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Numerical Modelling of Residual Stresses Generated due to Orthogonal Cutting of AISI 52100 Steel

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ABSTRACT

Residual stresses induced by machining processes are a consequence of thermo-mechanical and microstructural phenomena generated during the machining operation. In this study, a numerical approach has been developed to predict the near surface residual stresses resulting from turning in orthogonal cutting of AISI 52100 alloy steel. Effect of cutting parameters, namely cutting speed and depth of cut on induced residual stresses in machined surface was investigated by modelling using ABAQUS/CAE software. An Explicit Dynamics time integration with adaptive meshing finite element method is employed to simulate the 2D model. The Johnson-Cook material model is used to describe the work material behaviour to simulate high speed machining with an orthogonal cutting. While study residual stresses at different cutting speed with constant depth of cut and variable depth of cut with constant speed are concluded. As a conclusion we can say that residual stresses varies with both variable depth of cut and variable cutting speed. Results of residual stresses given by this numerical analysis are not streamlined. It gives that as the depth of cut or cutting speed increases values of compressive residual stresses also increases but this phenomena is not constant throughout the analysis. Therefore, more up and downs in the graphical comparison and it needs to validate by experimental results.

***Keywords*— ABAQUS Explicit, Numerical modelling, Orthogonal cutting, Residual stresses.**

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I. INTRODUCTION

Residual stresses are those present in a material or structural component free of external loads or temperature variations. All manufacture process, casting, welding, molding, heat treatment, etc., introduce residual stresses in structures and equipments. Another common cause of the residual stresses introduction are repairs or modification of the in service components. In most cases residual stresses are injurious and there are several documented cases in which these strains were predominant reasons for fatigue failure. A particularly dangerous aspect of the residual stresses is that their presence is generally not noticed. The knowledge of surface residual stresses is important to predict the onset of failure when the component or structure is under loading.

There has been a lot of research devoted to finding residual stresses. Measurement techniques have been developed and simulation techniques have been improved over the years. The reason for the present study is to see if calculations of residual stresses have reached a level where they could be performed on a daily basis or not. Residual stresses in a work piece are merely a function of its material processing and machining history [3].

According to their nature, residual stresses can enhance or impair the functional behaviour of a machined part. In the vicinity of the machined surface, tensile residual stresses have negative effects on fatigue, fracture resistance and stress corrosion. The result often is a substantial reduction in the component's life [4].

Residual stresses in the machined surface layers are controlled by choices of cutting tool, work material and cutting parameters (for example: cutting speed, depth of cut and feed).

This paper introduces a way of modelling 2D precision orthogonal turning by using finite element modelling with Arbitrary Lagrangian Eulerian (ALE) technique. The aim of this paper is to demonstrate the possibilities of using Finite Element Method (FEM) as a reliable tool for investigation of residual stresses in AISI 52100 at variable cutting conditions. Firstly, finite element modelling is described. Finally overall conclusions are pointed out and future research direction is discussed.

II. NUMERICAL MODELLING OF MACHINING

Umbrello, et al., [1] presents an experimental and numerical approach to predict residual stresses by incorporating the microstructural phase transformations induced during machining of AISI 52100 steel. Jacobus, et al., [2] focused on defining the residual stresses and importance of measuring it. They also stated that thermal effects resulting in increases in the tensile character of the machining induced residual stresses.

Capello, et al., [3] investigated relationship of residual stresses and surface roughness. They concluded feed rate plays major role on both these characteristics as compared to nose radius and cutting velocity. Batalha, et al., [4] studied the cutting parameters influence on the cutting forces as well as the residual stresses in bearing materials. Also they established relationship between residual stress and penetration force with varying feed rate and cutting depth. Ratchev, et al., [5] touched on various FEM based studies related to turning and come to an end that all efforts associated with prediction of residual stresses at different cutting conditions, mechanisms of residual stress generation, material are still not fully researched. They had studied the residual stresses with constant feed and cutting speed at different depth.

