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Impact of various ball cutter tool positions on the surface integrity of low carbon steel

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ABSTRACT

In this study, we report on the impact of different cutter tool positions on the surface integrity (residual stresses, micro-hardness, roughness and texture) of low carbon steel. The effects of different tool positions of the ball end cutter tool during 5-axis machining were studied and differences in the slope of the tilt and lead angle compared. The effects of the depth of the cut and coolant on the surface integrity were also studied. The results of the experiments should lead to a better understanding of the effect of the ball end cutter tool position on the surface integrity if low carbon steel during the 5-axis machining process. The study is designed to show the effect of different tool positions only, while the other parameters (e.g., cutting speed, feed rate, cutter tool slope) remain constant. The results show that the tilt angel has a larger impact on the surface integrity (both residual stress and roughness) compared to the lead angle.

1. Introduction

The aeronautic, automobile and other critical engineering industries have high requirements for the quality and geometrical accuracy of their products. There have been many studies on different approaches for controlling the surface integrity of the materials, for example, the tool position [1–4] and the tool itself [4], the cutting conditions (like cutting speed and depth of cut) [5], and the computer aided manufacturing (CAM) strategies [8].

Based on past knowledge [3], we know that the depth of cut (a_p), together with the cutting speed, and also, of course, the width of the cut (a_e), all have an important effect on the final roughness of the surface. The influence of the cutter tool position on the surface integrity has also been studied [1–3].

The aim of this study is to examine the influence of the depth of cut a_p and tool positions (lead, tilt angle) on the surface integrity (surface roughness, texture, micro hardness and residual stress) during high-speed milling (HSM) which according to the literature starts at about $300\,\mathrm{m\,min^{-1}}$ [5]. HSM is becoming very widely used, because of its many advantages, like high removal rates, reduction in dead times, low cutting force, dissipation of heat with chip removal, and increased part precision and surface finish. Common disadvantages are excessive tool wear and the requirement for expensive advanced spindles [5]. One technique that gives enormous advantages in machining operations is that of 5-axis milling, having potential for significant reduction in the amount of manual finishing required [3].

Another important goal of this study is to examine the effect of the position of the cutting tool (lead/tilt angle: −30, −15, 0, +15 and +30 deg) on the surface integrity. There are a variety of common cutting tool positions used in 5-axis milling and the tool position can have significant influence on surface integrity. We take into consideration synchronal movement of the tool on the X, Y, Z, B and C axes and the varied surface integrity results caused therefrom. The problem of optimization of CAM paths with respect to surface quality should also be taken into account. In most CAM systems, the cutting paths of the tool are mainly generated based on geometrical considerations. This phenomenon can have influence, not only on the surface integrity, but also on geometrical accuracy [10].

The focus here is on the residual stress, one of the most important factors of interest in evaluating surface integrity. Generally, the presence of compressive residual stress is beneficial and that of the tensile stress is detrimental [3]. Residual stress can have a significant influence on the fatigue life of engineering components [6,11]. Near surface tensile residual stress tends to accelerate the initiation and growth phases during the fatigue process, while compressive residual stress close to the surface may prolong fatigue life [6,11].

The residual stress depends on both the depth of the cut [5] and the cutting speed [1]. Tensile residual stresses are generally indicative of high cutting temperature, whereas compressive residual stresses are generally associated with lower temperature [1]. There is no existing rule related to the depth of cut. The change in the

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Nomenclature

a_e	width of cut (mm)	n	spindle speed (rpm)
a_p	depth of cut (mm)	V_c	cutting speed (m min^{-1})
α	tilt angle (deg)	V_f	feed rate (m min^{-1})
β	lead angle (deg)	σ_x	residual stress parallel to the feed direction (MPa)
d	tool diameter (mm)	σ_y	residual stress perpendicular to the feed direction (MPa)
f_z	feed per tooth (mm)		

depth of cut has an accidental impact on the magnitude of the residual stress [5].

The work is related to the ball end cutter tool. The ball end cutter is much more critical when we compare it with end mill cutter. The contact point of the cutter tool is all the time in contact with newly machined surface of the workpiece. It means that the contact point is exposed to thermal heat stress all the time when we compare it with end mill. Also the change of position of the ball end cutter tool cause different cutting speed at the newly machined surface. The cutting speed is proportional to the heat stress and the heat stress has effect on the magnitude of residual stresses. The cutting force changes with different cutter ball end also and of course it can affect the value of magnitude of residual stresses.

