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Influence of Process Parameters on Residual Stresses Induced by Milling of Aluminum Alloy Using Taguchi's Techniques

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Abstract: In this paper, the straight flute end-milling cutter used for machining of Al-Si-Mg-Fe alloy work pieces was investigated. The machining processes could induce residual stresses that enhance greatly the performance of the machined component. Machining residual stresses correlate very closely with the cutting parameters. In the experiments, the residual stress on the surface of workpiece was measured by using hole- drilling strain gauge method. This paper presents a study of the Taguchi design application for CNC end milling operations. The influence of high-speed end milling on residual stresses in Al-Si-Mg-Fe alloy work pieces, which were cast by the sand, investment and die casting method, was investigated. The magnitude and distributions of the residual stresses are closely correlated with cutting forces and temperature. The T6 heat treatment for Al-Si-Mg-Fe alloy offers a low average residual stress during the high-speed milling operation The results concluded that the residual stresses induced in the workpiece increases with increase in feed rate and increases with increase in depth of cut.

Keywords: End milling operations, Residual stresses, Taguchi design

1. INTRODUCTION

The quality of a mechanical component such as its geometrical stability and fatigue life are significantly affected by the surface integrity of the sublayer generated by the machining process. Surface integrity generally can be determined in terms of mechanical, metallurgical, chemical, and topological states. Residual stress is a major part of the mechanical state of a machined layer. It is generally believed that residual stresses result from plastic deformation, thermal stress, and phase transformation of the machined layer. Residual stresses in high performance alloys and steels are of considerable industrial importance because they can failure by fatigue, creep or cracking [1]. Machined components for the main structure of air craft require high fatigue strength and resistance to stress corrosion cracking. Generally, the surface of the machined component has tensile residual stress after machining. The bulk of the existing work on the surface integrity of the machined layer has been limited to experimental studies. Liu and Barash found three quantitative measures to define the mechanical state of a machined layer. They found that the effect of linear thermal expansion in the machined layer on residual stress distribution is negligible. They also showed that mechanical deformation of the workpiece surface is the one of the causes of producing both tensile and compressive residual stresses in machining [2].

Kono *et al.* presented findings that residual stress increases with the cutting speed, but does not monotonically change with the depth of cut in hard turning [3]. Development of an analytical model of residual stress in metal cutting has been slow due to the inherent complexity of machining processes. Okushima and Kakino considered the ploughing forces and the temperature distribution as the main causes of residual stresses [4]. The machining of aluminum alloys is one of the largest fields of high-speed machining applications. The sectors most commonly employing this technology are the aeronautic sector and the moulds and dies industry, especially in the manufacturing of blow moulds which, being more and more demanding and competitive, require greater dimensional accuracy and surface finish and, at the same time a reduction in costs and in manufacturing time [5].

High-speed machining is a relative term from a materials perspective, since different materials are machined with different cutting speeds to insure adequate tool life. The cutting speed determines whether a material would form continuous or segmented chips. The high-speed machining is used in the defense, aerospace and automobile industries. Most aerospace manufacturers have implemented high-speed machining in end milling using small-size cutters. The most common work material was aluminum; there was no tool wear limitation, particularly when carbide cutters were used. Also, in the aerospace industry, the major application of high-speed machining has been in thin walled structures [6].

In the present work, the influence of high-speed end milling on residual stresses in Al-Si-Mg-Fe alloy work pieces, which were cast by the sand, investment and die casting method, was investigated. The end mills have cutting teeth on the end as well as on the periphery of the cutter. In the present investigation, the straight flute end-milling cutter was used for machining of Al-Si-Mg-Fe alloy work pieces. The effects of high speed milling of cast Al-Si-Mg-Fe alloys was investigated in terms of residual stresses of work piece. The residual stresses were evaluated by the X-ray measurements.

2. EXPERIMENTAL SET-UP

Straight flute end milling cutters are generally used for milling either soft or tough materials. In order to develop monitoring functions, displacement sensors are installed on the spindle unit of a high precision machining center. The machine used in the study is a vertical type-machining center (figure 1).