Mohammadpour, et al., [6] develop a 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. Dehmani, et al., [7] studied numerically the effect of tool edge radius and heat generated by flank friction on the predicted stress profile is modelled. Commercial finite element software ABAQUS with its Explicit and Implicit modules was used. Moussa, et al., [8] a numerical approach has been developed to predict the near surface residual stresses and plastic strain resulting from turning in orthogonal cutting configuration. This approach is based on the Arbitrary Lagrangian–Eulerian (ALE) formulation using the commercial finite element code Abaqus– Explicit.

Arrazola, et al., [9] performed 3D Finite Element Method (FEM)-based numerical modelling of precision hard turning has been studied to investigate the effects of chamfered edge geometry on tool forces, temperatures and stresses in machining of AISI 52100 steel using low-grade Polycrystalline Cubic Boron Nitrite (PCBN) inserts. Stenberg, et al., [10] studied a thermo-mechanical numerical simulation of the machining operation is presented. The purpose of the simulations is to obtain the residual stresses. The FE-simulations are compared to measurements of a machined axis.

III. MODELLING METHOD AND MATERIALS

The reason for this study is to see if calculations of residual stresses have reached a level where they could be performed on a daily basis or not. ABAQUS [11], a commercial and state of the art software package, is used to provide 2D as well as full three-dimensional (3D) FE simulations of the turning operation. Every engineering based process has certain limitations and obstacles that add to its level of complexity. Understanding these limitations could provide a wide range of solutions and possibly save time and money. The scope of this study is see how easy it is to utilise calculations with low calculation costs, therefore only 2D orthogonal cutting is considered. To reduce computation time while ensuring sufficient cutting distance for steady-state cutting.

A. Workpiece Material

In the turning trials a bearing steel material, AISI 52100 steel, is used. A popular material model for use in machining simulations is the Johnson–Cook model shown in Table. 2. The model incorporates both the rate and temperature dependencies on the yield stress. The model do however not include any viscous effects that in an ideal simulation should be included. But for common use in turning simulations it is suitable because it contain vital aspects of plasticity, and the calculation cost is relatively low. The workpiece dimensions is 65mm (length) × 15mm (height).

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^m\right] \quad \text{…eq. 1}$$

TABLE I
MATERIAL PROPERTIES

Material Properties	
Density	**7.81 kg/m^3**
Poisson's ratio	**0.3**
Young's Modulus	**210GPa**
Thermal Conductivity	**47.7W/m°C**
Specific Heat	**450J/kg/°C**
Heat Capacity	**4.3368N/mm^2/°C**
Thermal Expansion	**1.72 m/m/°C**

TABLE II
JOHNSON COOK MODEL

Material	**A (MPa)**	**B (MPa)**	**n**	**m**	**C**
AISI 52100	**2484**	**1498**	**0.19**	**0.66**	**0.01**

To determine the controlling mechanism of residual stress profiles, five simulation cases were conducted using the general finite element package ABAQUS with varying depth of cut and varying cutting speed as shown in Table 3. 2-Dimensional (2D) orthogonal cutting on hardened AISI 52100 steel (60 HRC).

TABLE III
CUTTING CONDITIONS

Cutting Speed (m/min)	**Depth of Cut (mm)**				
100	**1**	**2**	**3**	**4**	**5**
125	**1**	**2**	**3**	**4**	**5**
150	**1**	**2**	**3**	**4**	**5**
175	**1**	**2**	**3**	**4**	**5**
200	**1**	**2**	**3**	**4**	**5**

IV. RESULTS

There are 25 conditions from above table and for each condition residual stress has been calculated. Following graphs shows exact overview of residual stresses.

