Numerical analysis of surface integrity in parallel turning process Part I: Influence of cutting tool parting distance

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Abstract: Surface integrity is one among the prime quality features of turned parts. In the present research work, surface residual stress generated during parallel turning is analysed numerically using finite element method based software. Parting of cut-chip from uncut-work material is dealt by Johnson-Cook criteria. Tool-chip friction was modelled by penalty contact method. Cutting tool parting distance is an important process parameter in parallel turning. The main objective of the current research work is to evaluate the significance of parting distance on axial and circumferential surface residual stresses induced on machined work surfaces. The analysis revealed that with the increment in parting distance, the surface integrity raised. When the distances was raised from 0.4 to 0.8 mm, for a cutting velocity of 150 m/min and feed 0.2 mm/rev the axial and circumferential residual stresses elevated by 34% and 33% for surface machined by second tool. For all chosen parting distances, the stresses raised with the increase in cutting velocity. Parallel turning was advantageous in increasing the machined surface integrity.

1. INTRODUCTION

Surface integrity determines the quality of turned components. In parallel turning process the residual stresses are generated due to thermal and mechanical loading. Schematic of parallel turning process is shown in Figure 1. Tool parting distance is one of the important process parameter in parallel turning process apart from cutting speed, uncut chip thickness and feed rate. In the past several researchers had investigated the stresses induced during traditional turning process. Many experimental investigations were done on traditional turning to predict the residual stress of both ferrous and non-ferrous metals. The machined sub-surface stresses were found to be larger than the surface residual stresses. These stresses are also dependent on turning parameters [1]. Feed rate was significant whereas cutting speed had an insignificant influence. The surface residual stress was observed to elevate with the rise in feed. In certain cases the tensile residual stresses also elevated with the rise in cutting velocity. The same trend was observed for cutting tool nose radius. This parameter also affected the surface integrity of the finished work surfaces [2].

In this context it is worth mentioning that, larger nose radius causes higher surface finish. Numerical analysis on the significance of tool edge radius on residual stress can reveal the details of process mechanism [3]. The plastic strain at the primary shear zone and the magnitude of compressive residual stress increases with the increment in nose radius. Providing higher uncut chip thickness is a method of increasing the compressive surface residual stress. Some researchers revealed that the compressive surface residual stress of 400 MPa was attained when depth of cut was doubled while turning stainless steel with both coated and uncoated carbide tools [4]. The same was correlated with milling operation [5]. Minimum compressive residual stress was found at the milled surface when sharp secondary cutting edge milling cutter was employed. Finite element simulation was also
employed to evaluate the dependence of residual stress on cutting edge radius during micro cutting. Apart from cutting parameters work hardening had a significant effect on residual stress. Higher nose radius lead to deeper penetration of tensile residual stress during micro cutting of AISI 1045 steel [6]. Another simulation study employed Normalised Cockcroft and Latham failure criterion. Positive and neutral rake angle led to tensile residual stress [7]. It was observed that substantial work on residual stress was performed on traditional turning process. Parallel turning process posses many advantages such as improved surface integrity and tolerance, lesser cutting force and increased dimensional accuracy on comparison with traditional turning. Some works on multiple and duplex turning are reported as follows.

**Figure 1. Schematic of parallel turning process**

Multi-cutter turning process reduced chatter vibration and improved stability of the process [8]. This enhanced the surface integrity and dimensional tolerances of turned parts leading to superior quality. The machine tool vibration was also influenced by tool parting distances [9]. The vibration amplitude decreased with the increase in parting distances and cutting velocity. Research was also directed towards optimization of stability limits in two cutter symmetrical turning operation [10]. Maximum material removal rate was the objective function. Subsequently the optimized results were validated by experimental values. An experimental study was performed on multiple tool turning operation to determine the influence of parting distance on tangential forces and work material thermal property [11]. These forces were uninfluenced by the changes in parting distance. The second cutting tool experienced lower feed force for some machining parameters. This was attributed to reduced friction at the interface of second tool and chip. Experiments were conducted to find the impact of cutting conditions on surface integrity in two tool turning [12]. The surface integrity was significantly affected by secondary depth of cut rather than primary depth of cut. Higher surface finish was obtained by the combination of lower secondary depth of cut and feed. Apart from experiments, computational study was performed on two tool turning process [13]. The significance of parting distance on cutting temperature and main cutting force was analysed numerically. The cutting force variation between the two tools was found to be less than 7%. The highest cutting temperature was 900°C for certain machining conditions. Recently multiple response optimization was performed by combining grey relational analysis with Taguchi method in duplex turning of nickel alloy. The contribution of feed was highest and primary uncut chip thickness was lowest in achieving optimal surface finish [14].

It can be noted from the published literature that some research work was done on multi-tool turning
in determining the stability, dimensional accuracy, cutting forces, cutting temperature and optimization. However no work was done on residual stresses and its variation with change in process parameters in parallel turning. The main objective of this research is to perform numerical analysis on the influence of tool parting distance over surface residual stresses generated during parallel turning process.

2. NUMERICAL MODEL

The first step in numerical modelling involves creating two dimensional geometry with necessary feature and assigning material property. The material model is based on Johnson-Cook. AISI 4340 steel and carbide are taken as work and tool material. Explicit dynamic analysis was performed with contact model and meshing. Finally boundary conditions were applied followed by post processing. The complete details of numerical procedure are given in recently published literature [15]. The values of process variables employed in the numerical analysis are cutting velocities in the range of 150 to 250 m/min, 0.1 to 0.2 mm/rev feed and parting distances are varied with an increment of 0.1 mm in the range of 0.4 to 0.8 mm.