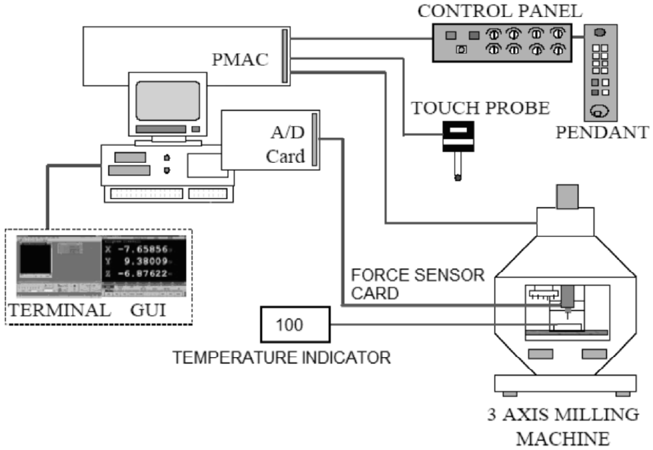

Figure 1: High Speed Vertical Milling Center

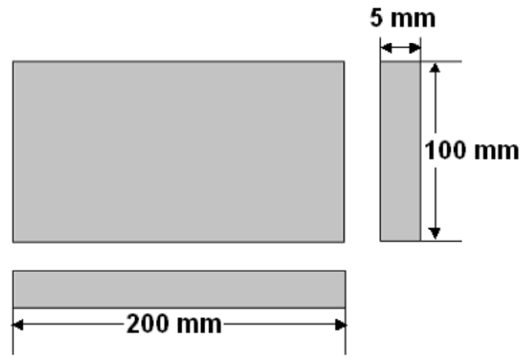

Figure 2: The Dimensions of Workpiece used High-speed Milling

The PCD end-milling cutter having four straight flutes was used in this investigation. High-pressure coolant jet was employed for cooling and lubrication of the high-speed machining operations. The spindle has constant position preloaded bearings with oil-air lubrication, and the maximum rotational speed is 20,000 rpm. The dimensions of the workpiece used in the high-speed milling are shown in figure 2. The temperature of the workpiece material was measured using thermocouple.

3. DESIGN OF EXPERIMENTS

The chemical composition of alloy is given in Table 1. The sand mould, investment shell, and cast iron mould were employed to prepare the samples for high-speed end milling.

Table 1
Chemical Composition of Alloys

Alloy	*Composition determined spectrographically, %*						
Element	*Al*	*Si*	*Mg*	*Fe*	*Cu*	*Mn*	*Cr*
%	85.22	9.0	2.0	3.5	0.01	0.25	0.02

3.1. Selection of the Quality Characteristics

The selection of quality characteristics to measure as experimental outputs greatly influences the number of tests that will have to be done statistically meaningful. The quality characteristics, which were selected to influence the high-speed end milling of Al-Si-Mg-Fe alloy, are residual stresses.

3.2. Selection of Machining Parameters

This is the most important phase of investigation. If important parameters are unknowingly left out of the experiment, then the information gained from the experiment will not be in a positive sense. The parameters, which influence the performance of the high-speed end milling, are:

- Microstructure of Al-Si-Mg-Fe alloy
- Cutting speed
- Feed rate
- Depth of cut
- Coolant

Since the high-speed milling involves high cost of machining, the process parameters were optimized using Taguchi's method.Taguchi techniques offer potential savings in test time and money by more efficient testing strategies. Not only are savings in test time and cost available but also a more fully developed product or process will emerge with the use of better experimental strategies.

Table 2
Control Parameters and Levels

Parameter	*Symbol*	*Level – 1*	*Level – 2*	*Level-3*
Casting	c	Sand casting	Investment casting	Die casting
Cutting speed, m/min	n	600	1200	1800
Feed rate, mm/min	f	1000	3000	5000
Depth of cut, mm	d	0.2	0.4	0.6

Control parameters are those parameters that a manufacturer can control the design of high-speed end milling. The levels chosen for the control parameters were in the operational range of the high-speed end milling. Trial runs were conducted by choosing one of the machining parameters and keeping the rest of them at constant values. The selected levels for the chosen control parameters are summarized in Table 2. Each of the four control parameters was studied at three levels.

3.4. Assignment of Control Parameters

The orthogonal array, L_9 was selected for the high-speed end milling. The parameters were assigned to the various columns of orthogonal array (OA). The assignment of parameters along with the OA matrix is given in Table 3.

Table 3
Orthogonal Array (L_9) and Control Parameters

Treat No.	*n*	*f*	*d*	*c*
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.5. Analytical Techniques

After all tests were conducted, the decisions were made with the assistance of the following analytical techniques:

- ***Analysis of variance***: ANOVA is a statistically based, objective decision-making tool for detecting any differences in average performance of groups of items tested. The decision takes variation into account. The parameter which has Fisher's ratio (F-ratio) larger than the criterion (F-ratio from the tables) are believed to influence the average value for the population, and parameters which has an F- ratio less than the criterion are believed to have no effect on the average. Percent contribution indicates the relative power of a parameter to reduce variation.
- ***Plotting method***: To plot the effect of influential factors, the average result for each level must be calculated first. The sum of the data associated with each level in the OA column divided by the number of tests for that level would provide the appropriate averages. Plots may be made with equal increments between levels on the horizontal axes of the graphs to show the relative strengths of the factors. The strength of a factor is directly proportional to the slope of the graph.

