Multistep hybrid approach applied to material removal operation using cutting tool

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Abstract : *Cutting processes are widely used in different industries to cut different engineering parts. Usually the optimization of these processes is made by experimental or numerical simulations but the major inconvenience of those methods is the cost and the time needed. For all these reasons, in manufacturing industry, a highly interest in analytical methods are usually researched because there are very practice to use but those methods don't take into account all the aspects of the contact between the work material and the tool. In particular ploughing and spring back are usually not considered, what is pertinent for small cutting radius but not for bigger ones (used tools). In this paper en hybrid approach is presented. Both analytical and numerical approaches are used in order to model and understand physic during removal processes. In particular a multi-steps model for orthogonal cutting has been developed in order to study the influence of the cumulated strain and temperature induced by the different steps on the residual stresses. The effect of tool edge radius and heat generated by flank friction on the predicted stress profile is analytically modelled. In fact, in the case of most of industrial processes, like turning, milling, grinding, the cutting tool is in contact with a part of material that was the finished piece in the previous step Commercial finite element software ABAQUS with its Explicit and Implicit modules was used. Computed Numerical predicted stress fields are compared against measured residual stresses obtained by X-Ray diffraction. Moreover, in order to take into account all the physics in the tool-work material interface, spring-back simulation was performed using both ABAQUS Explicit and ABAQUS Implicit.*

1. Introduction

Surface integrity is an important aspect of successful machining operation. In fact, a great surface integrity level is required for many applications that request high quality and reliability such as aeronautic, nuclear, medical, automotive and chemical. As one of the major element of surface integrity, residual stresses induced by materiel removal have a major influence on the lifetime of machined pieces especially in its corrosion resistance and fatigue life [1, 2]. Due to their importance, the predictions of the residual stresses have been the subject of many works [3, 4, 5]. Many numerical models have been developed to simulate metal cutting process in order to understand the physical phenomena that will occur during the material removal as residual stresses, tool wear prediction, and thermal aspects. The final goal of these approaches is to predict the residual stress in the machined part. Kortabarria and al [6] proves that the difference between numerical and experimental results is due to the traditional model used for the prediction of residual stresses profile which is not able to reproduce all the complexity of machining. Other types of model have been used such as the model developed by Mondelin and al [7] in order to study the Residual stresses induced by the turning of a 15-5PH martensitic stainless steel using a hybrid model. In this study, the chip and the tool are replaced by equivalent thermo mechanical loadings moved on the final machined surface in order to predict residual stresses induced by material removing operation. These kinds of models are developed only for a single step. They does not consider the effect of hardening or thermal softening on the residual stresses induced by the material removal which is, in the reality, a multi-steps operation such as milling and grinding. There are few papers treating the effect of sequential cutting on the residual stress profile. In this context Li and al [8] developed a FE model in order to predict residual stress induced by milling. In this model two same cutting tools were employed to model continuous feed milling process. They found that the stresses had trend to increase after the second step which makes clear the effect of heritage between each step. Otherwise calculated and experimental residual stresses curves have the same trend and started from the same surface values which clarify that multi-steps modeling gives better result for the prediction of residual stress profile than a single steps model. For the same objective Liu et al [9] have developed a two steps model to investigate the effect of sequential cuts on residual stresses in a machined layer. The results showed that the region of the affected layer in the second cut becomes thinner and residual stress may be changed by optimizing the second cut. In this paper a multi-steps FE model for orthogonal cutting has been developed in order to study the influence of the cumulated strain and temperature induced by the different steps on the residual stresses. Also heat generated by frictions and spring back are simulated in order to obtain more coherent results. Experimental tests are presented in first, after that the numerical approach and the conclusions.

2. Numerical approach

In this part different modeling details are given to develop a model in order to simulate multi-steps chip formation. A 2-D plane strain thermo-mechanical Finite Element model was developed to simulate multi-steps chip formation and study the residual stress induced by material removing (Cf. figure 1).