TABLE IV
CONDITION 1

Condition 1					
Cutting Speed	**100**	**100**	**100**	**100**	**100**
Depth of Cut	**1**	**2**	**3**	**4**	**5**

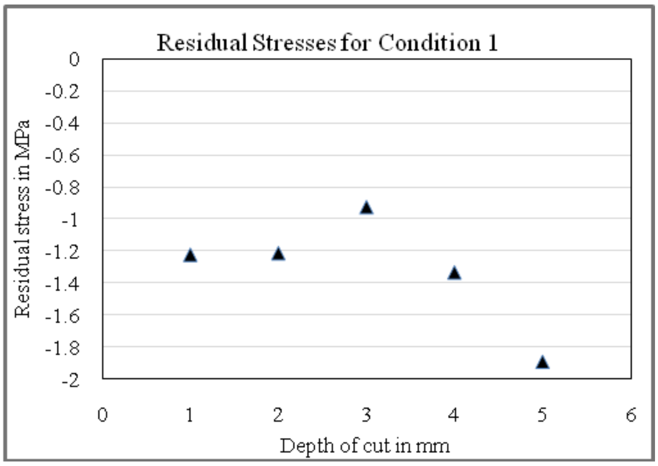

Fig.1 residual stresses at 100 m/min velocity and 1mm, 2mm, 3mm, 4mm, 5mm depth of cut.

TABLE V
CONDITION 2

Condition 2					
Cutting Speed	**125**	**125**	**125**	**125**	**125**
Depth of Cut	**1**	**2**	**3**	**4**	**5**

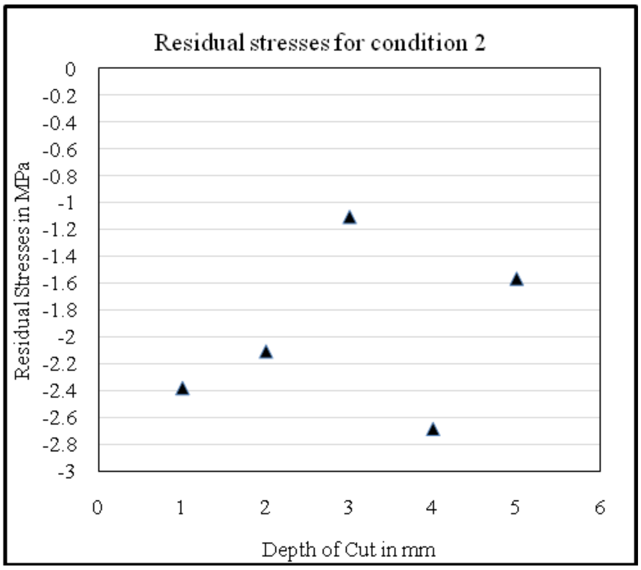

Fig.2 residual stresses at 125 m/min velocity and 1mm, 2mm, 3mm, 4mm, 5mm depth of cut.

TABLE VI
CONDITION 3

Condition 3					
Cutting Speed	**150**	**150**	**150**	**150**	**150**
Depth of Cut	**1**	**2**	**3**	**4**	**5**

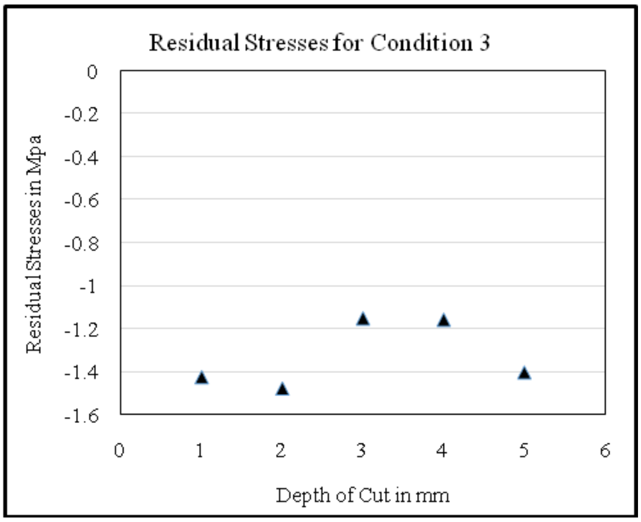

Fig.3 residual stresses at 150 m/min velocity and 1mm, 2mm, 3mm, 4mm, 5mm depth of cut.