3.6. Hole –Drilling Strain Gauge

The most widely used practical technique for measuring residual stresses is the hole-drilling strain gauge method described in ASTM Standard E837 (fig. 3). With this method, a specially configured electrical resistance strain gauge rosette was bonded to the surface of the test object and a small shallow hole was drilled through the center of the rosette. The drilled hole is typically 2.0 mm both in diameter and depth. The local changes in strain due to introduction of the hole were measured and the relaxed residual stresses were computed from these measurements.

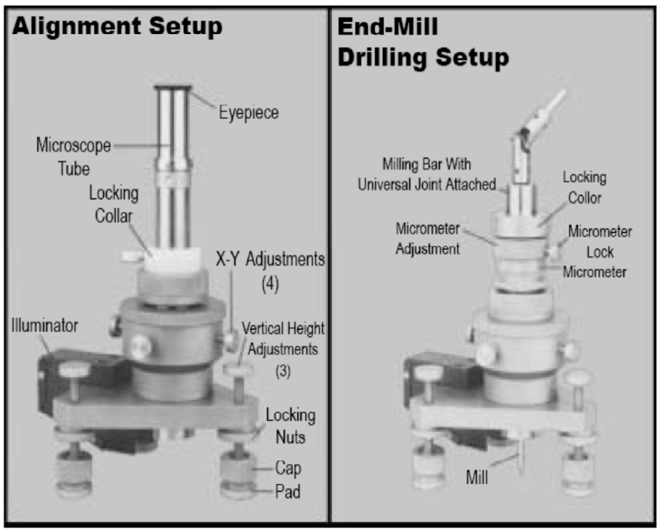

Figure 3: Hole Drilling Strain Gauge Method (ASTM Standard E837)

4. RESULTS AND DISCUSSIONS

The Influence of Process Variables on the Residual Stresses

The residual stresses were measured in two (x- and y-) directions on the workpiece surfaces such as (i) X-milling direction on the workpiece surface aligned with workpiece longitudinal axis and (ii) Y-direction on the workpiece surface perpendicular to x-axis. It is assumed that the stress in the direction perpendicular to the milled surface is negligible.

Table 4
Experimental Results of Residual Stress

Treat No.	*Stress, N*	
	x-direction	*y-direction*
1	-54	-51
22	0.5	1
3	14	15
4	2	1.5
5	8	7
6	-32	-35
7	5.5	5
8	-26	-28
9	6	5.5

The measured stresses are tabulated in Table 4. The ANOVA summary of residual stress is given in Table 5. According to the analysis of variance, depth of cut and feed rate have significant influence on the variation of residual stress. The percent contribution indicates that the variable d (depth of cut) all by itself (90.26%) contributes the most toward the variation observed in the residual stress. The variable f (feed rate) contributes over 4.67% of the total variation observed. The variables n (cutting speed) and c (type of casting) have negligible effect the total variation in residual stress.

The effect of feed rate on the residual stress induced in the workpiece is shown in Figure 13. The residual induced in the workpiece increases with increase in feed rate. The surface residual stresses in the milling direction x- and in the orthogonal direction y- detected for every milling condition are always compressive. The influence of depth of cut is severe on the induction of residual stresses in the workpiece (Figure 14). The induced residual stresses during milling can be attributed mainly two reasons:

Table 5
ANOVA Summary of Residual Stress

Column No	*Source*	*Sum 1*	*Sum 2*	*Sum 3*	*SS*	*v*	*V*	*F*	*P*
1	n	925.04	392.04	170.67	153.03	2	76.51	55.09	1.82
2	f	1380.17	234.38	117.04	396.86	2	198.43	142.87	4.67
3	d	8512.67	45.38	495.04	7718.36	2	3859.18	2778.61	90.26
4	c	1027.04	504.17	77.04	273.53	2	136.76	98.47	3.23
5	e	– –	– –	– -	12.5	9	1.39	– – – – -	– – – – -
6	T	– –	– –	– –	8554.27	17	– – – –	– – – – -	– – – – -

(i) The spreading of material (plastic deformation) by the cutting tool leads to residual compressive stresses.

(ii) The thermal heating due to the friction between workpiece surface and tool, which leads to tensile residual stresses.

For working condition with a higher material removal rate probably the thermal effect is more important than the spreading of material. In the SEM micrography (Figure 6(a)), the white lines parallel to the milling direction are caused by the tearing of material. The tearing of material is observed with deeper depth of cuts. In Fig. 6(b) the white lines caused by tearing are less evident and the spreading of material is observed. The spreading of material is resulted with lower depth of cuts.

The tearing is the result of deeper depth of cuts. The T6 heat treatment for Al-Si-Mg-Fe alloy offers a low average residual stress during the high-speed milling operation. The presence of aluminum dendrites, primary silicon, eutectic phase and intermetallic compounds might be attributed to the improvement of surface finish on high-speed machining of the Al-Si-Mg-Fe alloy work pieces.

