundary. The elements in the upper side are expected to be displaced in the negative axis of x direction, limited only by the interaction with other neighboring elements. This arrangement could justify the stress field observed in the left top corner of Fig. 7a. The elements in this region are restricted not only by the surrounding elements but also by the boundary conditions, resulting in a large area with high stresses concentration. Besides the boundary conditions, the forces applied to the model are also a source of asymmetry in the stress field developed in the finite element model showed in Fig. 7. The cutting pressure acting on the lower side of the model is about twice as big as the feed pressure acting on the left side. This probably is the reason for the stress fields, surrounding the tips of the inclusions, to be bigger in the lower side in Fig. 7. This effect can also be observed in the up and low stress relief areas. The upper relief region is higher than the lower one.

The correspondent scale of equivalent Von Misses stresses is also shown. It is important to mention that all simulations were synchronized in time in order to allow for a result comparison. The qualitative results obtained from the simulations show that the stress distributions are asymmetrical and they are critical for certain regions (i.e. the inclusions tips). In order to facilitate the cutting process involved in the machining of materials these critical regions are important.

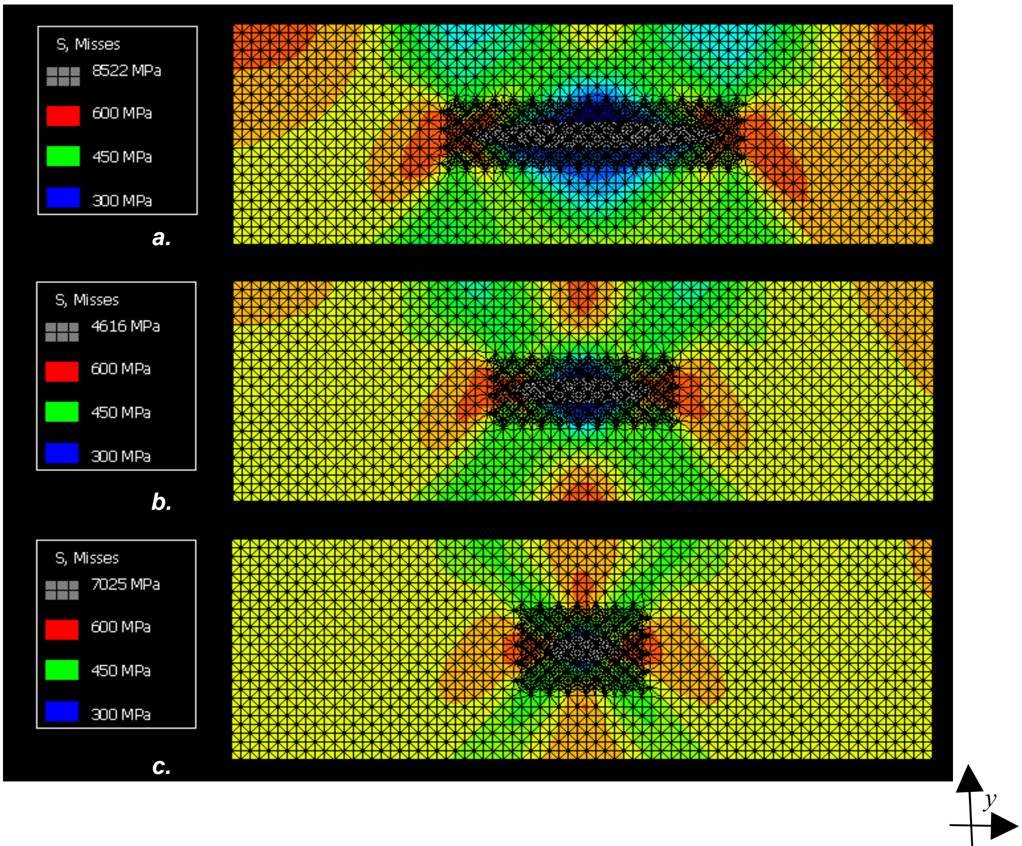

Figure 7. Simulation results of the effect of length of inclusions on FEM in the steel matrix. The three lengths analyzed were: 50 μm (a), 30 μm (b) and 15 μm (c).