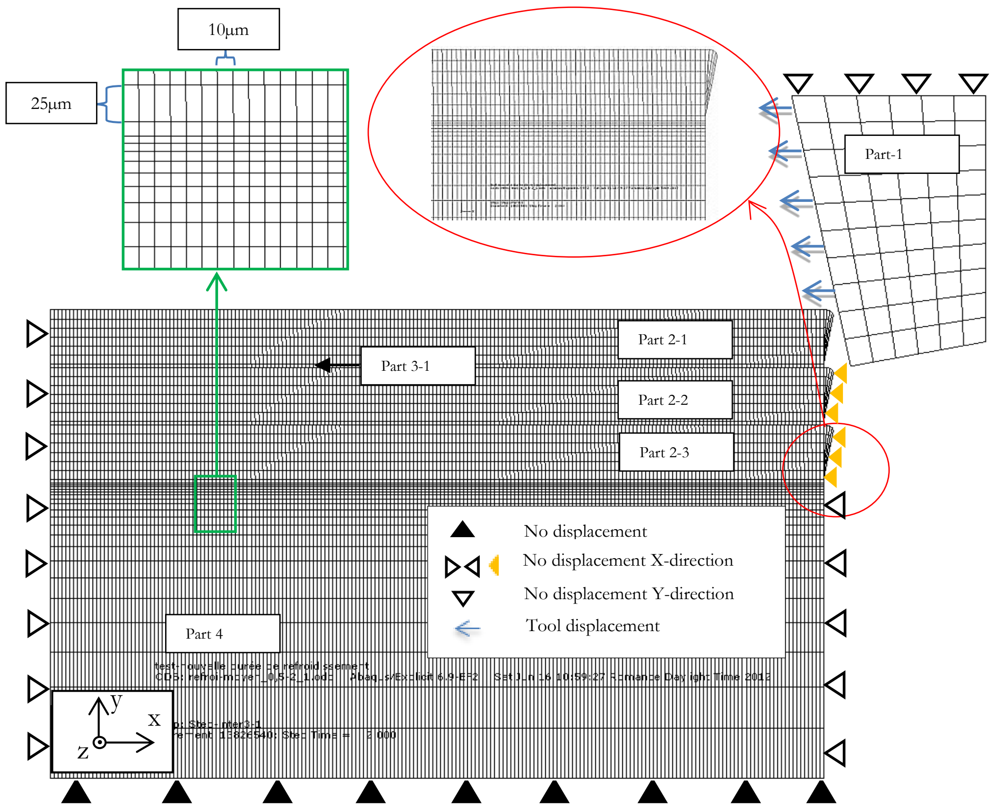

FIG. 1 - Geometry and boundary conditions.

The commercial finite element software ABAQUS [10] with its Explicit and Implicit approach was used in order to understand physical phenomenon during machining operations which influence the residual stress generation. Afterwards it is possible to study the effect of accumulated strain and temperature induced by the steps of machining on the residual stress final profile.

A multi-parts model was used according to Mabrouki and al. [11, 12]. The part dimensions are 2 mm of length and 1 mm of width. Machining parameters were taken similar to those adopted by Salvatore and al. [4]. The chip thickness f was equal to 0.15 mm and the depth of cut ap was equal to 7 mm. It should be noticed that work piece interaction was considered under dry machining conditions. The use of the cutting tool radius causes numerical problems related to the mesh distortion using the Lagrangian formulation. To avoid these problems, new tool geometry was employed. It has no cutting radius but only an equivalent rake angle γ^* in order to simulate the effects of the tool radius and the real rake angle on the machined piece (Cf. figure 1). This angle is analytically calculated using the method developed in [12]. This approach is based on the contribution of the angle created by the cutting radius and the real cutting angle γ. Otherwise the tool flank angle was taken equal to 11° which is the real angle.

The material constitutive model of AISI 4140 follows the Johnson–Cook (J-C), this low is suitable for modeling cases with high strain, strain rate, strain hardening and non-linear material properties such as metal cutting. For these reasons, it has been widely used and proved a satisfactory description in the modeling of cutting processes. The parameters of the Johnson-cook low for AISI 4140 and its physical propriety are taken from Barge study [13].
The simple Coulomb friction low widely employed in orthogonal cutting simulation was used. Simulations were performed using a constant coefficient equal to 0.2 according to [14]. In the proposed numerical model, the tool and the work piece are meshed with a four node bilinear quadrilateral continuum elements reduced integration referenced as CPE4RT in ABAQUS®. This type of element is used for a coupled temperature displacement calculation in which both displacement and temperature are the nodal variables. These elements are generally utilized for complex nonlinear analysis involving contact, plasticity and large deformations. The mesh density is variable. In fact tools are meshed with a greater size of element than the work piece witch in its turn meshed with a different density. In fact, the mesh is refined in the top of the finale work piece near of the tool passage zone in order to get maximum information about the residual stress on the surface. The mesh dimension in the cutting direction is equal to 10 µm, after a sensitivity study for this parameter.
Using a tool with no radius the heat generated by friction flank of the tool on the final surface is not taken into account. So in our case, the modeling of this heat is performed by applying a heat flux on the machined surface before the cooling step.

