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RESIDUAL STRESSES IN MACHINING USING FEM ANALYSIS – A REVIEW

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Abstract. Residual stresses play an important role in the performance of machined components and structures, namely, in the following aspects fatigue life, corrosion resistance and part distortion. This article will give a brief review on residual stresses during machining of materials with special emphasis in stainless steel. The case study presented in the current work reported on residual stresses in machining of stainless steel AISI 316 using FEM analysis.

1. INTRODUCTION

Surface integrity can be divided in three main fields: surface roughness, microstructure transformations and residual stress. Surface roughness is affected by cutting tool geometry, depth of cut, cutting speed, feed rate, workpiece microstructure and the rigidity of the machine-tool. When the cutting parameters are not selected properly, the cutting tool wears quickly or gets broken abruptly. The parameters affecting the surface roughness are, in order of importance: feed rate, insert radius and depth of cut. A good combination among these parameters should be addressed to provide better surface quality [1-2]. An evident way to judge the surface quality is surface roughness. However, residual stress is not as evident as surface roughness but plays a decisive role in component performance.

Fatigue life is an important property and it is strongly affected by the surface condition produced during machining. The fatigue crack, in general, nucleates at the surface of the part, and then propagates into the bulk. As the crack extends, the resistant section is reduced and when the residual section can no longer withstand the applied load, component fatigue occurs. Consequently, it is the state of stress at the surface, where the crack nucleates, that is of paramount importance. This state is the sum of the stress due to the applied load and of the residual stresses (or self stresses) generated during machining. Residual stress is the result of various mechanical and thermal events, which occur in the surface region during machining [3].

2. LITERATURE REVIEW

It is commonly found that the absolute value of the residual stress close to the surface of the workpiece is high and decreases as the depth increases. Residual stress can be tensile or compressive and the stressed layer can have multiple depths, depending upon the cutting conditions, working material, cutting tool geometry and contact conditions at the tool/chip and tool/workpiece interfaces. Compressive residual stresses generally improve component performance and life because they promote a service (working) tensile stresses and prevent crack nucleation. On the other hand, tensile residual stresses tend to increase service (working) stresses which lead to premature failure of components. These residual stresses may affect dramatically the performance of the machined part causing its premature failure, excessive wear,

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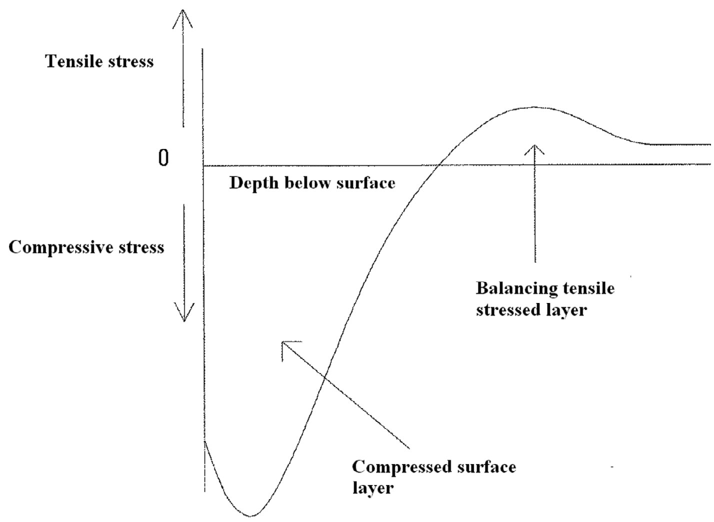

Fig. 1. Example of a residual stress distribution along the depth below surface.

corrosion, part distortion (which leads to assembly problems), *etc*. [3-5]

To optimize processing factors and tool geometry and to predict the final surface residual stress, cutting temperature and thermal deformation all can improve the accuracy and integrity of the machined surface. With advancements and development of advanced science and technology and the increase in requirements regarding machining accuracy, the optimization for cutting parameters and prediction for machined surface quality are essential [6-7].

Residual stresses increase with most of the cutting parameters, including cutting speed, uncut chip thickness and tool cutting edge radius [5]. Compressive residual stresses are usually desirable on the machined surface and the subsurface, because these stresses generally increase the fatigue life [4]. An example of a desirable residual stress profile is given in Fig. 1.

The cutting edge geometry has a direct impact on the stress levels generated in finish hard turning because the increased edge hone radius on the insert generates higher cutting forces. A higher passive force tangential to the surface generates higher compressive residual stresses. When using a large hone radius together with low feeds and depths, solely the radius cuts the material. In tests performed by Capello [8], the influence of feed rate and nose radius was reported to have an impact on residual stresses at the surface. Increased feed generates significantly higher compressive stresses [9]. In general, the more the feed rate, the more residual stresses. However, the affected depth by the tensile stress remains practically the same among all feeds. The study was made in AISI 52100 using solid CBN inserts (CBN 100).

