Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 1261-1266

Optimized Processing for Distortion Control in Milling of Al-Zn-Mg Alloys

Ole Karsten[1], Christian Grote[2], Kai Schimanski[1], Axel von Hehl[1], Hans-Werner Zoch[1]

[1]Lightweight Materials, IWT - Foundation Institute of Materials Science, Badgasteiner Str. 3, 28359 Bremen, Germany

[2]Manufact. Techn., IWT - Foundation Institute of Materials Science, Badgasteiner Str. 3, 28359 Bremen, Germany

Economical manufacturing makes it more and more necessary to go easy on resources. In this context the control of distortion is unaltered one of the major challenges. As a presupposition for distortion reduction within the Collaborative Research Centre SFB 570 "Distortion Engineering" a system orientated approach was developed which enables to understand distortion mechanisms in consideration of the whole process chain during manufacturing of steel components. Nevertheless a transfer of this approach from steel to aluminum materials has just taken place selectively. This can be reached by a consequent system orientated examination of the whole process chain in view of the distortion potentials in each manufacturing step to discover mechanisms which are responsible for dimension and shape changes during the manufacturing of aluminum products.

In order to analyze the distortion development during machining of aluminum model geometries were derived from industrial manufacturing processes. The distortion potentials in milling of an Al-Zn-Mg aluminum alloy (EN AW-7022 T652) have been investigated based on Design of Experiments (DoE) and were evaluated concerning their significance. Contour deviations were therefore ascertained via coordinate measuring machine. Furthermore in-situ cutting force measurements of the milling process and temperature measurements were applied to identify distortion potentials. The objective is to derive distortion mechanisms through system orientated investigations. Finally compensation strategies are presented to decrease dimension and shape changes of aluminum alloys to provide optimized processing during milling.

Keywords: *Milling, Distortion, System orientated analysis, Design of Experiments, Aluminum*

1. Introduction

The distortion control of components in manufacturing processes is still a significant challenge for the industry with regard to adequate economic capacity. As a result of rising demands on tolerances, improvements in machining and especially the aim for weight reduction, which led to designs of thin walled components, the reduction of shape and size deviations is attached of highly importance [1-2]. Removal of contour deviations often necessitates additional process steps and leads to additional costs due to rising processing time, which cannot be tolerated, even if arised distortions are controlled through mechanical finishing [3].

As a conclusion of these challenges within the Collaborative Research Centre "Distortion Engineering" a system orientated approach was developed which enables to understand distortion mechanisms through a system orientated view in consideration of the whole process chain. By analysis of distortion potentials and their consequent use like residual stresses, geometry, microstructure and element distribution of each manufacturing step the knowledge of these influencing values can be used for the compensation of distortion [4].

The aim within the running investigation is to analyze distortion mechanisms during milling of Al-Zn-Mg alloys with special focus on the process chain of continuous casted and rolled aluminum products. The intention is to analyze interactions between machining and heat treatment of aluminum alloys, in consideration of the order of the process steps.

In order to analyze distortion mechanisms in the process chains of wrought aluminum alloys it is necessary to investigate the causes of geometric deviations. First the initial material state has to be characterized by light microscopy, element distribution and hardness measurements. During machining the process forces, temperatures and strains should be studied. Especially the formation and size of residual stresses play a major role in the context of part distortion, which has to be investigated by X-ray diffractometry after each process step.

2. Experimental procedure

Aluminum plates from EN AW-7022 T652 blocks were prepared with dimensions of 100 mm x 100 mm x 20 mm and 100 mm x 100 mm x 35 mm by cutting with a bow saw and were face and side milled to dimensions of 95 mm x 95 mm x 15 mm and 95 mm x 95 mm x 30 mm. Side and face milling was conducted with constant parameters: cutting speed of v_c = 460 m/min, feed speed of v_f = 3500 mm/min, feed per tooth f_z = 0.25 mm and a cutting depth of a_p = 1 mm in each step.

To analyze also geometric influences on distortion different aluminum model geometries were derived from industrial manufacturing processes: a) frame, b) plate, see Fig. 1.

