Influence of the cutting regime on the residual stresses generated by carbon steel milling

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All technological operations based on the material deformation generate residual stress. Milling is a complex process that involves effects like heat generation, plastic strains and residual stress. Some of the most important parameters used in the milling operation that influence the type of residual stress are: cutting speed, cutting feed and depth of cut. Residual stress distribution can affect the mechanical characteristics of the workpiece. The present paper is an experimental and theoretical study regarding the influence of the working parameters on residual stress distribution generated by milling. The experiments are carried out on carbon steel K945. The cutting regime is varied as: \( v = 16 \) to 1036 m/min; \( f = 375 \) to 1400 mm/min; depth of cut \( ap = 0.15 \) to 0.5mm. A small cutting depth (equal to 0.15 mm) generated the lowest values of residual stress. The use of high cutting feed (equal to 1400 mm/min) lead to large variations of residual stress. Simulations by finite element method using AdvantEdge software have been conducted and compared with the experimental results. There is a good agreement between results of FE analysis and the experimental study.

**Keywords:** Residual stress, Milling, Cutting parameters, K945 carbon steel, FEM analysis

Residual stress is present in a free body due to processing or in serving conditions. Residual stress can lead to unexpected and premature failures and geometric distortions of a component/structure, especially those subjected to alternating service loads and/or corrosive environments. It arises from the elastic response of material to inhomogeneous distribution of non-elastic strains, e.g., precipitation, phase transformation, thermal expansion, etc. As the design of engineering components becomes less conservative, there is increasing interest in how residual stress affects mechanical properties. This is because structural failure can be caused by the combined effects of residual and applied stresses. In practice, it is unlikely that any manufactured component would be entirely free of the residual stresses introduced during processing. Furthermore, in natural or artificial multiphase materials, residual stresses can arise from differences in thermal expansivity, yield stress, or stiffness.

The importance of residual stress originates in the uncertain nature of stress patterns that are generated after the component manufacturing and the effect that it has on its performance. The effects of residual stress may be either beneficial or detrimental, depending upon their magnitude, sign and distribution with respect to the load induced stresses\(^1\)\(^-\)\(^3\). The adopted cutting regime is one of the most important factors that affect the distribution of residual stress. The deployment of different cutting speeds, depths and feeds, tool geometries etc. leads to different types of residual stress distribution in surface layer\(^4\)\(^-\)\(^8\). The aim of present paper is to determine the influence of different machining parameters on residual stress distribution when milling carbon steel K945.

**Experimental Procedure**

Carbon steel material type K945 was selected, as this material is often used for the manufacturing of: industrial plant machinery, cutting tools, agricultural tools or parts with complex geometry that require multiple types of processing. Good workability and increased wear resistance make it a highly used material in machining. The chemical composition and mechanical properties of the material are presented in Tables 1 and 2.

The hole drilling technique was used to measure the residual stress in the surface layer to a depth of 0.6 mm. The measurements were conducted using a RESTAN device from SINT, consisting of a
SINT 2—mechanical drilling machine, electronic assembly SINT 1, digital data logger SPIDER 8 and a computer (Fig. 1). The strains were measured using a strain gauges rosette, type HBM 1.5/120RY61S, bonded on the surface of the tested material. The gauge rosette sends the signals to the computer through the data acquisition system. The obtained data were processed using the “integral” calculation method. The measurements were made in 16 steps for a depth range between 0.05-0.8 mm. Initial measurements have been conducted on the materials prior to milling, in order to determine the initial residual stress distribution.

The milling was performed on a CNC machining centre capable of delivering a maximum spindle speed of 12000 rot/min. The tool was a cylindrical mill with 50 mm diameter and 5 inserts with an edge radius of 0.025 mm, 90° cutting insert orientation (Fig. 2). The milling operation was performed on prismatic parts. The worked surface has had the following dimensions 150×60×50 mm and the radial width of cut was equal to 50 mm.

To determine the influence of the cutting parameters on the residual stress distribution, the following parameters were used: cutting speeds 157 m/min, 200 m/min and 250 m/min, cutting depth from 0.15 to 0.5 mm and cutting feed from 375 mm/min to 1400 mm/min.