TABLE VII

CONDITION 4

Condition 4					
Cutting Speed	**175**	**175**	**175**	**175**	**175**
Depth of Cut	**1**	**2**	**3**	**4**	**5**

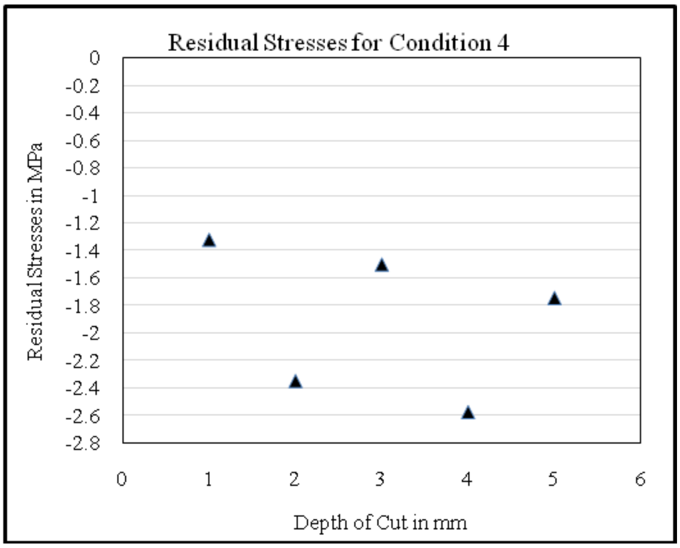

Fig.4 residual stresses at 175 m/min velocity and 1mm, 2mm, 3mm, 4mm, 5mm depth of cut.

TABLE VIII
CONDITION 5

Condition 5					
Cutting Speed	**200**	**200**	**200**	**200**	**200**
Depth of Cut	**1**	**2**	**3**	**4**	**5**

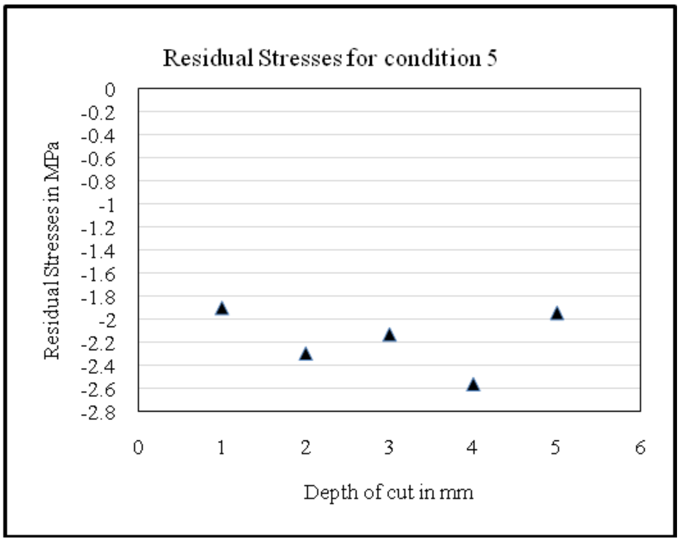

Fig.5 residual stresses at 200 m/min velocity and 1mm, 2mm, 3mm, 4mm, 5mm depth of cut

Now we will see the results of residual stresses with constant depth of cut and variable cutting speed.