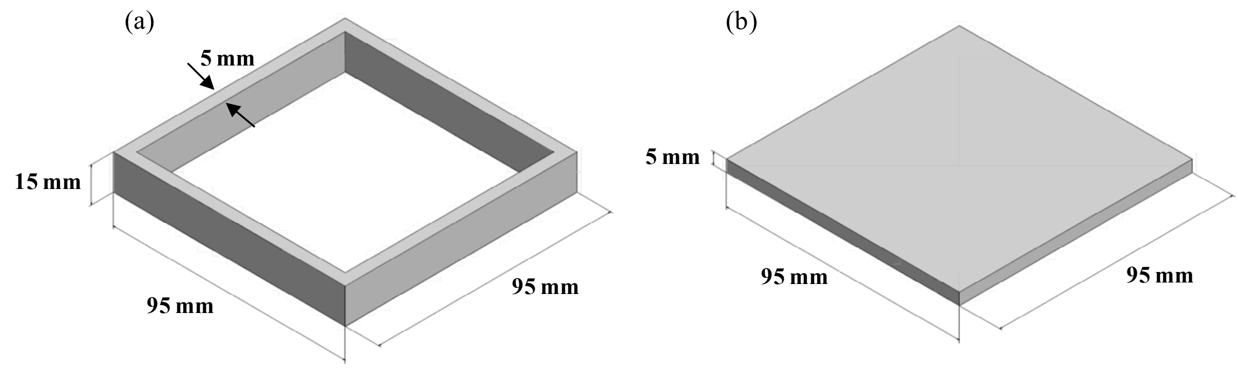

Fig. 1: Aluminum geometries frame (a) and plate (b)

The milling tests were performed in a machining centre Deckel Maho DMC 65 V ($P_{max.}$ = 16 kW; $n_{max.}$ = 18,000 rpm). The face and side milling of both geometries and the final machining of the plate geometry was conducted with an face-milling cutter with a diameter of 63 mm. Cutting inserts out of cemented carbide H13 coated with titanium nitride were used in the experiments due to their high lifetime and the accuracy grade during milling of aluminum alloys. Final machining of the frame model geometry was carried out with a solid carbide cutting tool of 20 mm diameter, coated with Zirconium Nitrogen oxide (ZOX). Samples with a thickness of 30 mm were used for the final machining of this geometry due to avoid distortion caused by clamping forces. Therefore a pocket with a depth of 25 mm was milled into the aluminum sample, followed by a slitting process to 95 mm x 95 mm x 20 mm and a final face milling to 95 mm x 95 mm x 15 mm.

The influence of temperature distribution in the workpieces during machining was investigated by inserting four NiCr-Ni thermocouples, type K, with a diameter of 0.5 mm in each of 16 samples of the plate model geometry. Thermocouples were positioned in a depth of 1 mm, 2 mm, 3 mm and 4 mm below the final surface of the plate. Test frequency was set up at 250 Hz.

Process forces during milling of the model geometries were captured via a workpiece based three-component-force measurement system. Results were evaluated based on design of experiments. In order to analyze distortion mechanisms during machining by means of Design of Experiments the parameters were varied in a two step 2^3 full factorial test plan, shown in Table 1 [5]. Process parameters were chosen as agreed upon with partners from the industry. The cutting depth of the model geometry plate was just varied in the last step, during machining of the frame geometry the depth of cut was kept constant in every cutting step. Feed per tooth was varied with regard to the tools used for machining of each geometry. Concerning the plate geometry feed per tooth was set up at $f_z = 0.3$ mm (size 1) and $f_z = 0.24$ mm (size 2). Regarding the frame geometry feed per tooth was varied between $f_z = 0.1$ mm (size 1) and $f_z = 0.075$ mm (size 2).

Table 1: Full factorial test plan

Parameter	**Size 1 [-]**	**Size 2 [+]**	**Size 1 [-]**	**Size 2 [+]**
	plate geometry		**frame geometry**	
Cutting depth	1 (mm)	2 (mm)	1 (mm)	2 (mm)
Cutting speed	395 (m/min)	495 (m/min)	220 (m/min)	280 (m/min)
Coolant	None	Emulsion	None	Emulsion

The shape and size deviations of the workpieces were measured before and after the final milling of the model geometries with a precision coordinate measuring machine of the type PMM 654 by Leitz. The measurement uncertainty of this device is (1.2 + L/300) µm. The measurements were focused on planarity and parallelism based on DIN ISO 1101.

3. Experimental results

Within the investigated machining parameters of geometry plate no significant influence on the planarity of plane E1 (Fig. 2) after final milling has been observed. Neither the variation of the cutting depth in the last step nor the variation of the cutting speed influenced significantly the planarity of the samples. Fig. 2 shows the change of planarity of E1 of two systems concerning the variation of the cutting depth and the cutting speed with coolant use. The mean change of planarity is about 0.04 mm. The reason for missing influence of the machining parameters might be the fact, that the residual stresses caused by milling of plane E2 are homogenous. These homogenous residual stresses caused nearly the same bending of the plane E1. Deformation of plane E1 is mainly driven from the residual stresses, which have been inserted through final milling of plane E2.