Gunnberg *et al,* [10] also concluded that cutting speed increases the tensile residual stress on the surface and that the heat generated from higher cutting speeds does not penetrate more deeply into the workpiece. As Dahlman *et al.* [9] had already stated, Gunnberg *et al.* [10] also concluded that increased feed generates higher compressive stresses and a more negative rake angle produces more compressive stress. However, feed and nose radius has the greatest effect on the geometric surface values like already expected.

Capello [8] also performed an interesting analysis on how the residual stresses evolve. This researcher concluded that a material with higher mechanical properties will present larger (more tensile) residual stresses. This author verified once again that the influence of the process parameters on residual stresses is as follows; feed rate, tool nose radius and, to a minor extent, entrance angle influence residual stresses. The depth of cut, on the contrary, does not seem to influence residual stresses. Dahlman *et al.* [9] also showed that the depth of cut doesn't have a big impact in residual stress formation. In this investigation, the residual stress profiles are almost the same for the various depths of cut in the machining of AISI 52100 using solid CBN inserts (CBN 100).

Also the cutting speed and the primary rake angle play a minor role. Consequently, it can be stated that the key parameters that control residual stresses in turning are the feed rate and the nose radius. Several researchers showed that these results are consistent with three investigated steels, suggesting that the residual stress mechanism is influenced by process parameters in a common way [8-9].

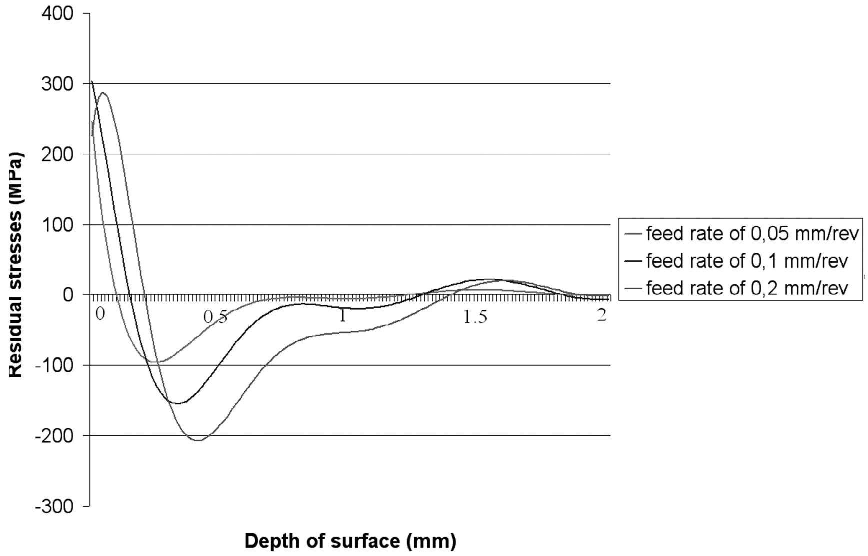

Fig. 2. Residual stress distribution along the depth of surface in the machining of the AISI 316 with a cutting speed of 100 m/min and a depth of cut of 1 mm in function of feed rate, reprinted with permission from [11] (© 2010, Elsevier Sc.).

Besides several researchers stated that the rake angle has a minor influence in residual stress, it is acknowledged that a greater negative rake angle gives higher compressive stresses as well as a deeper affected zone below the surface. In case of an increase of rake angles, the maximum stress position is located into the material [8,9].

3. CASE STUDY: RESIDUAL STRESSES IN MACHINING OF STAINLESS STEEL AISI 316 USING FEM ANALYSIS

In order to perform a comprehensive study on FEM analysis in machining, cutting parameters such as feed rate as well as rake angle were simulated to evaluation of residual stresses in stainless steel AISI 316 [11]. Advantedge™ software was used in this study. The tool materials used to machining the AISI 316 workpiece were coated and uncoated cemented carbide.

In Fig. 2, the distribution of the circumferential residual stress can be seen along the depth of the workpiece (obtained by numerical simulation with coated tools with several feed rates). Although the maximum tensile residual stress has common values among all feed rates (varying from 250 to 300 MPa), the same cannot be said for the compressive residual stresses. About -100 MPa were reached with a feed rate of 0.05 mm/rev. The compressive residual stress keeps increasing with the increase of the feed rate reaching about -150 MPa for a feed rate of 0.1 mm/rev and about -200 MPa for a feed rate of 0.2 mm/rev. These maximums are reached at 0.26 mm, 0.35 mm and 0.42 mm respectively. The tensile stressed layer also increases with the feed rate being about 0.1 mm for a feed rate of 0.05 mm/rev, about 0.17 mm for a feed rate of 0.1 mm/rev and about 0.2 mm for a feed rate of 0.2 mm/rev [11].