TABLE IX
CONDITION 6

Condition 6					
Cutting Speed	**100**	**125**	**150**	**175**	**200**
Depth of Cut	**1**	**1**	**1**	**1**	**1**

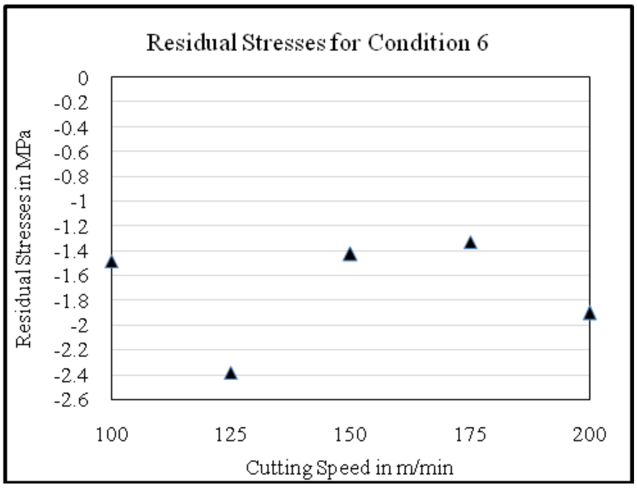

Fig.6 residual stresses at 1 mm depth of cut and 100m/min, 125m/min, 150m/min, 175m/min, 200m/min cutting speed

TABLE X
CONDITION 7

Condition 7					
Cutting Speed	**100**	**125**	**150**	**175**	**200**
Depth of Cut	**2**	**2**	**2**	**2**	**2**

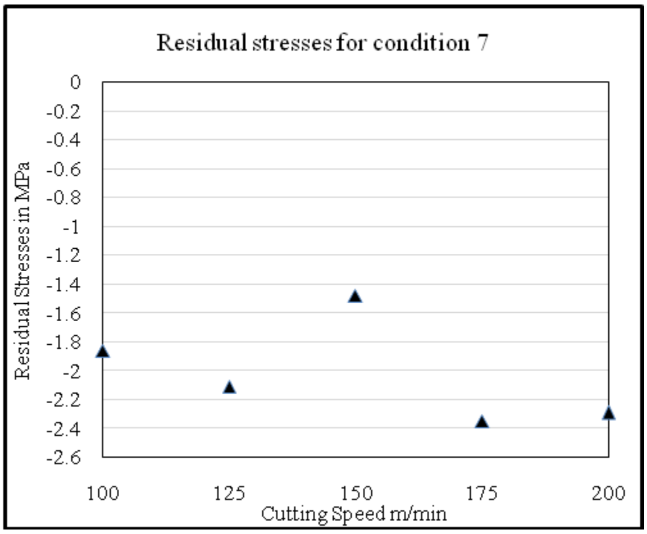

Fig.7 residual stresses at 1 mm depth of cut and 100m/min, 125m/min, 150m/min, 175m/min, 200m/min cutting speed

TABLE XI
CONDITION 8

Condition 8					
Cutting Speed	**100**	**125**	**150**	**175**	**200**
Depth of Cut	**3**	**3**	**3**	**3**	**3**

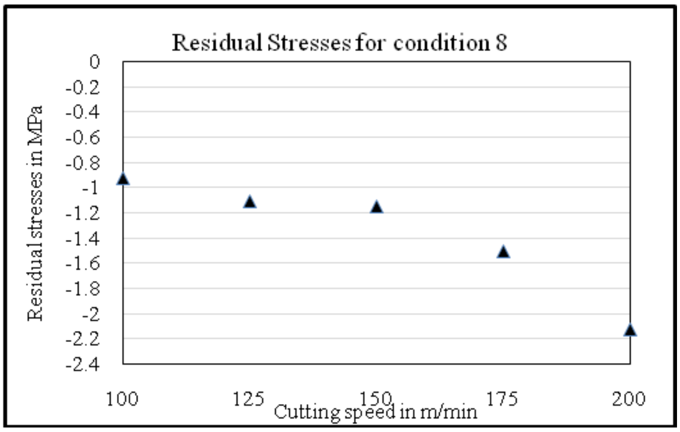

Fig.8 residual stresses at 3 mm depth of cut and 100m/min, 125m/min, 150m/min, 175m/min, 200m/min cutting speed