3. Numerical simulations

3.1 The influence of cooling on residual stress

To simulate the real piece cooling, a step is performed after every chip formation. In which the heat is dissipated by conduction and convection. In order to simulate the chip formation step we need approximately 0.25 ms, or to simulate only one cooling steps we need 13.67 ms which is the duration of complete piece rotation before the second material removing using a speed of 478 m/min. So in order to reduce the calculation time, simulations are performed with a step time equal to 0.5 ms which is the double of the chip formation duration. For the final cooling step the duration is equal to 2 ms in order to simulate the final cooling (Cf. figure 2).

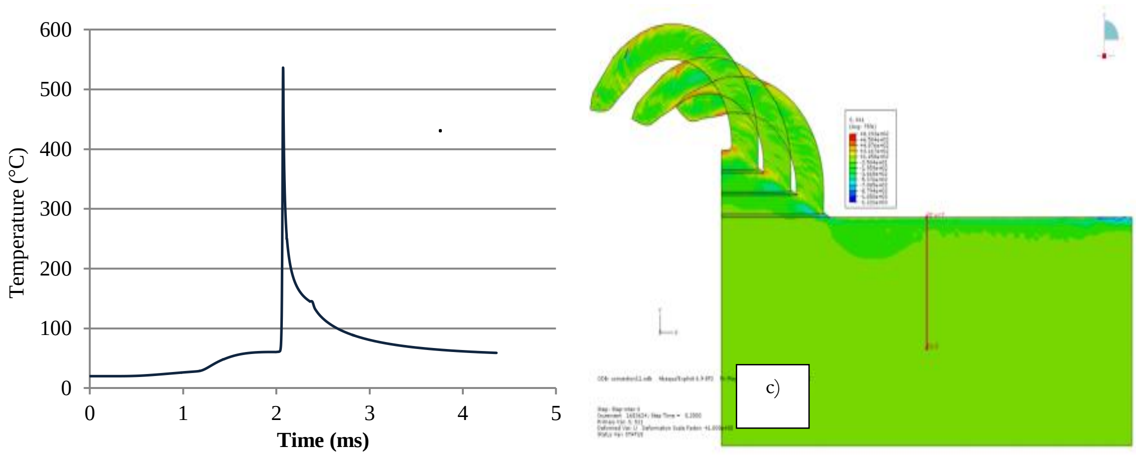

FIG. 2 - Temperature in the final surface after tree steps (c).

3.2 Residual stress profile determination

In order to determine the residual stress profile in the machined surface after every step, the use of sliding path is necessary. In fact, after the first step the path start from the first machined surface and end in depth of the piece. When the second step is done, the path will begin from the second machined surface and end in depth of the piece, and so on for the third step (Cf. figure 3).

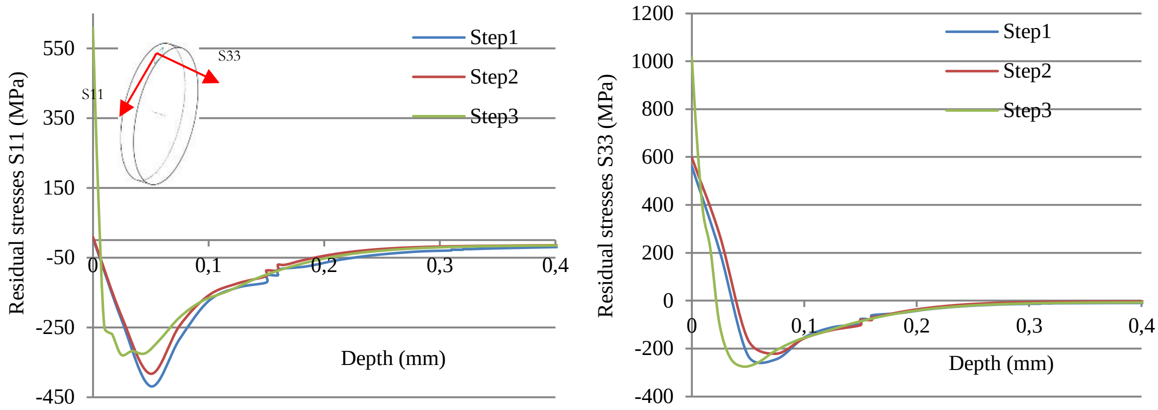

FIG. 5 - Residual stresses after three steps (Explicit Calculation, angle -11.5°, f=0,15mm).

