INFLUENCE OF EFFECTIVE MILLING STRATEGIES ON THE RESIDUAL STRESS

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Abstract

The article deals with the evaluation of residual stress after machining of surfaces using effective milling strategies programmed by CAM systems. Milling of the shaped parts containing pockets and grooves, the cutting tool must be driven into corners with lower feed rate, because angle of entry, cutting depth increase and then a chip is tamped and leaving from the place of cut is very difficult. Application of standard strategies affects the beginning of tool wear, decreased durability and tool life, raised roughness parameters of the machined surface and increased residual stress. Aspects of efficient milling strategies programmed by CAM systems allow to machine with the entire cutting length of the tool with a constant angle of entry for the entire machining time. These strategies have a positive effect on residual stress in the material. It was confirmed by the machining test of an experimental piece from material Toolox44. The residual stress was measured by non-destructive method with using the device Proto iXRD operating on the principle of X-Ray diffraction. This measurement was realized in cooperation with the Department of Machining and Manufacturing Technology at University of Žilina in Žilina.

Keywords: Residual stress, X-Ray diffraction, machining, milling strategy, CAM systems

1. INTRODUCTION

Process computer support of production is composed of two parts: geometrical (choice of trajectory of cutting tool) and technological (choice of cutting tool and choice of cutting conditions). Choice of strategy has a high influence both on the final machined surface - surface quality and on economic aspects of production. The milling strategies are divided into machining of flat and face surfaces, profiles, fitting, etc. In case of milling of grooves and corners are coming problems: due to influence of increase of angle of entry and radial cutting depth occurs to tamping of chip, which doesn't leave from the place. Therefore they select suitable cutting parameters, so that cutting tool continuously cuts, it ensures of leaving chips from place of cut and the whole process has positive influence on tool life and final state of machined surface. This article is focused by influence of effective milling strategies on the residual stress in terms of direction and size [1, 2, 3].

2. EFFECTIVE MILLING STRATEGY

Size of angle and radial cutting depth is changed during process with used conventional strategy according to machined shape. Cutting depth achieves to 90% of diameter of tool and angle of entry is up to 140° at milling standard strategy. In this case they are ineffective strategy. Continuously meshing of tool teeth and favourable leaving of chip from place of cut is ensured when radius of corner is (75-100) % of diameter of tool. The both alternative of angle of entry are shown in **Figure 1** [2, 3]. Problems with angle of entry and increasing depth of chip eliminate effective milling strategy, which are available as accessory module in CAM systems. These strategies can optimize angle of entry of cutting tool with use its full cutting edge. Strategies generate continual trajectories, which are not interrupted during machining and feed rate is usually calculated from define material properties of semi-finished product and parameters of cutting tool. Principle of machining of effective strategy is that beginning of machining arises in the centre of machining area (for groove). Cutting tool is bored into required depth and subsequently tool is starting to move in shape equidistant to required shape of contour of part. Axial cutting depth a_p meets the length of cutting part of tool and maximum allowable angle of entry is defined during programming of strategy. CAM systems calculates trajectory, so that angle of entry was not changed or was not exceeded maximum required value in process of machining [2, 3].

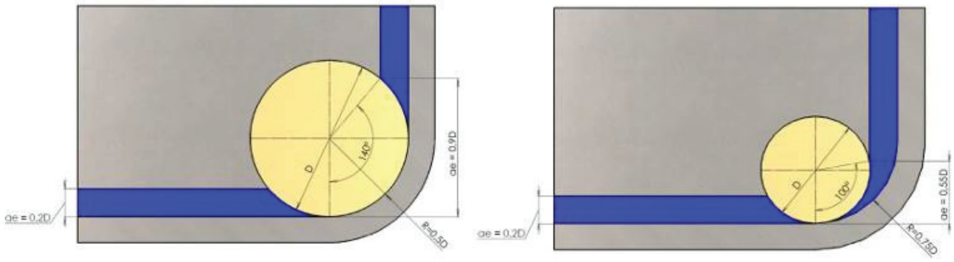

Figure 1 Milling of Corner Part [2]

3. RESIDUAL STRESS AND ITS EVALUATION

Residual stress is brought into material during machining. Size and direction of stress can be influence by choice of technological process. Residual stress can contribute to improvement of components properties - higher surface strength of material. In the opposite case the residual stress are unfavourable - causes corrosion, cracks or reduction of fatigue limit. The most frequent mechanisms of these defects are uneven plastic deformation, heating or cooling during thermal treatment, structural distribution and chemical process. It cannot be to forget the influence of technological conditions and structure of material.

