A THEORETICAL AND EXPERIMENTAL RESEARCH ON RESIDUAL STRESSES DISTRIBUTION GENERATED BY SUCCESSIVE MILLING

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Abstract: In the case of manufacturing mechanical processes, all technologic operations based on material deformation generate different types of residual stresses that can be useful or detrimental, critical or insignificant. For the milling operations, the level and type of residual stresses depend on material proprieties and chemical components, working parameters and working conditions. The present paper analyses the experimental and theoretical results concerning the distribution of residual stresses generated in surface layers by succesive milling operations. Two, respectively three types of cutting speeds have been used successively (first, a cutting speed equal to 250 m/min followed by a cutting speed equal to 1036 m/min, and second, a triple cutting speed 157, 250 and 1036 m/min). For each cutting speed, different cutting depths were used. FEM simulations have been conducted in order to confirm the experimental results. The determination of residual stress distributions on surface layer was made by using the blind hole drilling method.

Key words: milling, residual stress, cutting speed, succesive milling

1. INTRODUCTION

Milling operation has an important role in the manufacturing metallic parts. Generation of residual stresses is one of the effects that milling generates on machined material. The machining technologic operations generally induce the following two types of residual stresses: thermal and mechanical, (Callister, W. D., 2007). The thermal induced stresses arise because of high temperatures that are locally generated by inadequate machining parameters, material properties (low thermal conductivity), tools behaviour (intensive flank wear), cooling system etc. The mechanical residual stresses occur when between the external and internal material layers some differences exist because of incompatibility between the material permanent deformations generated by the action of different loadings or machining operations that constrain the materials or the parts. In the case of multiple manufacturing operations, the residual stresses generated in blanks previous to their transformation in final part can affect the next machining operations, (Totten, G. E., Howes, M. A., 2002). Such residual stresses can lead in some cases to the improvement of the materials mechanical behaviour but in other cases the above mentioned stresses must be eliminated. The knowledge of the residual stress effects can bring more advantages for the constructive and technologic design of parts because it can permit the avoidance of some unfavourable states of residual stresses, can increase the parts reliability, can lead to a smaller risk of premature destruction or to material properties needed for a good part operating, (Brabie, G., 1995, Withers, P. J., 2001, Yang, B.-Q., et. al., 2009). The technical literature presents a small number of papers regarding residual stress distributions generated by milling operations. Most of the studies were conducted to analyse the distribution of residual stresses generated by changing different influence factors such as: machining working parameters, tool geometry, and chemical compositions of the analysed work piece. Nowadays research is oriented to change the state of stress distribution (compressive / tensile). There are different ways to change the distribution of initial residual stress. Shot penning and laser penning are somee of the methods that can change the distribution of residual stress. Usually, using shot penning, the residual stress distribution will be changed from tensile to compressive residual stress; on the other hand the use of laser penning will generate tensile residual stress with higher amplitude, (Ali, A., 2007, Hatamleh, O., 2008, Masaki, K., et al., 2007). Changing the type of distribution can be made also by changing the geometry of tool. Using a ball nose mill, tensile residual stress can be changed from tensile to compressive residual stress, (Segawa, T., et al., 2004); in this case the used mill is a combination between a traditional mill and a ball having the same effect as shot penning. A mill can also be used to change the amplitude of residual stress distribution on weld materials, (Dattoma, V., De Giorgi, M., Nobile, R., 2006, Davim, P., 2010). The thermal effect generated when the materials are welded will induce high tensile residual stress, milling the welded material will reduce the amplitude of tensile residual stress distribution. The effect of reduction (of residual stress) is bigger when the mill is applied directly on weld, (Dattoma, V., De Giorgi, M., Nobile, R., 2006). The present research was conducted in order to determine the influence of multiple milling operations on residual stress distributions in surface layers.

2. EXPERIMENTAL CONDITIONS

A carbon steel material (K 945 – EN DIN C45U) was used for this experiment. The chemical composition and mechanical proprieties of the used material are presented in Table 1 and 2.