In particular, in figure 3 the tensile peaks at the surface is more important after every step. Otherwise, compression peaks are located in the same depth but for the third step they are closer to the surface. This may be due to the thermal effect in terms of cumulative temperatures and deformations induced by previous steps. In addition, simulations are made using explicit module of ABAQUS so without considering spring back phenomena which is responsible for the stress relaxation which affects the results. In order to obtain more consistent results, the simulation of spring back phenomenon is necessary [15]. Therefore a specific method was used. Result of Explicit calculation was imported to the Standard module of ABAQUS [16]. In fact, the finite element software offers the capability to transfer a deformed mesh and the data related to the chip formation, heating and cooling to standard module. In this case it is possible to have a stable configuration after the spring back phenomena.

3.3 Numerical results

In order to have the same experimental conditions of a machined piece, spring back simulation is performed to take in account the stress relaxation after the cutting and cooling operations. The difference of residual stress curves obtained before and after spring back simulation is illustrated in figure 4. It is clear that there is no difference at surface but the profile is relatively different in depth

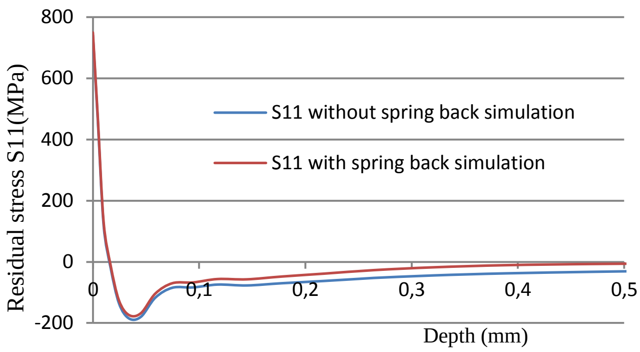

FIG 4: S11 residual stresses before and after spring back simulation

4. Experimental tests

Orthogonal tests are performed using disks of AISI 4140 with a thickness of 7 mm and 70 mm of diameter. It was cut using coated carbide insert (SM30) with a cutting edge radius of 30 µm. these test are used for the model validation and there are taken from Salvatore [4] works. Residual stresses measurements are performed using the X-ray diffraction machine PROTO. This technique use the Bragg's low to measure the inter-reticular distance. It should be mentioned that for the measurement in depth of piece, electro erosion technique is employed to make a hole in the piece to reach the desired depth. This technique is illustrated in figure 5. Experimental data are presented in figure 6.

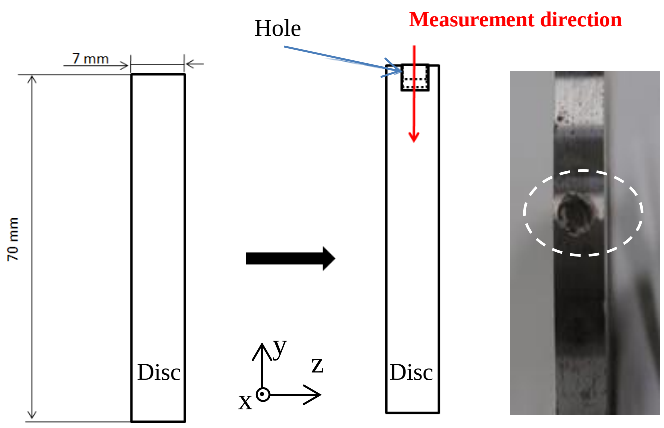

FIG. 5 - Residual stresses measurements in depth.

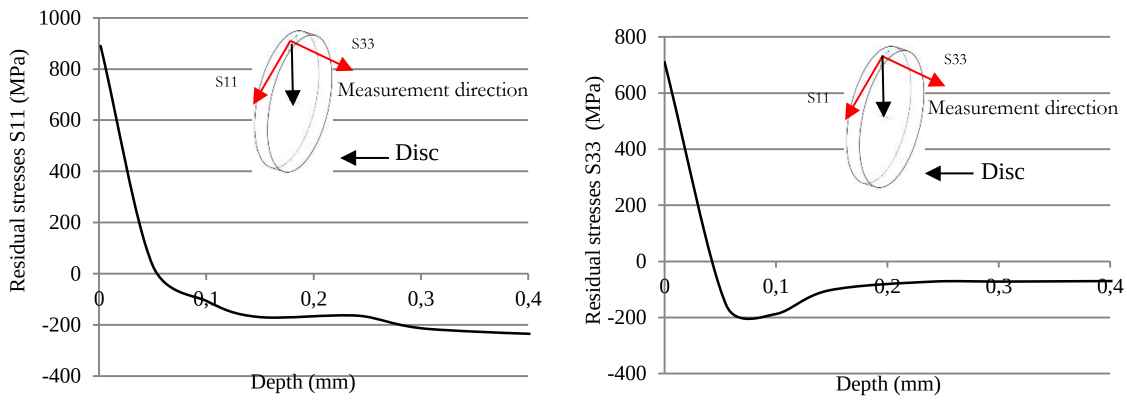

FIG. 6 - Measured residual stresses.

