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Modelling the effects of tool-edge radius on residual stresses when orthogonal cutting AISI 316L

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Abstract

Tool-edge geometry has significant effects on the cutting process, as it affects cutting forces, stresses, temperatures, deformation zone, and surface integrity. An Arbitrary-Lagrangian–Eulerian (A.L.E.) finite element model is presented here to simulate the effects of cutting-edge radius on residual stresses (R.S.) when orthogonal dry cutting austenitic stainless steel AISI 316L with continuous chip formation. Four radii were simulated starting with a sharp edge, with a finite radius, and up to a value equal to the uncut chip thickness. Residual stress profiles started with surface tensile stresses then turned to be compressive at about 140 μm from the surface; the same trend was found experimentally. Larger edge radius induced higher R.S. in both the tensile and compressive regions, while it had almost no effect on the thickness of tensile layer and pushed the maximum compressive stresses deeper into the workpiece. A stagnation zone was clearly observed when using non-sharp tools and its size increased with edge radius. The distance between the stagnation-zone tip and the machined surface increased with edge radius, which explained the increase in material plastic deformation, and compressive R.S. when using larger edge radius. Workpiece temperatures increased with edge radius; this is attributed to the increase in friction heat generation as the contact area between the tool edge and workpiece increases. Consequently, higher tensile R.S. were induced in the near-surface layer. The low thermal conductivity of AISI 316L restricted the effect of friction heat to the near-surface layer; therefore, the thickness of tensile layer was not affected.

Keywords: Finite element modelling; A.L.E.; Tool-edge radius; Residual stresses

1. Introduction

Tool-edge geometry has a significant effect on almost all cutting parameters such as cutting forces, tool life, surface integrity (surface finish and residual stresses (R.S.)), and temperatures. Therefore, understanding the effects of different edge preparations and predicting them, if possible, is of a crucial importance; especially that using such tools is mandatory in certain cases. Furthermore, even if cutting starts with an up-sharp tool, the tool tip will eventually wear out or break off and cutting will be continued with a non-sharp edge. The effects of different edge preparations on induced R.S. are critically important, as nearly all machining operations induce R.S. Furthermore, R.S. play a crucial role in controlling part performance as they affect its properties in many different ways [1]. The current work is concerned with rounded-edge tools and the effects of edge radius on induced R.S.

Experimental investigations have been always an important method for studying different phenomena in metal cutting. Some experimental studies on the effects of tool-edge radius on R.S. could be found in [2–5]. Thiele and Melkote [2] have found that tool-edge radius has a significant effect on surface R.S. and microstructure when finish hard turning AISI 52100 steel. R.S. in the axial and circumferential directions were more compressive with

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larger edge radius. Microstructural analysis showed thermally induced phase transformation, white layer, at all feeds when using edge radius of 122 μm and only at high feeds when using sharp tools (radius of 23 μm). Jang et al. [3] studied the effects of different machining parameters (cutting speed, feed rate, depth of cut, and tool-edge radius) on surface R.S. when turning AISI 304 stainless steel. Tool-edge radius was found to have the most significant effect on R.S., where larger radius resulted in higher surface tensile R.S. in cutting direction. The authors reported that the effect of edge radius on inducing tensile R.S. in stainless steels is more noticeable than in other steels, and attributed this to the low thermal conductivity of stainless steels. Liu and Barash [4] found that larger edge radius results in less near surface tensile R.S. in the cutting direction when orthogonal and oblique cutting AISI 1008 steel. The same result was found by Arunachalam et al. [5] when machining (facing) Inconel 718.