Table 1. Chemical composition of carbon steel K 945

Material %	C	Si	Mn	P	S
Carbon steel K 945	0.480	0.300	0.700	0.055	0.055

Table 2. Mechanical proprieties of material

Steel	Tensile Yield Strength	Ultimate Tensile Strength	Hardness, Vickers (initial measured)
	$R_{p0.2}$ [MPa]	R_m [MPa]	[HV]
Carbon steel	622	1027	218

The residual stresses in surface layers were measured using the hole-drilling measuring technique. The main components of the equipment used in experiment (Fig. 1) were as follows: the Hottinger device (formed by a mechanical assembly for hole drilling called SINT2 and an electronic assembly called SINT1), the digital data logger (SPIDER 8-30), and a control computer that ensures the control of individual operations (vertical position fine adjustment, compressed-air inflow, measured strain recording dependent on the hole depth etc.). The strains were measured by using a gauge rosette, type HBM 1.5/120RY61S, bonded on the tested material. The rosette sends the signals to a 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 - 0.7 mm. Initial measurements has been conducted on the material in order to determine the initial residual stress distribution.

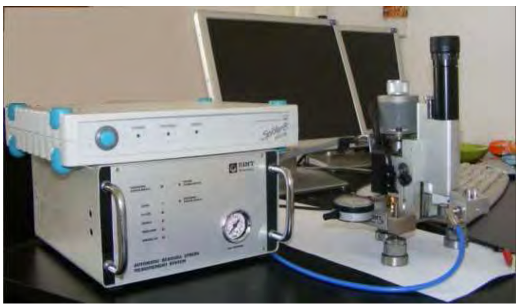

Fig. 1. Hole-drilling residual stress measuring equipment

Milling was performed on a CNC 3 axes machine having the maximum spindle rotation equal to 12.000 rot/min. The tool used was a cylindrical mill having a diameter equal to 50 mm and 5 inserts with an edge radius equal to 0.025 mm. The milling operation was performed on a prismatic part. The worked surface has had the following dimensions 150 x 50 x 50mm and the radial width of cut was equal to 50mm.

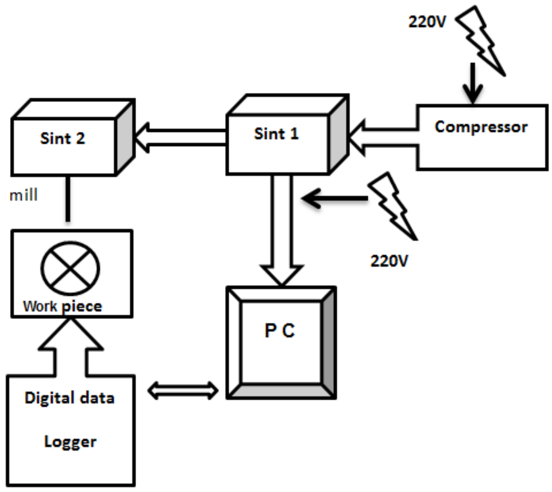

Fig. 2. Schema of the hole-drilling residual stress measuring method [11]

The tool used was a cylindrical mill having the diameter equal to 50 mm and 5 inserts with an edge radius equal to 0.025 mm (fig 3a), and 90º cutting insert orientation (fig.3 b) [1; 10].

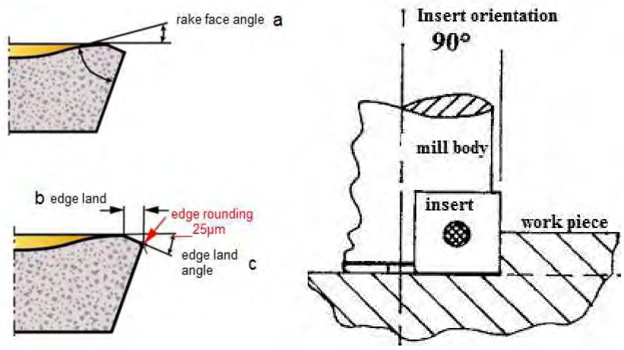

Fig. 3. Geometry of milling insert and orientation of cut

The temperature measurement has been made by using a FLIR A325 Infrared Camera. Data aqusition was made using the FLIR R&D software 1.2.