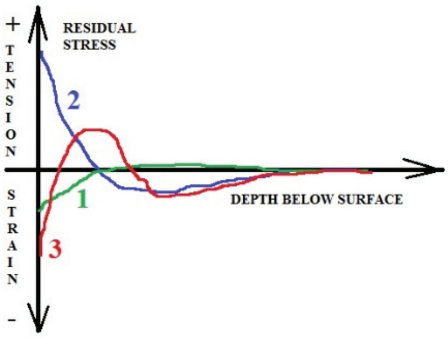

Figure 2 Distribution of Residual Stress [4]

Distribution of the residual stress according to their character is shown in **Figure 2**, when curve (1) represent progress of stress from plastic deformation on surface to deformation in surface layers. It is compressive stress, which is dependent on surface state, surface roughness and profile of protrusions. Blue curve (2) describes stress during heating and subsequent cooling of material - tension. Red curve (3) shows compressive stress changing under the surface to tensile stress [4, 5].

Substance of genesis of these stress are elastically-plastic deformation in area of chip creation. Every technological operation ensures restructuring of the residual stress in such a volume of material, which is able to produce plastic deformation. Measuring of residual stress, it can be measured by destructive and non-destructive methods. Due to extensive problem is described principle used non-destructive method working on the principle of X-ray diffraction. The ray of wavelength (10^{-9} - 10^{-12}) m penetrates into material and begins diffraction from crystallographic plain to diffraction cone. Reflective cone is detected by detector on scan head. Direction of ray is shown in **Figure 3**. This method ranks among the most promising method, but due to the high acquisition costs and complexity of evaluation of results is not easy [6, 7].

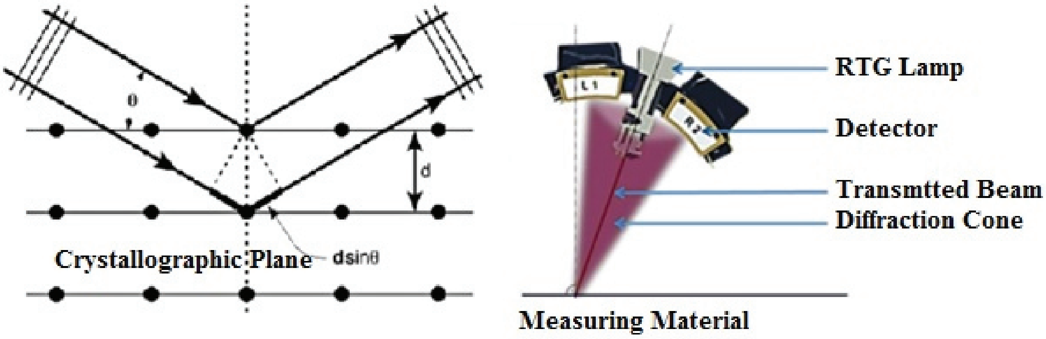

Figure 3 Principle of Measuring by RTG diffraction [8]

4. CONDITIONS OF EXPERIMENT

The aim of experiment was compare different effective milling strategies programmed in available CAM systems and to evaluate their influence on residual stress in material. Conditions of experiment (machine tool, cutting tools, semi-finished product and cutting conditions) were the same for every strategy. Special shape of component (**Figure 4**) contains internal circular pocket (**Figure 4**, position 1), groove parallel with coordinate system (2), groove deviated against coordinate system (3), groove in shape arc (4), thin-walled rig (5), slanting area (6) and lateral open pocket (7), see **Figure 4a**. The object of experiment was monitored other effects as are parameters of roughness and wear of tools. For evaluation of effects of effective strategies the residual stress was measured on four milling areas see **Figure 4b**).

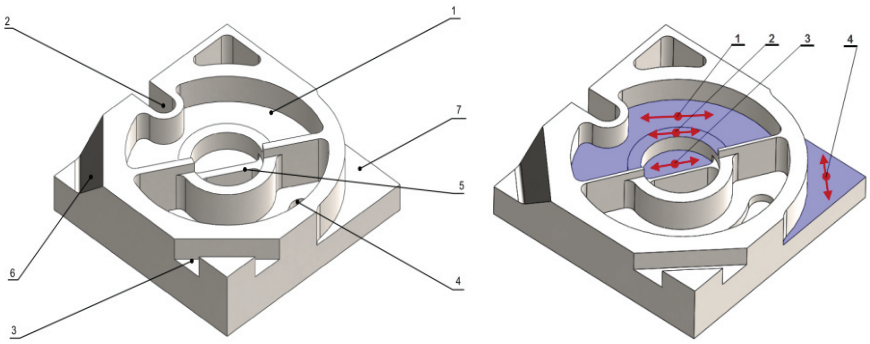

Figure 4 a) Model of Component, b) Distribution of Measuring Points

For execution was selected these available effective milling strategies: Adaptive roughing (HSMWorks), iMachining (SolidCAM), TrueMill (SurfCAM), VoluMill (WorkNC), Vortex (Featurecam), Waveform (Edgecam).

