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ORIGINAL RESEARCH PAPER

A THEORETICAL STUDY REGARDING THE INFLUENCE OF CARBON AMOUNT ON RESIDUAL STRESS DISTRIBUTION IN SURFACE LAYER

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Abstract: The aim of the present paper is to investigate the residual stress distribution generated in surface layers by machining. Experiments revealed that an increase of residual stress value in tensile zone (546 MPa) is connected with a high value of carbon percentage for up to 0.9 % from surface layer, while the decrease of residual stress value from approximately 550 to 300 MPa corresponded to a level 0.6 % of carbon.
A theoretical investigation based on a finite element model (FEM) was carried out in order to check the influence of the carbon content on the residual stress distribution. Six types of materials containing various amounts of carbon (from 0.4 % C up to 0.96 % C) but with constant content for the other alloying elements were used in the simulations. The cutting parameters were kept constant in order to assess the influence of carbon presence over residual stress. From the FEM simulation a correlation between the carbon percentage and the distribution of the residual stresses in the surface layer was observed.

Keywords: *carbon amounts, finite element model, residual stress distribution*

INTRODUCTION

The residual stresses are generally induced in mechanical components either by the manufacturing processes or by different mechanical loadings that lead to material deforming, as well as by heating and chemical. In the case of mechanical manufacturing processes, all technological operations based on material deformation generate different types of residual stresses that can be useful or detrimental, critical or insignificant [1 – 5]. Milling generally induces two types of residual stress: thermal and mechanical. Thermal induced stress occurs as a consequence of the excessive heat developed during machining. Chemical composition of the material, inhomogeneity of the material, low thermal conductivity, intensive flank wear, can affect the distribution of residual stress in surface layer [6 – 8].
Knowing the effects of the residual stress can bring more advantages for the constructive and technological design of parts because it can allow the avoidance of some unfavorable states of residual stresses, it can increase the parts reliability, it can lead to a smaller risk of premature destruction and can achieve some material properties needed for a good part operating [9, 10].
The aim of the present paper is to investigate the influence of carbon content from the surface layer composition on the residual stress distribution measured in the same area. For the experimental part, three different cutting speeds were used on C45 material in order to observe the residual stress distribution. In order to observe the influence of carbon presence, finite element analysis (FEM) was also conducted on six type of materials that have generally a similar composition (C40, C45, C50, C53, C70, C98).

MATERIALS AND METHODS

Materials

The experimental procedures were conducted on C45 steel, for which the chemical composition and the mechanical properties are presented in Tables 1 and 2. This material is often used in industry because of its good workability and machinability.

Table 1. *Chemical composition of EN 10083-2 C45 steel*

C [%]	**Si [%]**	**Mn [%]**	**S [%]**	**P [%]**
0.45	0.3	0.7	0.05	0.04

Table 2. *Mechanical properties of C45 steel*

$R_{p\ 0.2}$ [MPa]	**R_m [MPa]**	**Elongation [%]**	**Hardness [HV]**
340	560-620	16	90

$R_{p\ 0.2}$ = Yield limit; **R_m** = Tensile strength

Experimental procedure

Milling operation was performed on a CNC milling machine (Knuth, Germany), capable of delivering a maximum spindle speed of 12000 rot·min^{-1}, with a tool (Coromil 490) with 50 mm diameter and 5 inserts. The influence of tool wear was

eliminated by using a new cutting edge for each test. The processed surface has had the following dimensions 150 x 60 mm and radial width of cut was equal to 50 mm. For the experimental study, three values were used for the cutting speed (200, 250, 1036 $m \cdot min^{-1}$) in order to observe the influence of cutting parameters on residual stress distribution. The depth of cut and cutting feed were kept constant (0.25 mm for cutting depth and 0.08 mm/tooth for cutting feed).
The determination of chemical change in surface layer was made by using a Scanning Electron Microscopy (SEM) type Zeiss EVO (Germany). A square of 10 mm^3 was prepared and analyzed to determine the chemical composition in surface layer of material.
Measurements of residual stress were realized using a RESTAN acquisition system from SINT Italy (Figure 1). Hole drilling method was used to measure the residual stress in the surface layer to a depth equal to 0.8 mm. The obtained stress was calculated by using "integral" method. The strains were measured using a strain gauge from HBM – 1.5/120RY61S.