In order to determine the influence of cutting speed on residual stress distribution, three different cutting speeds have been used. First it have been used a cutting speed V_1 equal to 157 m/min and a depth equal to 0.5 mm; secondly a cutting speed V_2 equal to 250 m/min and a depth of cut equal to 0.25 mm and thirdly a higher speed has been used on the same surface using a V_3 speed equal to 1036 m/min and a depth of cut equal to 0.15mm. The milling operation was carried out without cooling liquid.

The simulations have been made using the AdvantEdge 5.8 simulation software that is specialized for metal cutting (Fig. 4)

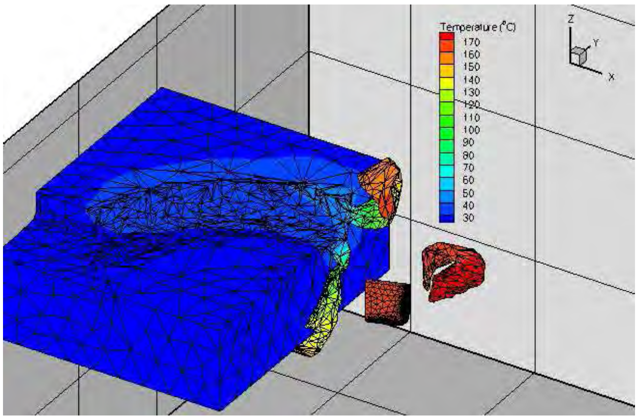

Fig. 4. AdvantEdge interface simulation process

3. RESULTS AND DISCUSSIONS

3.1 Initial residual stress distribution

In order to compare the distribution of residual stresses generated by multiple milling operations, three determinations have been conducted: before milling, after milling with cutting speed V_1, V_2, V_3 and finally after the use of multiple milling V_1+V_2+ V_3, V_2+ V_3, V_3+V_2 on the same surface.

The maximum residual stress values were measured on a direction parallel to the feed rate direction. The distributions of residual stresses before milling are presented in Fig 5.

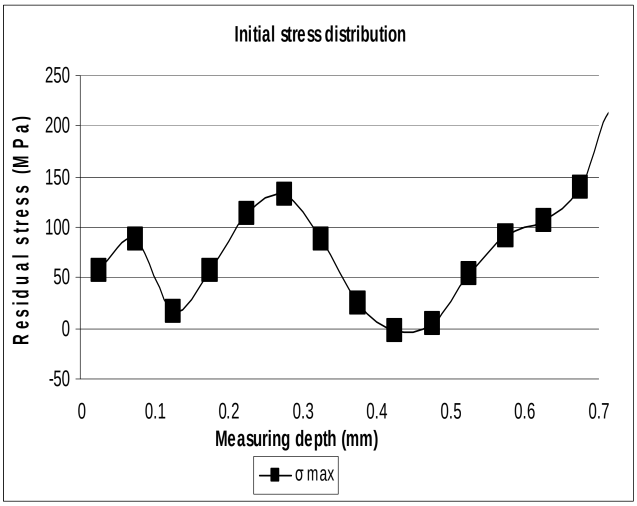

Fig. 5. Residual stresses distribution before milling

From the graphic results (fig.5) it can be observed that the initial residual stress is tensile. At 0.2 – 0.4 mm measuring depth the residual stress has values equal to 130MPa. Going into the depth of material the residual stress will decrease in value till 0MPa at 0.45mm depth and will increase to a high value equal to 200MPa at 0.7MPa where the measurement was finished. This nonlinear behaiviour was generated most probably by a thermal operation made before.

3.2 Influence of cutting speed on residual stress distribution

In order to determine the influence of multiple milling on residual stress distribution, each material has been milled with separate cutting speed V_1 V_2 and V_3 and analysed. The graphic results (Fig. 6) lead to the conclusion that generally the distribution of residual stress is having tensile values. In the surface layer at a depth between 0.1 – 0.15 mm the residual stress has high values up to 550 MPa at V_2 due to the thermal effect generated by milling without cooling. On the other hand the increase of the speed till 1036 m/min will lead to a reduction of residual stress value in surface layer at 320 MPa. This is happening because of the increased temperature value (equal to 165ºC) that will affect the surface layer and will prevent the rapid contraction of ferrite so the apparition of dislocations in grain. The use of a bigger depth (equal to 0,5 mm) and a cutting speed V_1 will lead to a lower residual stress value in surface layer (equal to 80 MPa), value that will remain high in comparaison with those generated by other speeds (v2 v3) most probably because of the higher temperature value.