4.1. Material, cutting tool and machine tool

Material was tool steel DIN EN ISO DIN EN ISO 1.2342/1.2344 - business name: Toolox44. This material is used for production of form for pressing plastic and swages, pressing tools and part of machine. During machining is put requirement on sharp tools and toughness of machine tool. Chemical composition of steel is mentioned in **Table 1**. Mechanical properties are shown in **Table 2**.

Table 1 Chemical Properties of Material (wt. %) [9]

C	Si	Mn	P_{max}	S_{max}	Cr	Ni	Mo	V	CEV	CET
0.31	0.6	0.9	100 ppm	40 ppm	1.35	0.70	0.80	0.145	0.96	0.57

Machining was realized at 3-axis vertical CNC milling centre Quaser MV 184E with control system Heidenhain TNCi530. For machining of areas was selected monolith roughing carbide milling cutter with 4 edges. Cutting conditions are shown in **Table 3**.

Table 2 Mechanical Properties of Material [9]

Hardness	410-475 HBW 41-47 HRC
TS	1450 MPa
YS$_{p0.2}$	1300 MPa
El$_5$	13 %
Size of inclusion	6 μm

Table 3 Cutting parameters [10]

PARAMETER	**Recommended cutting parameters**	
	Full	**Side cut**
Tool	D12	
Cutting speed v_c	120 m·min^{-1}	150 m·min^{-1}
Speed n	3183 min^{-1}	
Feed per tooth f_z	0.06 mm	0.09
Feed rate v_f	764 mm·min^{-1}	
Axial cutting depth a_p	9 mm	12 mm
Minimum radial cutting depth a_{emin}	0.18 mm	
Maximum radial cutting depth a_{emax}	1.31 mm	
Cooling	air	

4.2. Measuring and evaluation of the residual stress

Measuring of the residual stress was realized in cooperation with Department of Machining and Manufacturing Technology at University of Žilina in Žilina. Machined parts were measured by X-ray diffractometer Proto iXRD. This device works on the principle X-ray diffraction non-destructive method (see in **Figure 5**). Principle of the device was described in chapter 3. Device is put from X-ray lamp with chrome tube, cooling device, vertical positioning of goniometer, mapping device, detector and PC software. The device was set to voltage 20 kV and current 4 mA.

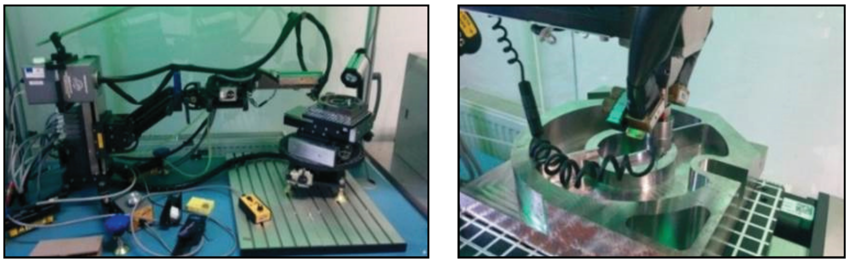

Figure 5 Measuring Device iXRD Proto

The results of measuring were processed with use software XrdWin. During measuring was necessary set correct angle and direction due to reflection x-ray from other area. Angle of tilt of x-ray head was in range ±30°. Due to availability angle was limited in range from +18° to -18°. Depth of measuring was 10 μm. The values are evaluated in Gauss distribution. The results of measuring are statement with values tensile and compressive stress, parameters of measuring and graphs of residual stress.

5. THE RESULTS OF MEASURING

The residual stress was measured and evaluated with use X-ray diffractometer iXRD in material Toolox44 after machining by six different effective milling strategies. For every strategy were measured 4 points. In **Table 4** is summary of results normal stress for individual points and strategies.

According to results in the table and in the graph, it follows that the smallest residual stress was measured after machining of surface with use strategy Volumill. In point 4 the resulting tensile stress was measured (+1.9 ± 8.4) MPa. The highest value was measured on the machined surface Adaptive Machining - this time the residual stress was compressive stress (-536.8 ± 21.4) MPa.