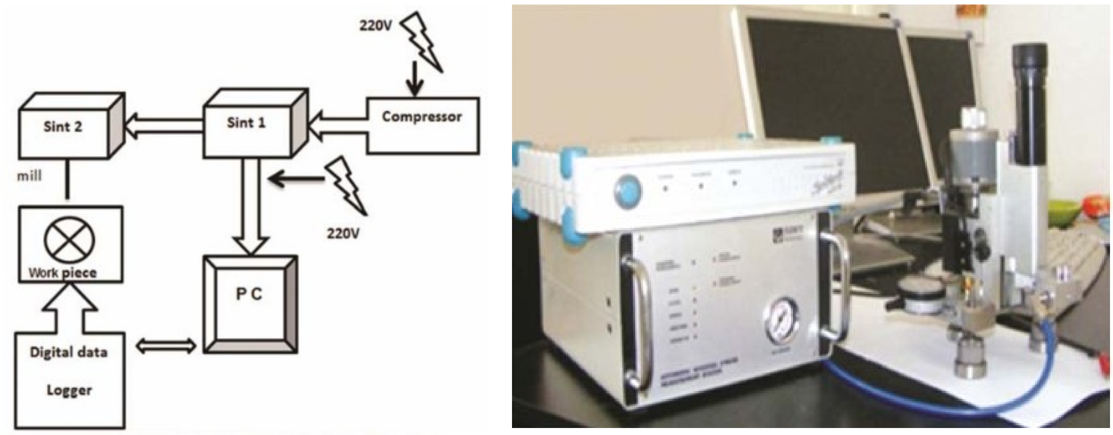

***Figure 1**. SINT residual stress measuring equipment*

The behavior of residual stress distribution in surface layers with different percentages of carbon content was also analyzed using finite element simulation (FEM) on AdvantEdge 5.9 produced by Third Wave System USA. The FEM software was developed specially for metal cutting and analysis of important parameters such as cutting force, residual stress, cutting temperature, etc. All the experimental conditions (material type, cutting parameters, etc.) were replicated in the created model. Cutting parameters were kept constant (Table 3) while several materials with similar composition but with small carbon variation were used. The residual stress was determined for depths up to 0.25 mm with increments of 0.05 mm.

***Table 3**. Main cutting parameters for simulation*

Cutting speed [$m \cdot min^{-1}$]	Feed [mm/tooth]	Depth of cut [mm]
300	0.3	0.75

The chemical composition of materials used in the FEM analysis is presented in Table 4.

Table 4. *Chemical composition according to ISO 683-1:2016 [11]*

Material	C [%]	Mn [%]	S [%]	P [%]
C40	**0.40**	0.75	0.05	0.04
C45	**0.46**	0.79	0.05	0.04
C50	**0.51**	0.75	0.05	0.04
C53	**0.53**	0.75	0.05	0.04
C70	**0.7**	0.75	0.05	0.04
C98	**0.96**	0.4	0.05	0.04

RESULTS AND DISCUSSIONS

Residual stress distribution and carbon percentage in the material surface layer was analyzed. The cutting speed was varied in the machining tests between 200 and 1036 m·min^{-1}, while keeping constant the rest of cutting conditions. The measurements have revealed a series of values for the residual stress in surface layer as presented in Figure 2.

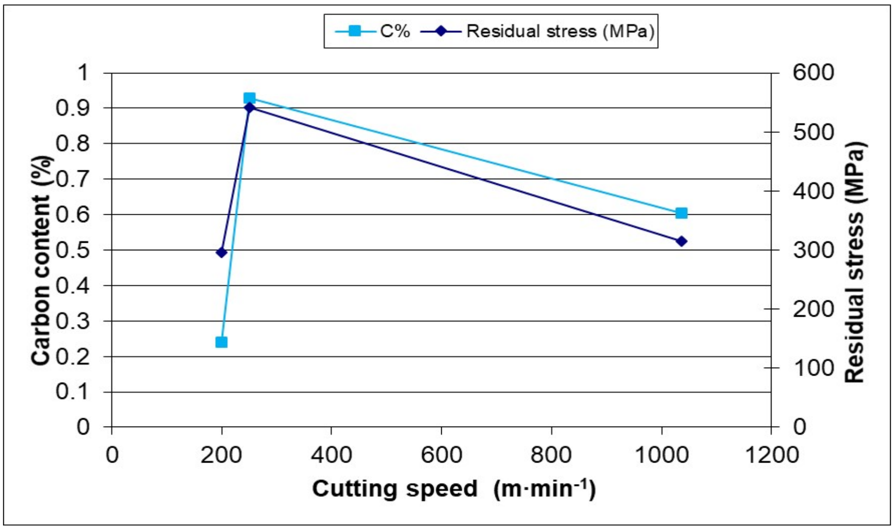

Figure 2*. Distribution of residual stress and carbon presence in surface layer*

From the presented graph it can be observed that the use of a 200 m·min^{-1} cutting speed led to a tensile residual stress of 296.66 MPa. Increasing the speed to 250 m·min^{-1} led to an increase of residual stress distribution up to a critical value of 542.87 MPa. Further increase of the milling speed to 1036 m·min^{-1} has generated a residual stress value of 315.69 MPa. The high values of residual stress in surface layer are generated by the relation time-temperature that led to a thermal influenced stress. The increase at 1036 m·min^{-1} led to a higher value of temperatures that would lead also to a thermomechanical model but with higher influence of the mechanical model, as similarly described by Yao *et al.* [12].

