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Numerical analysis of the tool wear effect in the machining induced residual stresses

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ABSTRACT

Machining is a dynamic process involving coupled phenomena: high strain and strain rate and high temperature. Prediction of machining induced residual stresses is an interesting objective at the manufacturing processes modelling field. Tool wear results in a change of tool geometry affecting thermo-mechanical phenomena and thus has a significant effect on residual stresses. The experimental study of the tool wear influence in residual stresses is difficult due to the need of controlling wear evolution during cutting. Also the involved phenomena make the analysis extremely difficult. On the other hand, Finite Element Analysis (FEA) is a powerful tool used to simulate cutting processes, allowing the analysis of different parameters influent on machining induced residual stresses.

The aim of this work is to develop and to validate a numerical model to analyse the tool wear effect in machining induced residual stresses. Main advantages of the model presented in this work 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.

1. Introduction

Machining is a dynamic process involving high strain rate, elevated strain and high temperature in the workpiece. One of the most important characteristics of the machined surface integrity is the level of tensile residual stress induced during machining. The analysis of residual stresses due to machining operations has been an active subject of research. The reliability of structural components obtained by machining operations is influenced by the state of residual stresses resulting from processing. Tensile residual stresses in the vicinity of the machined surface, has negative effects on fatigue, fracture resistance and on stress corrosion and therefore can substantially reduce the component life [1]. The residual stress level is strongly related to both mechanical and thermal phenomena induced during chip removal [2]. As is well known these phenomena depend on the tool geometry.

During cutting, tool geometry is changed due to the tool wear effect. Depending on the type of tool wear, the change of the contact surface in the interface chip/tool is produced together with a variation of the effective tool rake angle. Moreover an increase of the contact area between clearance surface and machined surface is observed. In general, different wear mechanisms occur simultaneously during cutting operation, thus it is not easy to carry out experimental analysis due to the impossibility to control both, type and level, of tool wear during machining tests. Depending on cutting conditions, tool

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material and workpiece material, one type of wear is prevalent over the rest. Main progressive wear types observed in cutting tools are flank wear, usually observed at intermediate cutting speed; and crater wear, commonly related to high-speed machining [3]. In this work it is also considered the influence in residual stresses of rounded cutting edge. The cutting edge radius is always larger than zero and it is influenced by several factors, not only by cutting evolution, but also by coating layers or the initial definition of cutting edge [4].

The effect of tool wear in the component surface integrity has been received considerable attention in scientific literature. Liu and Barash [5] observed significant influence of tool geometry in residual stresses induced by orthogonal cutting of low carbon steel. Similar trend was observed by Liu et al. [6] in the case of hard turning of bearing steel. Enhanced level of tensile residual stress at the machined surface due to the rounded cutting edge was observed by Thiele et al. [7] when machining AISI 52100 and Arunachalam et al. [8] in the case of Ni alloy Inconel 718. Changes in the clearance angle and flank wear also influence tensile level of residual stresses due to the increased amount of friction heat generated in this zone, as was shown by Chen et al. [9]. On the other hand the influence of chamfer tool geometry, directly related with effective rake angle, was studied by Hua et al. [10].

Most works referred in literature, develop experimental approaches to study the influence of tool wear in residual stresses; however, numerical approaches have also been used to predict the influence of tool wear and geometry in surface integrity [1,11–13]. Finite element is a powerful tool to analyse the effect of different factors involved in generation of residual stresses because it is possible to uncouple different contributions [2] and has been extensively used for decades to simulate cutting.

Commercial FE codes, mainly DEFORM and ABAQUS, have been used to predict residual stresses in orthogonal cutting. The commercial FE software DEFORM-2D is a Lagrangian implicit code with adaptive remeshing [10,11], meanwhile ABAQUS is one of the most versatile general-purpose code allowing both ALE and Lagrangian analysis, as well as implicit and explicit integration schemes [12,13]. ALE formulation presents advantages when compared with the Lagrangian approach and has been widely used to simulate residual stresses using ABAQUS code. The model commonly used to predict residual stresses in literature is described in detail in [2,12] and it is schematically shown in Fig. 1.

Main drawback of this model is the necessity to define the chip geometry and its mesh in order to deal with the high level of distortion that appears in this zone. An iterative work is needed to obtain the precise geometry and appropriate mesh that are able to deform without stopping the calculation due to distortion. Another problem is workpiece elements enlargement, especially those located at the interface chip–tool, due to the use of Lagrangian boundary in the upper contour of the chip.

One of the main machining simulation drawback, especially in case of residual stresses simulation, is the extremely high computational cost of simulations. A computational time of days or even weeks may be needed even to simulate few milliseconds of orthogonal cutting using 2D models. This very low time introduces several problems if the focus of the analysis involves thermal issues, related to heat generation and diffusion into the tool [14,15]. In fact, no steady-state conditions are reached during the numerical simulation. Technical literature shows that it is relatively easy to predict some process variables such as cutting and thrust force, the chip geometry, shear angle and the contact length [16] however, numerical prediction becomes poor when temperatures on the rake face and inside the tool are investigated [17]. In case of residual stresses simulation strongly dependent on thermal phenomena, it is necessary to simulate a long length machined surface to ensure steady state conditions and stabilized level of residual stresses at the machined surface.

It is commonly admitted that tensile residual stresses in machining result from heating the machined surface during the cutting operation. The high temperature level reached in a thin thermally affected layer near the workpiece surface produces thermal expansion and plastic flow. During the subsequent cooling, the thermal contraction of this layer is higher than the one reached in-depth in the workpiece, and this phenomenon is believed to be at the origin of tensile residual stresses observed in machining. Although common understanding is that, in absence of thermal effects the mechanical loading exerted onto the workpiece leads to compressive residual stresses; it is shown in [2,18] that even in absence of thermal effects, a substantial level of tensile residual stresses can be obtained by solely pure mechanical effects. However the level of tensile residual stress is also strongly influenced by thermal effects, thus the prediction of temperature should be as

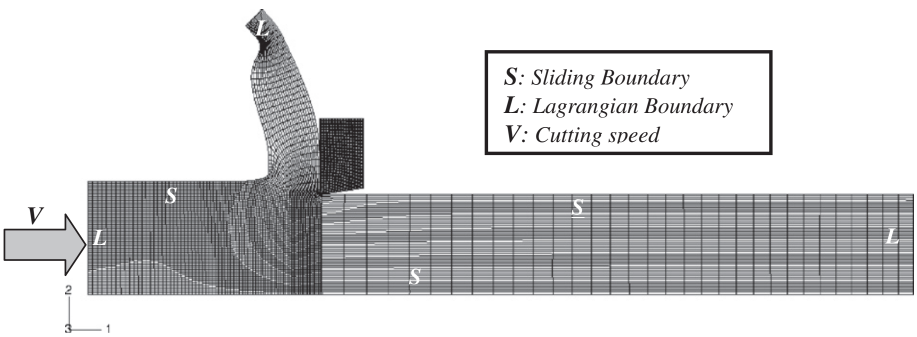

Fig. 1. Type of contour used in model commonly used in ALE formulation with ABAQUS to predict residual stresses. See details in [2,19].