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<th>Table 1 – Chemical composition</th>
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<td>Type of material</td>
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<th>Table 2 – Mechanical properties of the materials</th>
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<td>Material</td>
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Fig. 1 – Hole-drilling residual stress measuring equipment

Fig. 2 – Mill type (a) insert geometry, (b) insert orientation and (c) coromil 490
Finite element simulations were conducted using AdvantEdge 5.9, a software developed specially for metal cutting applications (Fig. 3). All the experimental conditions (material type, cutting parameters, etc.) were carefully replicated in the software model.

**Results and Discussion**

In order to compare the different types of influences on the residual stress distribution in the surface layer, the residual stress was measured in the material before milling. It can be observed from Fig. 4 that the distribution of the residual stress was of tensile type, with variations within 40 to 140 MPa intervals that was the most probably due to previous manufacturing operations.

**Influence of cutting speed on the residual stress distribution**

The influence of cutting speed on the residual stress distribution was analysed using three different values of the cutting speed (157 m/min, 200 m/min and 250 m/min) while keeping constant the other process parameters: cutting feed of 750 mm/min and cutting depth of 0.25 mm.

It can be observed from Fig. 5 that the residual stress distribution is mainly above zero axis, meaning that they are tensile stresses. For the cutting speed of 157 m/min the residual stress had the maximum value in the surface layer (264 MPa at 0.02 mm depth) and decreased to 14 MPa at 0.5 mm depth, passing to compressive stress (-50 MPa) at 0.6 mm depth. The increase of the cutting speed to 200 m/min leads to higher residual stresses, with a general behaviour similar with the ones generated by the previous cutting speed, but at higher values from the tensile zone. In the surface layer (0.02 mm depth) the residual stress was up to 246 MPa and decreased to 10 MPa at 0.05 mm in the subsurface layer. Going into the material depth we could observe that the stress had increased values (up to maximum 114 MPa at 0.45 mm depth and remained in tensile zone to the depth of 0.6 mm). On the other hand, the milling with cutting speed of 250 m/min lead to high tensile level of the residual stress (542 MPa at 0.02 mm depth), that decreased rapidly to -29 MPa at 0.155 mm. Generally, the distribution in this case was around 0 MPa (maximum tensile value in the subsurface layer was 45 MPa). Analysing the results for all three
cutting speeds we could observe that the lowest level of the distribution was close to 0 MPa, which is almost ideal for a machined material, and it was obtained using the cutting speed of 250 m/min.

**Influence of cutting depth on the residual stress distribution**

The cutting depth was the second parameter analysed, which could influence the residual stress distribution. The influence of different cutting depths on the residual stress distribution was studied by keeping constant the cutting speed and the cutting feed, at 157 m/min and 750 mm/min respectively, while deploying three different cutting depths 0.15 mm, 0.25 mm and 0.5 mm, respectively.

From the obtained results (Fig. 6), it can be observed that all three cutting depths generally lead to tensile residual stresses. The smallest value of the residual stress was obtained when using a cutting depth equal to 0.15 mm, while the largest variation was obtained for a cutting depth equal to 0.25 mm. Using a cutting depth of 0.15 mm leads to a residual stress value of 162 MPa in the surface layer (0.02 mm) that decreases rapidly to 17 MPa at 0.05 mm. Going into the depth it could be observed that residual stress had an approximately sinusoidal behaviour, it became compressive (-17 MPa) in subsurface layer at 0.3 mm, crossed again into the tensile zone at 0.4 mm, while at 0.6 mm the residual stress had a value equal to 80 MPa. The increase of the cutting depth to 0.25 mm leads to important modifications in the distribution of the residual stress, as: in the surface layer, at 0.05 mm, the residual stress had the highest values from all three of them (264 MPa) but decreased for the 0.2 mm depth to 36 MPa; below this depth it could be observed that the values increase to 138 MPa at 0.25 mm depth, and turn into compressive stress at 0.6 mm depth (-50 MPa). Using a cutting depth of 0.5 mm, leads to a higher level of the tensile stresses. The distribution was more stable than that in the previous cases; in the surface layer at 0.05 mm the stress had a value equal to 138 MPa and slowly decreases throughout the depth to 58 MPa at 0.35 mm, reaching the minimum value (1 MPa) at 0.5 mm depth. From this analysis we have concluded that a small amount of material removed from surface would lead to a lower level value of the residual stress. Thus, using the cutting depth of 0.15 mm generated a decrease of the residual stress values.