Going into the depth 0.15 – 0.3 mm it can be observed that the use of V_1 and V_3 cutting speed will generate tensile stress, while the use of V_2 cutting speed will generate compressive residual stress (equal to -30 MPa). This behaviour is due to the ferrite contraction from subsurface layer as it was observed by Totten, (Totten, G. E., Howes, M. A., 2002).

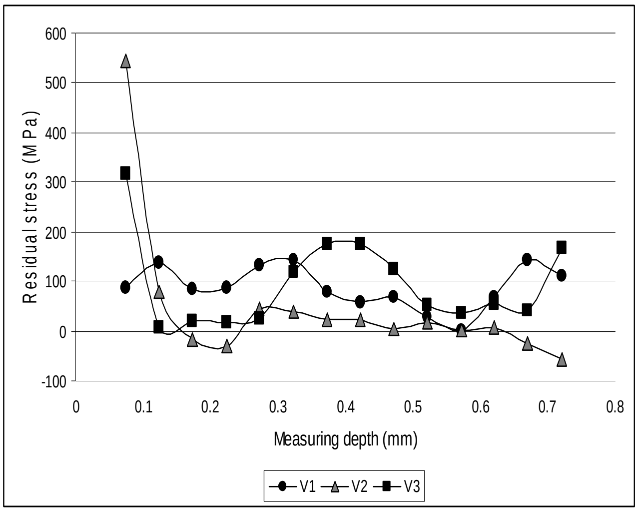

Fig. 6. Residual stresses distribution generated by milling operation on separate materials

The distribution changed between 0.3- 0.6 mm for all the tested cutting speeds. Milling with V1, respectively V2 generated a decrease in the residual stress till 1 MPa at 0.6 mm depth (V1 and V2). On the other hand, the use of a higher cutting speed (V3) will lead to an increase of residual stress to 175 MPa at 0.4 mm depth, while at 0.6 mm depth the residual stress value decreased to 55 MPa. This behaviour is due to the influence of temperature that rise to 165ºC (Fig.7) that termaly influence the surface layers leading to ferrite contraction at 0.35 mm depth. The higher surface layer temperature is also due to the fact that thiner chips are generated at this speed compared to those obtained with the previous cutting regime.

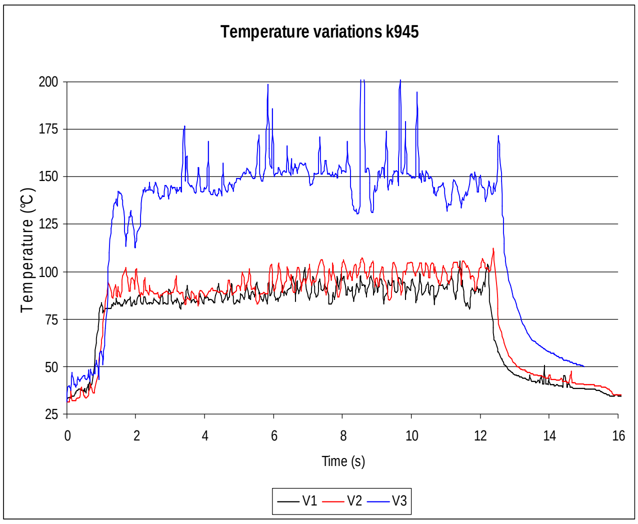

Fig. 7. Temperature variations when milling with different cutting speeds

3.3 Influence of multiple machining operation on residual stress distribution

The use of a triple cutting regime composed by V_1 (157 m/min and 0.5 mm depth) $+V_2$ (250 m/min and 0.25 mm depth) $+V_3$ (1036 m/min and 0.15 mm depth) induced a tensile residual stress in surface layer till 0.1 mm depth with high values (equal to 255 Mpa). Going into the depth between 0.1 to 0.2 mm a decrease of residual stress value is obtained due to the ferrite contraction from subsurface layer followed by a rise till 156 MPa at 0.3 mm. From 0.3 to 0.7 mm depth the residual stress decrease till 4 MPa due to the mechanical effect of milling force. The use of the last two cutting regimes V_2+V_3 lead to a complete change of residual stress variation. In surface layer till 0.1 mm depth, the residual stress has values up to 100 MPa and decrease rapidly to compressive with the decrease in depth. Because of the ferrite contraction mechanism, at 0.1-0.3 mm, the residual stress becomes compressive with high values (equal to -200 MPa). From 0.3 to 0.7 mm depth, the residual stress remains in the compressive area and will have compressive values till -100MPa.