Other study was conducted regarding residual stresses, although with different cutting tools, under different cutting conditions and in AISI 316L instead [11]. Fig. 3 shows the distribution of the circumferential residual stress along the depth of the workpiece (obtained by numerical simulation with uncoated tools with 0 and 15° of rake angle). If both distributions are compared, a big reduction of the maximum tensile residual stress can be verified (in the workpiece surface) for the tool with a superior rake angle (it diminished from 450 MPa to about 200 MPa from the tool with a rake angle of 0° to the tool with a rake angle of 15° respectively). The tensile residual stress thickness layer is the same for both tools (about 0.156 mm) and the compressive residual stress thickness layer is the same as well (about 0.75 mm). The maximum compressive residual stress reached -100 MPa in the tool with a rake angle of 0° and about -50 MPa in the tool with a rake angle of 15° [11].

Fig. 4 shows a study of residual stresses in function of the cutting edge radius. However, like shown in the figure, this parameter seems to not significant influence the residual stresses in any way. The tensile residual stresses are almost the same, the affected layers have the same depth and the com-

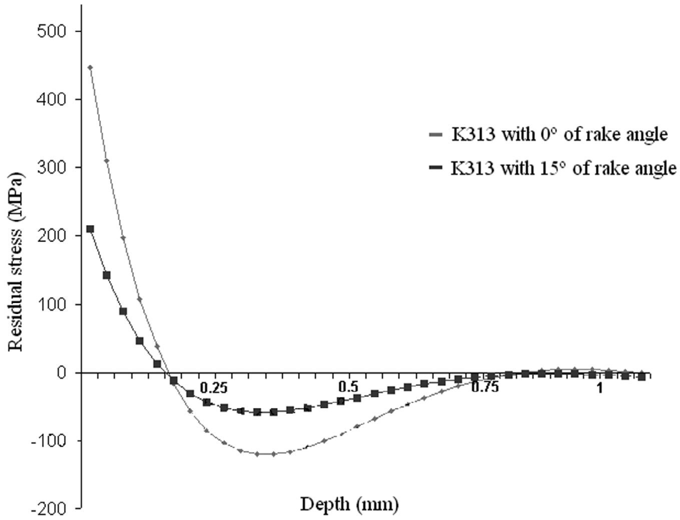

Fig. 3. Residual stress distribution along the depth of surface in the orthogonal cut of the AISI 316L stainless steel with a friction coefficient of 0.57 with a cutting speed of 150 m/min, a depth of cut of 4 mm and feed rate of 0.1 mm/rev, reprinted with permission from [11] (© 2010,Elsevier Sc.)

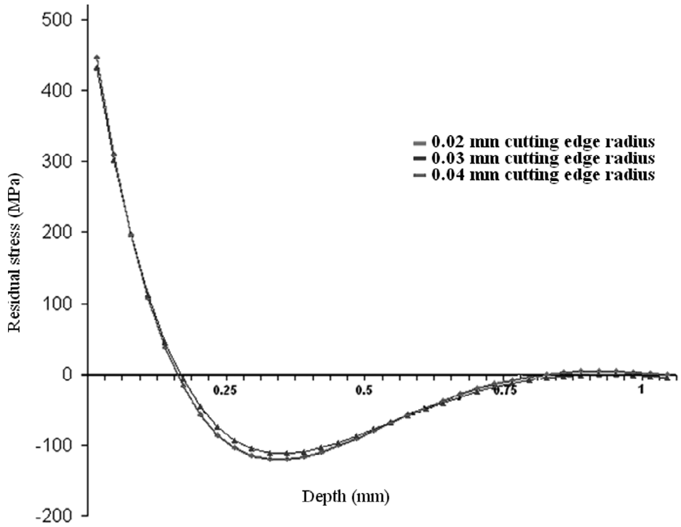

Fig. 4. Residual stress distribution along the depth of surface in the orthogonal cut of the AISI 316L stainless steel with a friction coefficient of 0.57 with a cutting speed of 150 m/min, a depth of cut of 4 mm and feed rate of 0.1 mm/rev, reprinted with permission from [11] (© 2010,Elsevier Sc.)

pressive residual stress also has similar values. It can be concluded that the cutting edge radius does not great influence on circumferential residual stresses [11].

4. SOME RECENT DEVELOPMENTS

In recent years, several works referred in literature [12-20] developed numerical approaches to predict the influence of machining parameters in surface integrity. FEM is a powerful tool to analyse the effect of different factors involved in generation of residual stresses during machining.

Munoz-Sanchez *et al.* [12] developed and to validated a numerical model to analyse the tool wear effect in machining induced residual stresses. Main advantages of this model are, reduced mesh distortion, the possibility to simulate long length machined surface and time-efficiency. The model was validated with experimental tests carried out with controlled worn geometry generated by electro-discharge machining (EDM). The model was applied to predict machining induced residual stresses in AISI 316 L and reasonable agreement with experimental results were found.