2. Experiments

2.1. Description of the material tested

The material used in the tests for the sample workpieces was low carbon steel. The material had a nominal composition of 0.16 C, 0.22 Si, 0.98 Mn, 0.05 P, 0.05 S (wt%). The Young's modulus was 210 GPa and the Poisson's ratio 0.28. The cutting tools selected were super-micro grain (carbide, cermet), 8 mm diameter ball mills, with two flutes with a helix angle of 35°. The tools were coated with AlTiN + PLC. The micro-hardness of the steel was 280 HV before heat treatment and 221 HV after heat treatment. The upper surface layer (2 mm) was removed before heat treatment. Stress-relief annealing was performed for another experiment for measurement of residual stresses in the upper surface layer. All specimens were processed by the down milling technique. All tests were performed on a five continuous axis milling machine center (produced by the Chuan Liang Company) having a maximum spindle speed of 20,000 rpm with an NUM 760 control system. The NC program was created in CAM NX 4.0. All specimen machining was performed using a cutting fluid coolant (10% oil in water). The surface roughness (R_a) was measured using a portable device (Mitutoyo SJ-301). The length was 10 mm. Hardness was evaluated using the Akashi MVK-61 (the load of the indenter was 50 g). The structure of the surface was observed under an optical microscope (Olympus BH2-UMA with a CCD camera). The residual stress was evaluated by the Hole-Drilling Strain Gage Method ASTM E837 – 08 [13].

The hole was made by use of carbide end mill with diameter of 2 mm. The machine used for drilling of the hole was milling machine with spindle speed of 50,000 rpm. This technique is allowed in the standard ASTM. Cause of this technique the uncertainty of measurement (errors of measurement) was set base on [9].

There is necessary divide the uncertainties into two groups uncertainty type A and uncertainty type B and then compute the combined uncertainty u_c, base on:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} [c_i u(x_i)]^2}$$

where the c_i is sensitive coefficient associated with x_i.

Then compute the expanded uncertainty U, is defined as the interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurement. It is obtained by multiplying the combined uncertainty by a coverage factor, k. For the normal probability distribution, the most generally used coverage factor is 2 which correspond to a confidence interval of 95%.

The uncertainty Type A was computed as standard deviation of each measured set (for each measurement was recorded the set of ε_1, ε_2, ε_3, σ_x and σ_y actually.

Type B depends on many factors like a: surface preparation, uncertainty of coefficients a and b etc. Base on the [9] the following budget of uncertainties is shown (Table 1).

The higher value of uncertainty was chosen as a final error of all measurement cause of huge amount of data and better representation of residual stresses.

The final value of all measurement is covered by uncertainty:

$$V = y \pm U$$

where V is the estimated value of the measurement, y is the test (or measurement) mean result, U is the expanded uncertainty associated with y.

The final uncertainty U was estimated to the value: $U_{\sigma x} = 24$ MPa and $U_{\sigma y} = 21$ MPa. This value shows the worst value of all measurements.

The equipment used for evaluation of the magnitude of the residual stress was a Vishay with an A/D system Omega – instruNet. The observation depth was between 0.3 and 2.4 mm and the drilling increment was 0.3 mm. The acceleration of the tool spindle was recorded in order to compare the chatter of the tool at different tool positions.

2.2. Experimental set-up

The experimental set-up for studying the tool inclination (tilt angle α, lead angle β), the depth of cutting (a_p) and cutting speed (V_c) of the tool on the surface integrity is shown in Figs. 1 and 2. In the experiments we tried to approximate the HSM process. The highest cutting speed was 332 m/min, so if we consider that HSM in steel starts at about $V_c = 300$ m/min [5] or a at spindle velocity of $n = 10{,}000$ rpm [11], we can consider our experimental set-up a good approximation. The cutting conditions are shown in Tables 2 and 3. The spindle speed for all specimens was 16,000 rpm. The variables were depth of cut ($a_p = 0.2$–0.4 mm) and tool inclination (tilt/lead angle = −30, −15, 0, +15 and +30 deg) proportional to cutting speeds of V_c (201–333 m/min). The recommended cutting parameters from the tool manufacturer were taken into consideration.