3. RESULTS AND DISCUSSION

The post processed results of numerical model along with corresponding discussions are elaborated here. The effect of tool parting distance on residual stresses induced by first and second cutting tool on the work surface is reported. With the increase in tool parting distance the circumferential and axial compressive residual stresses increases for the surface machined by the first cutting tool. This can be observed from the Table 1. In the Table 1, \( v \) and \( s \) represents cutting speed (m/min) and tool parting distance (mm). \( \sigma_{xx}^{1} \) and \( \sigma_{yy}^{1} \) are the circumferential and axial residual stresses of surface machined by first cutting tool. As tool parting distances are raised from 0.4 to 0.8 mm, \( \sigma_{xx}^{1} \) and \( \sigma_{yy}^{1} \) for the surface turned by first tool increased by 46% and 31% respectively. This is for a cutting velocity of 150 m/min and feed 0.2 mm/rev. As the cutting velocity is raised to 250 m/min for the same feed and same increase in tool parting distance, 38% and 26% increase in \( \sigma_{xx}^{1} \) and \( \sigma_{yy}^{1} \) are observed.Additionally, for all tool parting distances considered in this numerical study, with the increase in cutting velocity both \( \sigma_{xx}^{1} \) and \( \sigma_{yy}^{1} \) increased.

| \( v \) (m/min) | \( s \) (mm) | \( \sigma_{xx}^{1} \) (MPa) | \( \sigma_{yy}^{1} \) (MPa) |
|----------------|-------------|-----------------|-----------------|
| 150 | 0.4 | -700 | -654 |
| 150 | 0.5 | -789 | -629 |
| 150 | 0.6 | -890 | -657 |
| 150 | 0.7 | -1000 | -753 |
| 150 | 0.8 | -1023 | 
| 200 | 0.4 | -758 | -781 |
| 200 | 0.5 | -827 | -789 |
| 200 | 0.6 | -907 | -834 |
| 200 | 0.7 | -1038 | 
| 200 | 0.8 | -1066 | 
| 250 | 0.4 | -802 | -740 |
| 250 | 0.5 | -848 | -803 |
| 250 | 0.6 | -937 | -822 |
| 250 | 0.7 | -1067 | -898 |
| 250 | 0.8 | -1108 | -930 |
Figure 2. Compressive residual stresses of the surface machined by second cutting tool for various tool parting distance with 0.2 mm/rev feed (a) Circumferential (b) Axial

Figure 2 (a) and (b) reveals the variation of circumferential ($\sigma_x^2$) and axial ($\sigma_y^2$) compressive residual stresses machined by second cutting tool for various tool parting distance for the cutting velocities of 150, 200 and 250 m/min with 0.2 mm/rev feed. Similar to previous observations, $\sigma_x^2$ and $\sigma_y^2$ of the surfaces machined by second cutting tool increased with the increase in tool parting distance. For the selected range of tool parting distance, with increase in cutting velocity the surface residual stresses increased. When the tool parting distances raised from 0.4 to 0.8 mm, $\sigma_x^2$ and $\sigma_y^2$ of the surface machined by second cutting tool increased by 33% and 34% respectively. The cutting speed and feed are 150 m/min and 0.2 mm/rev respectively. When the cutting velocity is increased to 250 m/min, an increase of 37% and 23% was observed. The other parameters are same as previous cutting conditions.

The work surface temperature is increased due to the machining of first cutting tool. It is still further increased by the simultaneous machining of second tool. Hence the second tool machined surface temperature is higher than the first cutting tool machined surface. For a tool parting distance of 0.4 mm, 150 m/min cutting velocity and 0.2 mm/rev feed, the mean surface temperature of the surface machined by the first cutting tool is 475°C. This increases to 494°C when the surface is machined by the second tool. The time interval between machining of work surfaces by first and second tool is 0.16 milliseconds. Adiabatic heat transfer takes place between the machined work surface and environment due to small time duration, setting up a thermal gradient. Due to higher machined surface temperature of the second cutting tool the thermal gradient is higher when compared with the surface machined by the first tool. Higher thermal gradient induces higher residual stresses on the machined surface. When the tool parting distances are raised the thermal gradient on the machined work material increases. For the above mentioned cutting conditions when the tool parting distance is increased to 0.8 mm the mean surface temperature machined by first and second cutting tool are 540°C and 550°C respectively.

When the cutting speed is increased to 250 m/min both circumferential and axial compressive residual stress are increased due to further increase in work surface temperature. For 0.4 mm tool parting distance the mean surface temperature of the surfaces machined by first and second cutting tool is 543°C and 661°C respectively. When the tool parting distance is raised to 0.8 mm the temperature increases to 692°C and 781°C. Thus higher cutting speed and higher tool parting distance causes higher machined surface temperature resulting in higher compressive surface residual stresses.
4. CONCLUSIONS

- Parallel turning process is very advantageous in increasing the surface integrity. The surfaces machined by the second tool possess higher circumferential and axial compressive residual stress. Unstressed work surface is turned by the first cutting tool. On the other hand, pre-stressed work surface is turned by second cutting tool. This increases the compressive residual stresses on the turned work surface of the second tool. Additionally the hardness is expected to increases on the work surface during machining.

- When the tool parting distance is increased both surface compressive residual stress increased. Thermal gradient caused due to adiabatic heat transfer plays a major role in increasing the surface residual stresses of the workpiece.

- On increasing the tool parting distance from 0.4 mm to 0.8 mm, with 150 m/min cutting speed and 0.2 mm/rev feed the circumferential and axial compressive residual stresses of the surface machined by second tool increased by 33% and 34%. For all the chosen cutting speeds, increase of tool parting distances increased the surface compressive residual stresses.

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