Mohammadpour *et al.* [13] describe a study on finite element analysis based on the nonlinear finite element code MSC.Superform for investigating the effect of cutting speed and feed rate on surface and subsurface residual stresses induced after orthogonal cutting. The results from the model are compared to experimental measurements available in the literature, concerning orthogonal cutting of steel AISI 1045 and are in good agreement with experimental data.

Umbrello *et al.* [14] present an innovative experimental and numerical approach to predict residual stresses by incorporating the microstructural phase transformations induced during machining of AISI 52100 steel. Residual stresses induced by machining processes are a consequence of thermo-mechanical and microstructural phenomena generated during the machining operation. Hard machining of AISI 52100 bearing steel is a typical case where the microstructural phenomena associated with white and dark layers formation influences the residual stress distribution.

Nasr *et al.* [15] describe a modified time-efficient finite element (FE) approach for predicting machining-induced residual stresses using commercial FE software. This approach cuts down the computational time for residual stresses prediction from the order of days to just few minutes, which represents a significant contribution to the field of metal cutting and FEA applications. The commercial FE software ABAQUS (TM) was used in the current study; however, the presented approach could be applied to any other commercial FE software. Four different workpiece materials were used to validate the current work by comparing their predicted residual stresses profiles to their experimental profiles, which were obtained under similar cutting conditions.

Outeiro *et al.* [16] studied the influence of cutting process parameters on machining performance and surface integrity generated during dry turning of Inconel 718 and austenitic stainless steel AISI 316L with coated and uncoated carbide tools. A three-dimensional Finite Element Model was also developed and the predicted results were compared with those measured. According to the authors, this paper presents new knowledge on surface integrity in terms of residual stresses generated in turning of these two major difficult-to-machine materials.

Umbrello [17] presents a finite element model for white and dark layers formation in orthogonal machining of hardened AISI 52100 steel. According to the author, series of experiments was carried out in order to validate the proposed simulation strategy and to investigate the influence of material microstructure changes on residual stresses As main results, it was firstly demonstrated by surface topography analysis as both the white and dark layer are the result of microstructural alterations mainly due to rapid heating and quenching. Furthermore, it was found as both the presence of white and dark layers influence the residual stress profile.

Li *et al.* [18] studied with the help of finite element method for its significant influence on the quality of machined part. A two-dimension (2D) fully thermo-mechanical coupled finite element (FE) model was employed to evaluate residual stressses remaining in a machined component. The model was developed based on the effective rake angle and the variable undeformed chip layer. Johnson-Cook plasticity model was introduced to model the workpiece material. Coulomb friction was assumed at the tool-chip interface. Two same cutting tools were employed to model continuous feed milling process. Residual stresses profiles were obtained after the cutting and stress relaxation stages. According to the authors the predicted residual stresses profiles were in reasonable agreement with the experimental results

Miguelez *et al.* [19] describe the generation of residual stresses in orthogonal machining is analysed by using an Arbitrary Lagrangian Eulerian (ALE) finite element approach. According to the authors, the roles of thermal expansion, of thermal softening and of the Taylor-Quinney coefficient (controlling the heat generated by plastic flow) are considered separately. The influence of friction is also analysed by assuming dry cutting conditions and a Coulomb friction law. The friction coefficient has a complex effect by controlling heat generation (frictional heating) along the tool rake and clearance faces and the propensity for the chip to stick to the tool. Geometrical effects such as the tool rake angle and the tool edge radius are also discussed.

Lazoglu *et al.* [20] describe the predictions of residual stresses are most critical on the machined aerospace components for the safety of the aircraft. In this work, an enhanced analytic elasto-plastic model is presented using the superposition of thermal and mechanical stresses on the workpiece, followed by a relaxation procedure. Theoretical residual stress predictions are verified experimentally with X-ray diffraction measurements on the high strength engineering material of Waspaloy that is used critical parts such as in aircraft jet engines. According to the authors with the enhanced analytical model, accurate residual stress results are achieved, while the computational time compared to equivalent FEM models is decreased from days to seconds.

5. CONCLUSIONS

The current article reviewed some important aspects related with residual stresses on machining of materials with special emphasis in stainless steel. Based on the results of the above research on residual stresses in machining using FEM, the following conclusions can be draw:

- Compressive residual stresses generally improve component performance and life;
- The influence of the process parameters on residual stresses is as follows; feed rate, tool nose radius, rake angle;
- Residual stresses are mostly influenced by feed rate and nose radius;
- Increased feed generates significantly higher compressive stresses;
- Residual stress mechanism is influenced by process parameters in a common way.

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