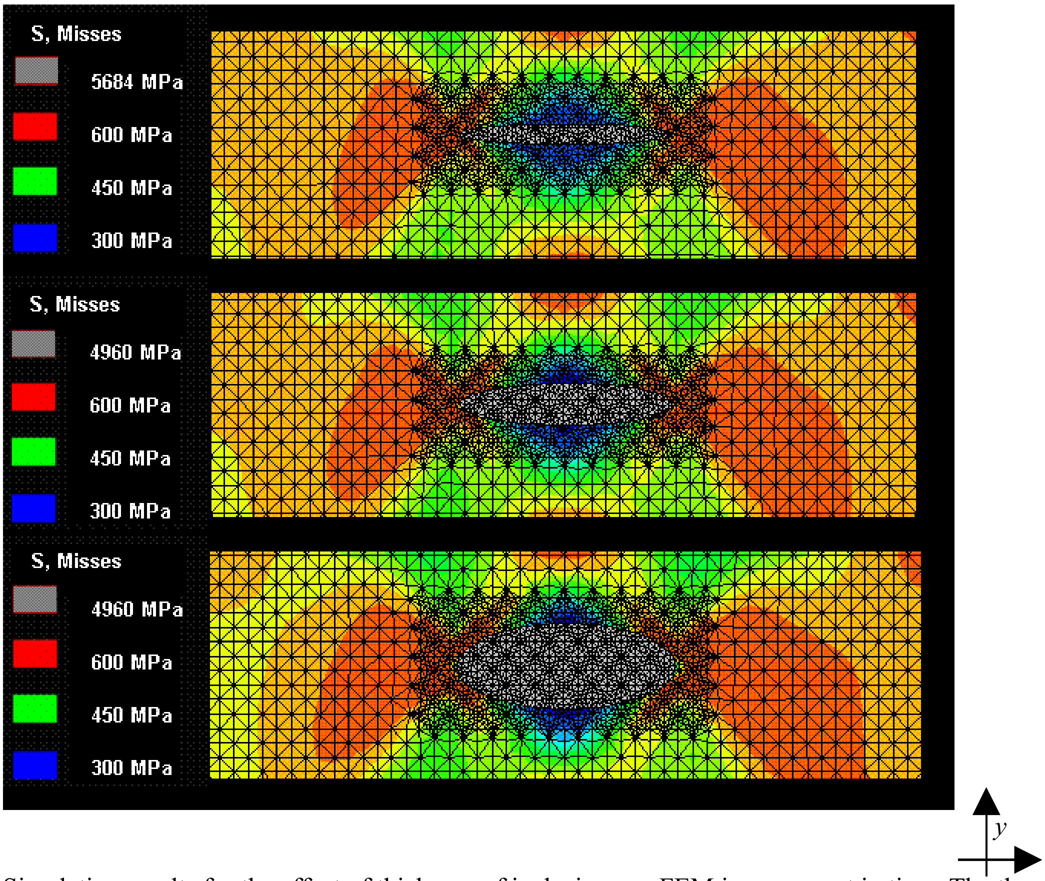

Figure 8. Simulation results for the effect of thickness of inclusions on FEM in a moment in time. The three thickness analyzed: 3 μm (a), 6 μm (b) and 12 μm (c).

4. CONCLUSIONS

This work allows drawing the following conclusions:

- A simplified numerical model was developed and it showed a good correlation with the obtained experimental results.

- It was confirmed that the inclusions are stress concentrators in the metal matrix and that their geometry (length and thickness) influences the material removal process.

- Longer inclusions generate higher stress fields (magnitude and area). Therefore, they seem to facilitate the removal of material during machining and reducing the consumed power. Variations in inclusion thickness did not provide stress variations in the matrix as significant as those obtained with different inclusion lengths.

5. ACKNOWLEDGEMENTS

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