On the other hand to verify the inverse behaivior of the cutting regimes V_2+V_3 an inverse regime was tested (V_3+V_2). From the graph (Fig. 8) it is observed that tensile residual stress was generated. The stress will have decreasing values from 200 MPa at 0.1mm depth to -6MPa at 0.3m depth (the smallest value). Going into the depth it is observed that the amplitude of residual stress will rise to a value equal to 220 MPa at 0.55 mm depth.

3.4 Simulations

To confirm the results experimentally obtained, the FEM simulations have been conducted. To simulate the condition of machining the adopted parameters were similar with those used in the experiments described in paragraphs 3.2 respectively 3.3.

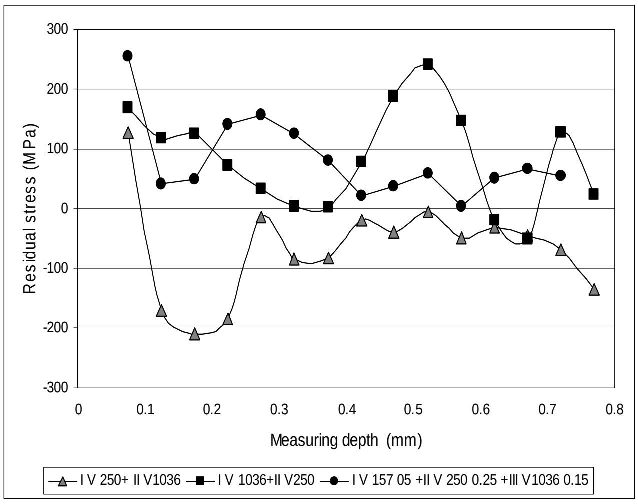

Fig. 8. Residual stress distribution generated by succsevive milling operations

3.4.1 The influence of the separate cutting speed on residual stress distribution calculated by simulation program

From the simulation result it can be observed that for a cutting speed equal to 157 m/min and a depth of cut equal to 0.5 mm generated similar results (Fig. 9). In surface layer till 0.05 mm depth the value of residual stress is higher than in experimental case; going into the depth it can be observed that the residual stress will decrease to 0 MPa in comparaison with the experimental results where the decrease reached to approximately 80 MPa. From 0.25 mm depth to 0.7 mm the results present similar values and variations. The difference resulted in surface layer is generated by the fact that the program considers the material being homogenus and with a perfect composition.

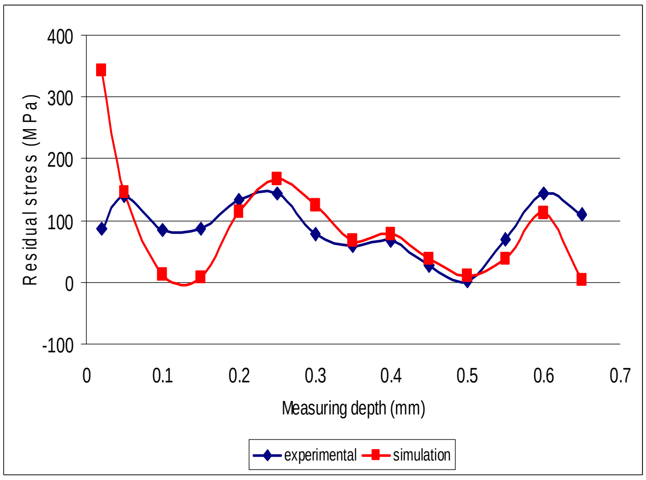

Fig. 9. Residual stress distribution generated by V 157 m/min and 0.5mm depth

By simulating the work with a cutting speed equal to 250 m/min similar results were obtained (Fig.10). The biggest difference occurs in surface layer till 0.2 mm depth where the simulation induced higher values by comparing with the real obtained values (450 MPa at 0.02 mm depth and 180 MPa at 0.2 mm). The difference can be generated by the variation of chemical composition between theoretical (considered by software) and real case.