5. Results and discussions

In figure 7 residual stress determination is presented in the final step (final piece).
The first component is comparing results obtained before and after application of heat flux. It is clear that there is no difference at surface but the profile is relatively close to the experimental in depth when the heat flux is applied. The second component is the comparison between the curves obtained after the application of heat flux, the spring back simulation and the experimental curve. For the stress in the cutting direction S11 numerical and experimental curves are relatively close on surface. But a bit far for the prediction of the compression peak and the stress state in depth. Otherwise in the Z direction there is a significant difference in the prediction of the traction peak in extreme surface. Elsewhere the FE predicted stresses are in very good agreement with the experimentally measured stresses in depth. In fact, the compression peaks are located at the same depth and compressive residual stress values are very similar especially in the Z direction. Numerical and experimental curves are coincidence in depth.

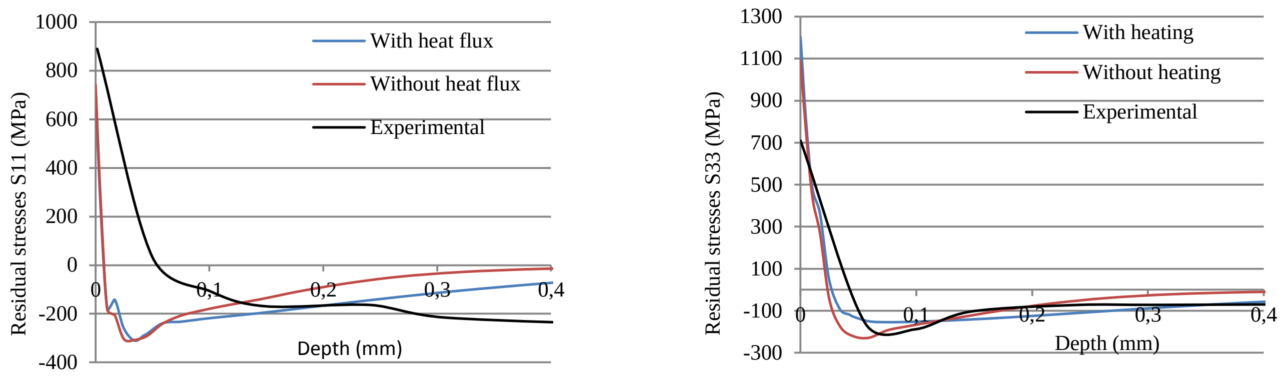

FIG. 7 - S11and S33 residual stresses in the final piece after spring back
(v=478 m/min, f=0.15, angle -11, 5°)

Accuracy discrepancy between numerical results and experimental measurements could be originated by insufficient cooling time after every step. The effect of tool wear on the profile of residual stresses is not been taken into account and heat flux can be modeled with more accuracy.

Conclusions

In this paper a thermo-mechanical FE model was built to predict the residual stresses distribution induced by machining operations. The particularity of this study is the effect of multi-steps simulation in terms of cumulative strains and temperatures on the residual stress profile. Otherwise, tool geometry with an equivalent rake angle was used in order to simulate the real tool radius and the effect of the real rake angle on the machined piece. The simulation of piece cooling is performed after every step of material removing. In addition a heat flux is used to simulate heat generated by friction flank of the tool on the final surface. Explicit calculation is used for material removing, heating and cooling after every step. Afterwards an elastic relaxation was performed using Standard module of ABAQUS. The results of the presented approach are close to reality mainly in depth. Also for reasons of long time of the cooling steps the total cooling duration is not reached. Also the use of a developed approach to simulate heat generated by friction such as dynamic heat source is conditioned by the long computation time. So as perspective, it is considered the extension of this approach used for turning operation to other processes such as grinding and milling. Also, the multistep approach will be used to study the effect of the tool wear on the residual stress induced by material removal processes.

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