TABLE XII
CONDITION 9

Condition 9					
Cutting Speed	**100**	**125**	**150**	**175**	**200**
Depth of Cut	**4**	**4**	**4**	**4**	**4**

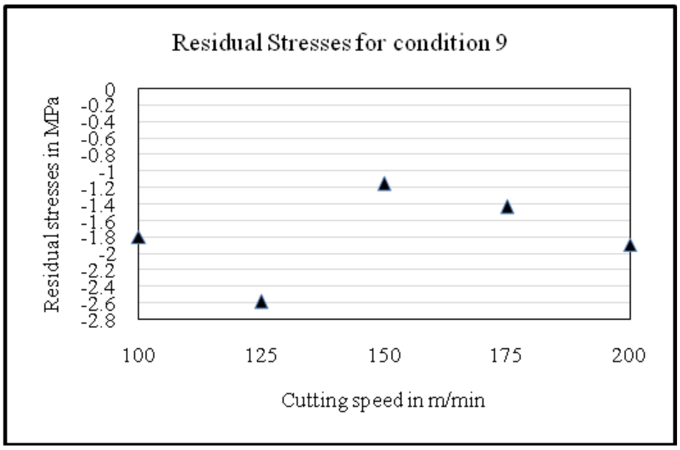

Fig.9 residual stresses at 4 mm depth of cut and 100m/min, 125m/min, 150m/min, 175m/min, 200m/min cutting speed.

TABLE XIII
CONDITION 10

Condition 10					
Cutting Speed	**100**	**125**	**150**	**175**	**200**
Depth of Cut	**5**	**5**	**5**	**5**	**5**

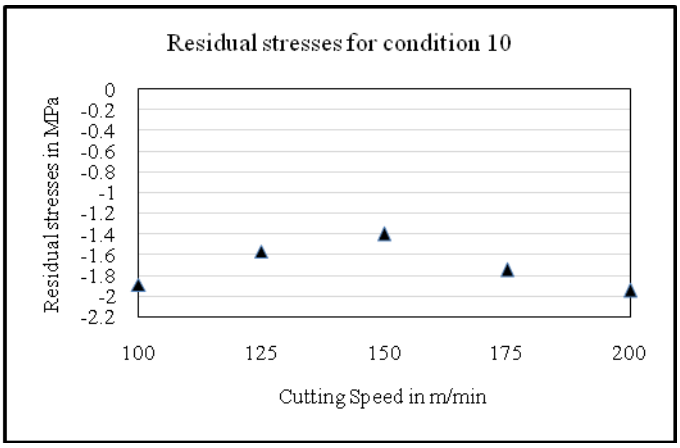

Fig.10 residual stresses at 5 mm depth of cut and 100m/min, 125m/min, 150m/min, 175m/min, 200m/min cutting speed.

V. CONCLUSION

In this study, a numerical approach has been developed to predict the near surface residual stresses resulting from turning in orthogonal cutting of AISI 52100 alloy steel. Effect of cutting parameters, namely cutting speed and depth of cut on induced residual stresses in machined surface was investigated by modelling using ABAQUS/CAE software. It has been observed that the predicted residual stress profiles in the cutting direction shows the compressive residual stress profile. The predicted pattern of residual stress does not give exact relationship between depth of cut and cutting speed.

The conclusion for constant cutting speed are as follows:

1) All the residual stresses are compressive in nature.

2) As above results except 3 mm depth of cut compressive residual stresses increases as depth of cut increases.

The conclusion for constant depth of cut are as follows:

1) Compressive residual stress increases as cutting speed increases.

2) Though all graph gives increasing nature of compressive stress, all graph points are not satisfies ascending flow nature.

Therefore from all above conclusions we only conclude that as depth of cut or cutting speed increases compressive residual stress increases. But this numerical modelling needs to validate with the experimental results.

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