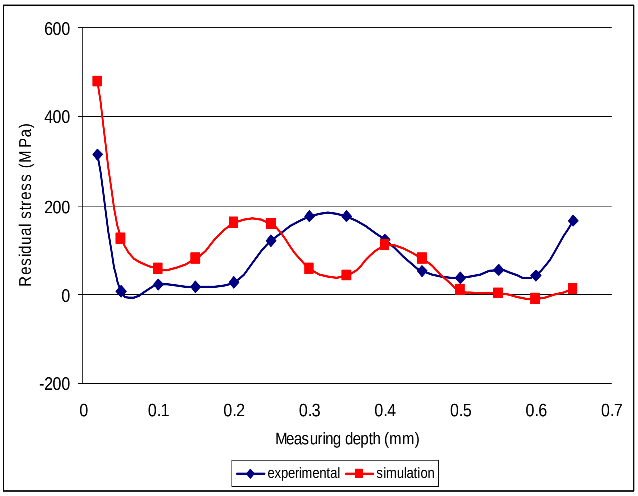

Fig. 10. Residual stress distribution generated by V 250 m/min and 0.25 mm depth

The simulation of a cutting speed equal to 1036 m/min (Fig. 11) has generated similar values and variations for the both determined distributions (theoretical and simulated). In this case there are also some small differences that can be explained like in the previous case.

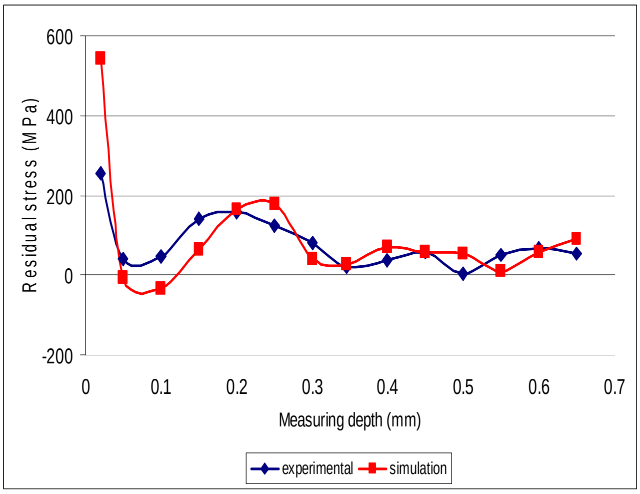

Fig. 11. Residual stress distribution generated by V 1036 m/min and 0.15 mm depth

3.4.2 The influence of successive cutting speeds on residual stress distribution calculated by simulation program

The simulation of successive milling operations have been carried for each conducted experiment.

In the case of triple successive simulation (V1 + V2 + V3) the generated results were generaly similar with the experimental values. From figure 12 it can be observed that a small difference obtained in surface layer of material where the simulation generated a higher value (up to 316 MPa at 0.02 mm depth) in comparaison with the experiment that have generated a value equal to 130 MPa. This difference is most probably due to the software program that considers the theoretical composition of material and not considers the inhomogeneity of material composition.

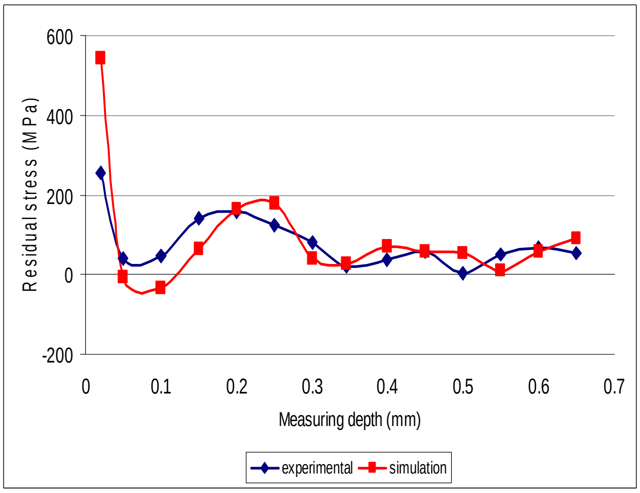

Fig. 12. Residual stress distribution generated by a triple cutting regime (V1 +V2+V3)