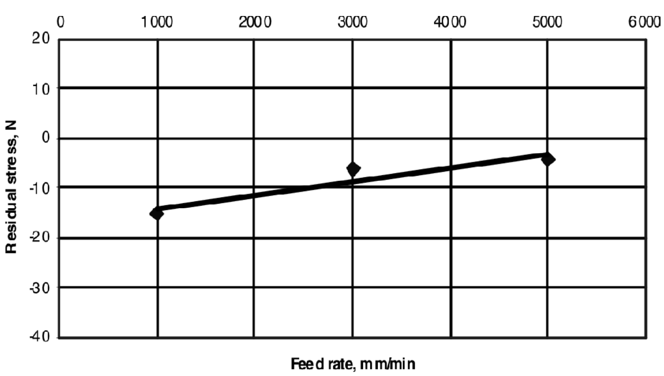

Figure 4: Effect of Feed Rate on the Residual Stress

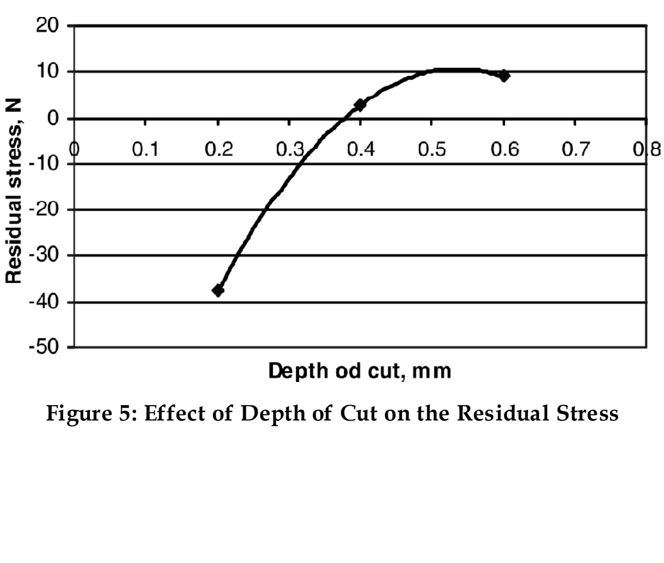

Figure 5: Effect of Depth of Cut on the Residual Stress

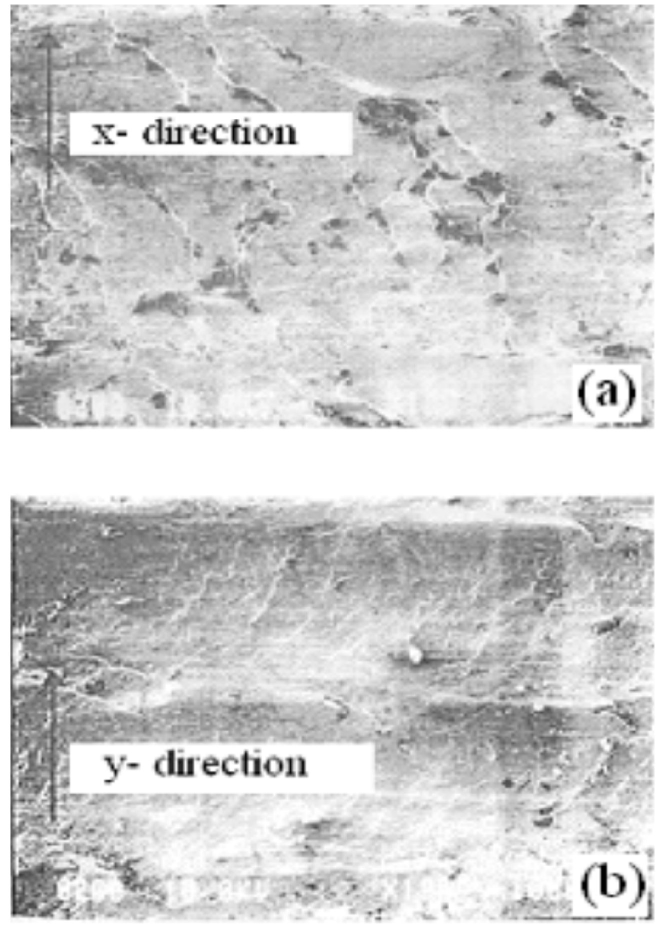

Figure 6: Surface Morphology after High-speed Milling (SEM)

5. CONCLUSIONS

The residual stresses induced in the work piece increases with increase in feed rate and depth of cut. This behaviour can be attributed to the tearing of material is observed with deeper depth of cuts.The white lines caused by tearing are less evident and the spreading of material is observed. The spreading of material is resulted with lower depth of cuts. The T6 heat treatment for Al-Si-Mg-Fe alloy offers a low average residual stress during the high-speed milling operations.

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