The chemical composition of the surface was analyzed using scanning electron microscopy. The results revealed a similar disposition tendency between the carbon content and the residual stress values (Figure 2). It was observed that the residual stress of 296.96 MPa corresponds to a carbon content of 0.24 % while the 542.87 MPa value corresponds to an amount of 0.93 % C. The decrease of residual stress value in the surface layer to 315.69 MPa corresponded to 0.6 % carbon content in the material.
In order to avoid a false positive effect generated by surface defects that can be present in surface layer [4] an average value up to 0.25 mm for residual stress distribution was also calculated (Table 5). The depth of 0.25 mm was considered because the SEM analysis was made on surface layer of material.

Table 5. *Residual stress distribution in surface layer up to 0.25 mm*

Measuring depth [mm]	**Residual stress distribution value [MPa]**		
	200 [m·min^{-1}]	**250 [m·min^{-1}]**	**1036 [m·min^{-1}]**
0.05	296.66	542.87	315.69
0.1	6.63	78.68	5.85
0.15	56.05	-17.91	20.93
0.2	39.21	-29.97	17.90
0.25	9.84	45.26	26.69
Average	**81.68**	**123.78**	**77.41**

From Figure 3 it can be observed that the repartition trend of residual stress average value and the amount of carbon presence were also similar. The increase of residual stress value corresponded this time to an increased amount of carbon presence in the analyzed layer. The variation may be determined most probably by material inhomogeneity in material layers [3, 4].

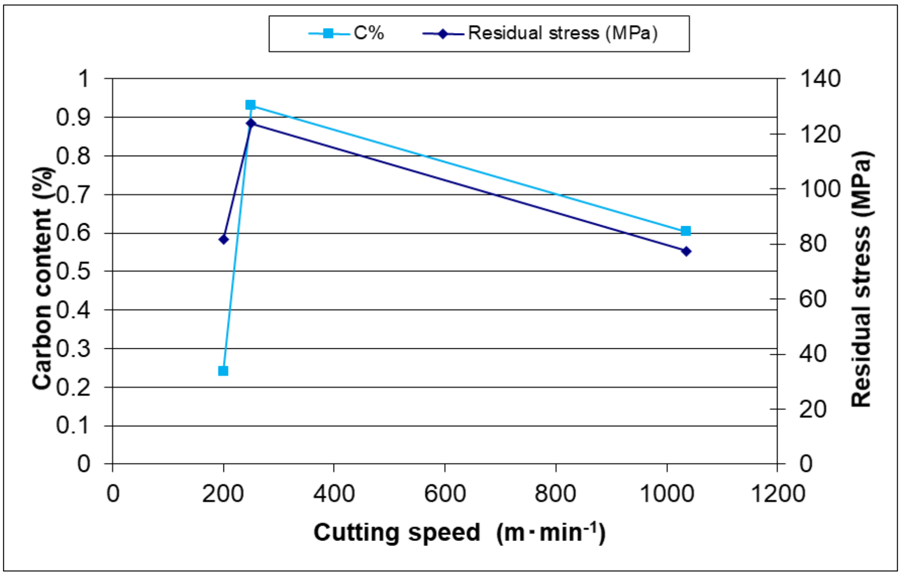

Figure 3. *Average of residual stress distribution (0-0.25 mm) compared with the distribution in surface layer of carbon presence*

Finite element analysis

Several simulations were conducted on AdvantEdge 5.9 in order to observe the influence of carbon content on residual stress distribution.

As it can be seen in Figure 4, an increase of the carbon amount in the chemical composition of the material could lead to a decrease of residual stress distribution values from high tensile to high compression in the surface layer.