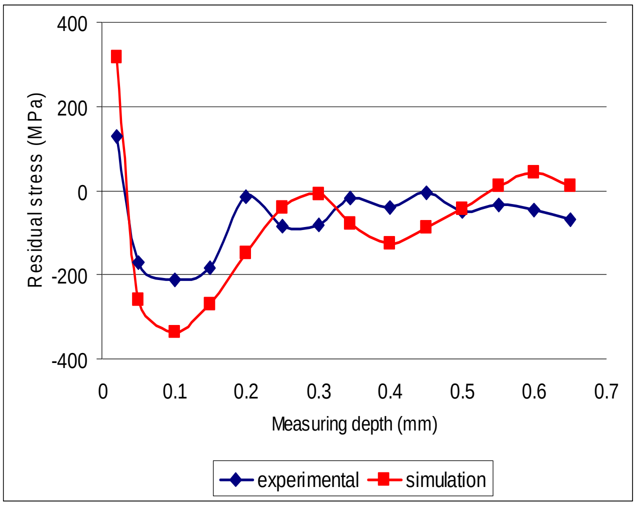

Fig. 13. Residual stress distribution generated by a double cutting regime (V2+V3)

The use of two successive cutting working parameters (V_2 250 m/min / 0.25 mm depth and second V_3 1036 m/min / 0.15 mm depth) led to the generation of similar values like in the experimental case (Fig 13). Small differences can be found between the values generated by simulation but the variation is similar. The use of a reverese cutting regime (V_3 1036 m/min / 0.15 mm depth and second V_2 250 m/min / 0.25 mm depth) will lead to the generation of a tensile residual stress generation with similar variation like in the experimental case (Fig 14).

The biggest difference between the experimental and theoretical model occur in surface layer till 0.2 mm depth where the generated residual stress has values equal to 220 MPa at 0.02 mm depth and decrease rapidly at -10 MPa at 0.05 mm depth. From 0.2 mm depth the variation and values of generated residual stress are aproximativ similar.

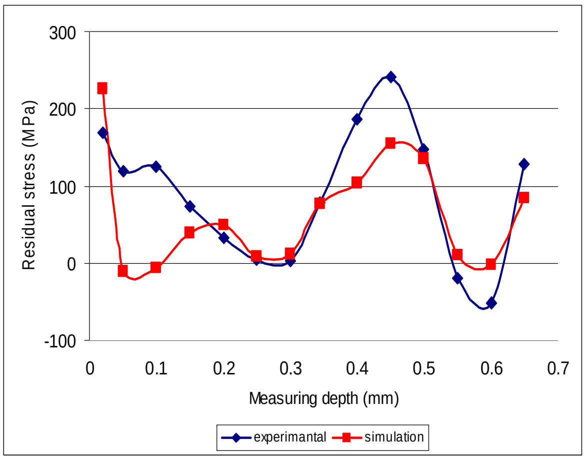

Fig. 14 Residual stress distribution generated by a double cutting regime (V3+V2)

4. CONCLUSIONS

The analysis of the obtained results leads to the following conclusions:

- the milling operation can change the distribution of residual stresses in all previous machined materials;
- the use of single milling operations generated different types of stress such us : tensile in the case of V_1 and V_3 and compressive when V_2 have been used;
- the application of a successive cutting regime can induce beneficial or detrimental residual stress; in the case of a triple cutting regime (v 157 m/min (0.5 mm depth) + v 250 m/min (0.25 mm depth) + v1036 m/min (0.15 mm depth)) tensile residual stress were generated with an aproximate linear variation and generally high values;
- the use of a double successive cutting working parameter (v 250 m/min (0.25 mm depth) + v 1036 m/min (0.15 mm depth)) will generate compressive stress with high values (-337 MPa) in surface layer at 0.1 mm depth; going into the depth of material compressive residual stresses with small variatons were observed.
- the use of a reverse cutting regime (v 1036 + v 250 m/min) lead to an opposite disposal of residual stress; the residual stress distribution will have high high tensile residual
- the use of FEM calculation software have generated similar results like in the case of experimental tests; the small differences cames from the simulation programme that considers the theoretical composition of the used material.

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