**Influence of the cutting feed on the residual stress distribution**

From Fig. 7, it could be observed that the amplitude of the residual stress distribution is generally higher than the previous analysed cases and that the distribution was also situated generally in the tensile zone. The cutting feed of 375 mm/min generated a stress value of 170 MPa in the surface layer (0.02 mm) and increased to a maximum value in the subsurface layers (0.3 mm) at 271 MPa. Going into the materials depth the distribution goes in the compressive zone (-121 MPa) at 0.5 mm and after that it rapidly increased to 45 MPa at 0.6 mm. The increase of the cutting feed leads to an increase in the residual stress value in the surface layer 0.02 mm (364 MPa), and like in the previous case the values decreased in the subsurface layers (36 MPa at 0.15 mm). The trend of the distribution was similar with the previous one, but this time the values were smaller (133 MPa at 0.3 mm), slowly decreasing into the material depth to -50 MPa (0.6 mm). The cutting feed of 1400 mm/min generated an increase of the residual stress (max 480 MPa at 0.05 mm) followed by a rapid decrease to zero and -13 MPa at 0.35 mm. Below 0.45 mm depth it could be observed that an equilibration effect occurred, the residual stress becoming tensile again with maximal values equal to 190 MPa at 0.55 mm depth.
FEM simulations

From the obtained results it could be observed that in almost all the cases there were some differences from the experimental data, most probably because of the inhomogeneity of material and the variation of temperature presented when experiments were conducted.

It can be also observed that generally the tendency of residual stress distribution is similar (in experiment and simulation), but there are some differences regarding the values generated by the software. For all the three cutting speeds it is observed that in surface layer the residual stress has higher values than that in experiments. The highest difference for cutting speed it is observed at the use of cutting speed of 157 m/min (Fig. 8) (from 36 MPa to -73 MPa at 0.2 mm). For higher speeds (200 and 250 m/min) the differences are smaller.

The simulation with the cutting depth of 0.15 mm is shown in Fig. 9a. It is observed that the most notable difference is in the surface layer at 0.2 mm depth. In the simulation the value of residual stress distribution was high (342 MPa), while in the experiment the measured value was 86 MPa at 0.02 mm. Generally, the tendency is similar for both used cutting depths. There are no major differences between simulation and experimental results.

The simulation for the cutting feed is shown in Fig 10. It is observed that there are also small differences. Using a cutting feed of 375 mm/min, the highest difference between simulation and experiment was observed at 0.5 mm depth, with -121 MPa for experimental value and -2 MPa from simulation. A smaller difference between values is observed when using a cutting feed of 1400 mm/min at 0.1 mm depth.

The differences between FE analysis and the experiments are most probably due to the fact that the experimental conditions are influenced by a series of random factors that are hard or impossible to control, while the simulation works with idealized conditions.
Conclusions

The distribution of the residual stresses is highly influenced by the parameters of the machining operations. A favorable distribution of residual stresses around zero was obtained when the machining parameters were set as: cutting speed of 250 m/min, cutting feed 750 mm/min and cutting depth of 0.25 mm. The use of smaller cutting depths (0.15 mm) leads to lower levels of residual stress (around 0 MPa) in the subsurface layer.

The most influential factor for residual stresses is cutting feed. The use of a smaller cutting feed (375 mm/min) leads to a more compact distribution of the residual stress, with lower variations. High cutting feed generated a rapid decrease of the residual stress from the surface to the subsurface layers with values closer to 0 MPa level.

The results from FE simulations showed no significant differences when compared to the experiments. The differences come most probably from the fact that the simulations consider an idealized structure of the material and from the inherent influences of the environment during the experimental determinations. When properly set, the finite element simulations can be used as a reliable and cheaper alternative for the experimental determinations.

References