The tensile residual stress was measured on the machined surface with use strategy Waveform and True Mill in all points. In the case of strategy iMachining it was established compressive stress for point 1. The compressive residual stress prevailed in strategy Vortex and Adaptive Machining.

Table 4 Results of Measuring Residual Stress

CAM System	Milling Strategy	S.P.	Stress [MPa]	CAM System	Milling Strategy	S.P.	Stress [MPa]
Edgecam	Waveform	1	+229.2 ± 11.8	HSM Works	Adaptive Machining	1	-54.3 ± 13.0
		2	+370.5 ± 15.0			2	+250.2 ± 13.1
		3	+165.6 ± 13.7			3	-536.8 ± 21.4
		4	+260.3 ± 14.0			4	-286.1 ± 20.1
SolidCAM	iMachining	1	-133.0 ± 12.6	Surfcam	True Mill	1	+73.1 ± 11.9
		2	+159.1 ± 14.0			2	+120.6 ± 12.5
		3	+22.3 ± 13.6			3	+46.6 ± 22.3
		4	+65.0 ± 10.6			4	+28.2 ± 12.4
FeatureCam	Vortex	1	-54.6 ± 9.8	Work NC	Volumill	1	+157.5 ± 14.6
		2	-417.6 ± 10.4			2	-47.5 ± 9.1
		3	-94.9 ± 11.9			3	-42.7 ± 14.1
		4	+350.6 ± 10.1			4	+1.9 ± 8.4

6. CONCLUSION

The aim of experiment was measured and evaluated residual stress after machining with use effective milling strategies. These strategies may have an influence both on geometrical accuracy of workpieces, quality of machined surface and residual stress. We chose 6 effective milling strategies: Wavefrom, iMachining, Vortex, Adaptive Machining, TrueMill and VoluMill for production of component made from Toolox 44 material. The residual stress was measured by non-destructive method - X-ray diffraction. The Department of Machining and Manufacturing Technology at University of Žilina in Žilina has this device available. The evaluated residual stress was both tensile (+) and compressive (-). Optimal distribution of stress in material is equation of this stress or approaching to zero value. In **Figure 6**, values are compared graphically.

According to direction and action the residual stress may be favourable - compressive stress into machined surface by strategies Waveform and TrueMill. The highest value of stress was measured in point 3 (circle pocket) and by strategy Adaptive Machining (-536.8 ± 21.4) MPa. It can be explained by concentration stress in small closed pocket.

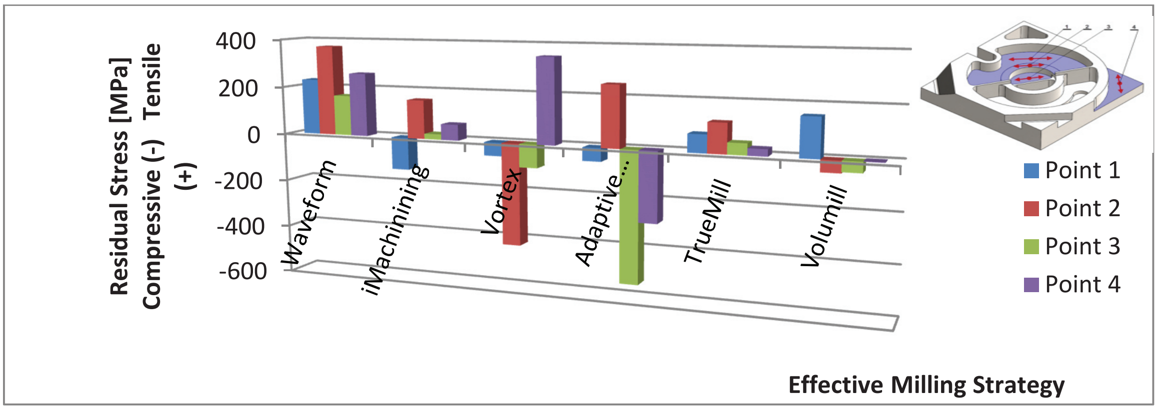

Figure 6 Dependence of Residual Stress on Surfaces machined by Effective Milling Strategies

The result of experiment established, that machining with use effective milling strategy have an effect on the residual stress into surface layer of material in direction and size. The overall assessment is based on the best result achieved strategy Volumill (CAM system WorkNC). This strategy is available in form of modules and it possible to integrate to different CAM systems. The residual stress may be reduced by finishing methods. This issue will be research in next scientific problems.

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