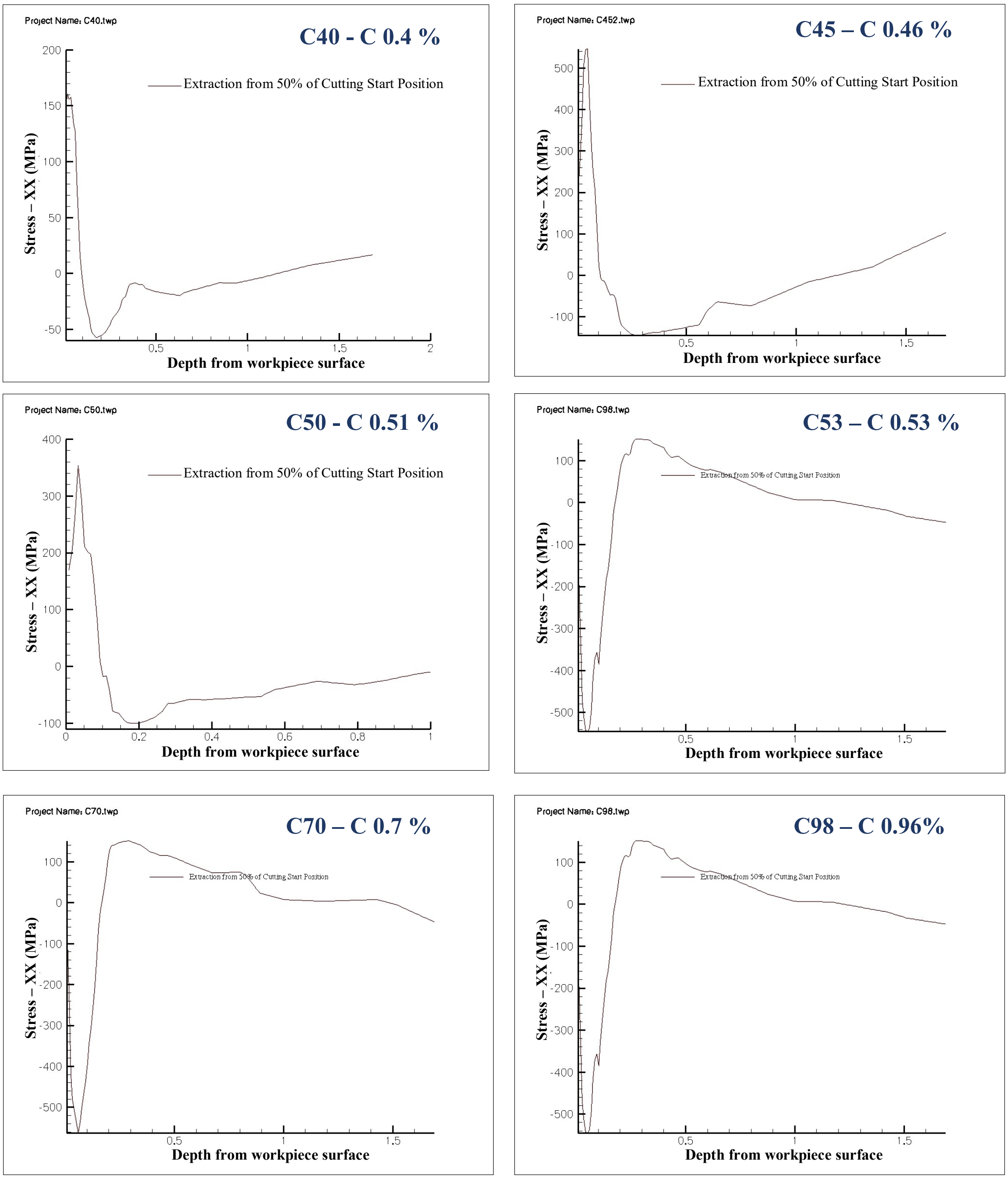

Figure 4. *Simulation of the residual stress distribution as function of carbon content in the material composition*

Apart from the C40 steel grade, all other materials follow the distribution pattern. The use of carbon steel with a carbon content up to 0.51 % lead to tensile residual stresses within the initial 0.2 mm depth of the surface layer, but after that, there is a compressive stress state up to 0.8 mm depth. On the other hand, the use of materials with higher amounts of carbon (0.53-0.96 %) would lead to strong compressive residual stress in surface layer, whereas the use of steel with smaller carbon amount (C40) generates a "linear" behavior of the residual stress distribution, close to the zero line.

CONCLUSIONS

The current study investigated the influence of chemical composition of carbon steel on residual stress distribution. From the presented results, the following main conclusions can be formulated.

There is a close correlation between the carbon content in the material composition and the residual stress distribution.

The variation curves for the carbon content and the residual stress follow the same evolution for each of the cutting speeds used during machining.

FEM simulations have revealed a clear connection between the percentage of carbon and residual stress distribution.

The increase of carbon content leads to the modification of the residual stress state from tensile to compressive stress. Low amount of carbon (up to 0.51 %) lead to a tensile distribution in surface layer (up to 0.2 mm depth) that turn to very low compressive values (up to -20 MPa) in subsurface layers.

The increase of carbon amount led to higher wear resistance of the materials that can be associated with the high values of compressive stress from the surface layer.

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