Analytical modelling has been used to understand the effects of tool-edge geometry on different cutting parameters in orthogonal cutting, such as in [6,7]. Manjunathaiah and Endres [6] presented an analytical model for tools with edge radius and verified it by orthogonal cutting 70–30 brass and mild steel. Both cutting and ploughing force components increased with edge radius. Higher strain and strain rate were obtained, which also resulted in higher specific cutting energy. It is important to note that the proposed model did not consider the stagnation zone or build-up edge phenomenon. Ren and Altintas [7] studied the effects of chamfer angle and validated their model by high-speed orthogonal cutting P20 mold steel. Cutting force components increased with chamfer angle, with more significant increase in the thrust component. Chip thickness was almost constant for different chamfer angles, i.e. constant shear angle, which was explained in terms of having a dead-metal zone that acted as the effective cutting edge making different edges almost the same. The main disadvantage of analytical modelling is its questionable and limited applicability as it is based on simplifications and assumptions that hardly agree with reality.

Finite element (F.E.) analysis has played an important role in simulating and understanding the metal cutting process by having an insight looking at what is going on during cutting, which cannot be achieved by experimental or analytical methods. Both the Lagrangian and Eulerian F.E. techniques have been used in studying the effects of tool-edge preparation in orthogonal cutting. Kim et al. [8] used the Eulerian approach to study the effects of tool-edge radius when orthogonal cutting 0.2% carbon steel. Cutting forces followed the same trend as in [6,7], the deformation zone extended deeper and wider into the workpiece, and the effective strain rate decreased with edge radius. Cutting temperatures increased with edge radius, which was attributed to more heat generation due to friction between the tool tip and workpiece as the contact area increased. No apparent change was noticed in chip thickness. Yen et al. [9] examined different edge preparations (honed and chamfered edges) while modelling orthogonal cutting of 0.2% carbon steel using Lagrangian formulation with continuous remeshing. More chip curling and larger sticking region were noticed with larger edge radius. Chip thickness increased while the shear angle decreased with edge radius. Tool-tip temperature decreased and then increased with edge radius, having a minimum at a certain edge radius. This was because larger edge radius results in larger contact area between the tool and workpiece, which increases heat generation due to friction but at the same time increases heat dissipation into the tool. These two contradicting effects balance out, resulting in an optimum radius for minimum tool temperature.

Each of the Lagrangian and Eulerian techniques has its own advantages and drawbacks that make it suitable for modelling certain cases and unsuitable for others, where the advantages of one of them are the disadvantages of the other and vice versa. The Eulerian approach handles material flow around tool tip in a perfect way without the need to define a failure criterion, which is mandatory for the Lagrangian approach and adds to its modelling errors. However, the chip shape has to be known a priori, which represents a huge drawback to the Eulerian technique. Furthermore, R.S. could not be estimated because the material elastic behaviour is not considered [10]. On the other hand, the chip is generated automatically in the Lagrangian approach as the mesh totally represents the underlying material but high element distortion may terminate the analysis. In Lagrangian formulation, a parting line, along which chip separation takes place, needs to be defined. This makes it unsuitable for modelling tools with blunt edges because such line cannot be predicted. Furthermore, remeshing has to be used with a very fine mesh around the tool edge, which makes the process very expensive numerically.

The Arbitrary-Lagrangian–Eulerian (A.L.E.) technique is a relatively new modelling technique that represents a combination of the Lagrangian and Eulerian techniques without having their drawbacks. It was first introduced in modelling the cutting process by the end of the last decade, and some of the recent A.L.E. cutting models were presented in [10–13]. Movahhedy et al. [11] presented the first A.L.E. model to study the effects of tool-edge preparation. They studied the effects of chamfer angle on orthogonal cutting of P20 mold steel. The model succeeded in simulating the cutting process showing a dead-metal zone trapped under the chamfer and filling almost all of the missing edge, which was also noticed experimentally. Cutting forces increased with chamfer angle, especially the thrust component. The size and shape of the shear zone were not affected greatly, which was attributed to the presence of the dead-metal zone that acted as the effective cutting edge and made the chip formation process almost the same for different cases.

Austenitic stainless steels are widely used in many applications, such as chemical industries and nuclear