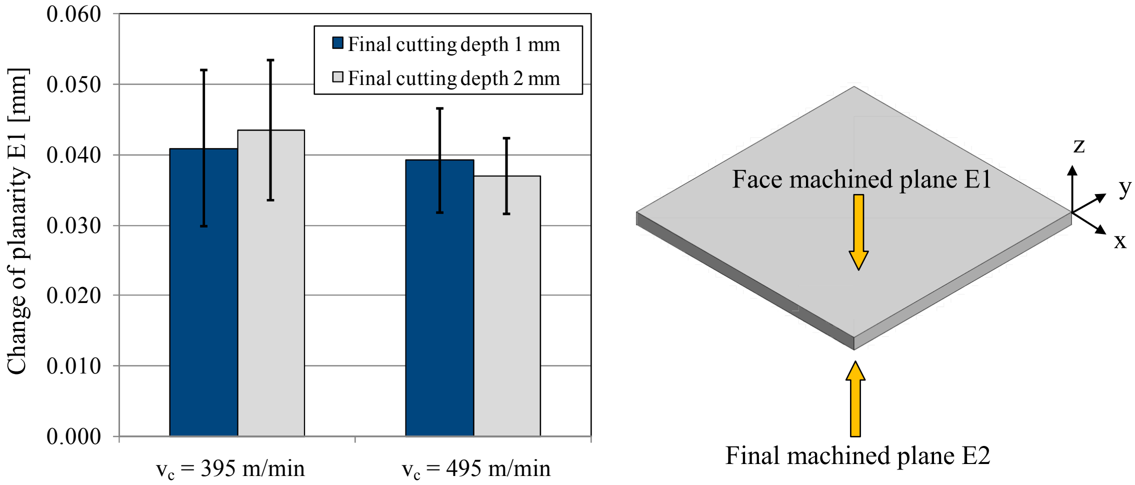

Fig. 2: Results of the shape deviation measurements of the plate geometry

Investigations of the frame geometry indicated nearly the same tendency concerning the influence of machining parameters. The change in parallelism of the side surfaces caused by final milling of the frame is mainly influenced by temperature loads in the milling process (Fig. 3). The only significant influence identified is the usage of the coolant.

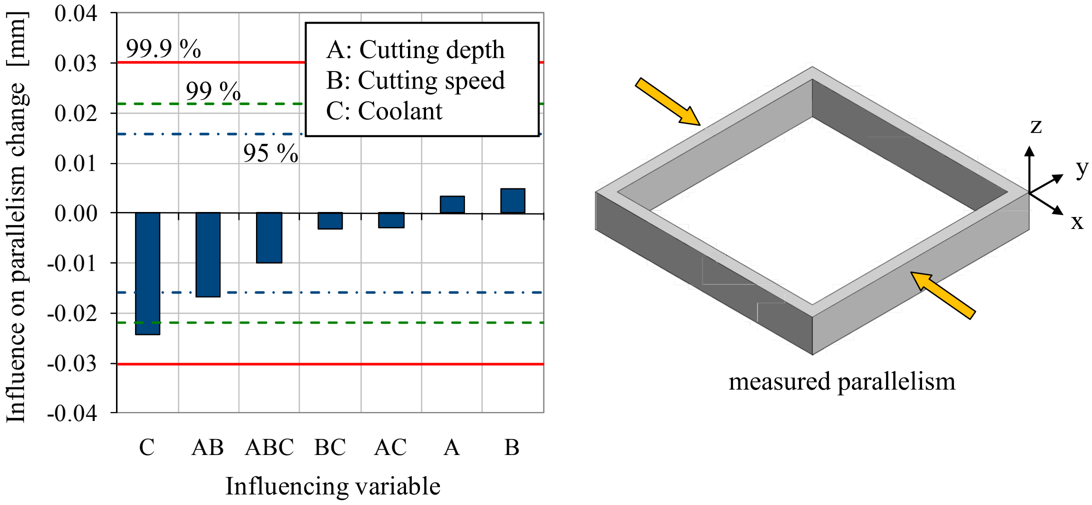

Fig. 3: Results of the shape deviation measurements based on the test plan of the frame geometry

The temperature measurements of the plate geometry showed three high significant influences on the temperature rise in the last cut of 2 mm. The highest influence on the temperature rise was figured out for the use of the coolant. A significant influence was noticed for the cutting depth and for the interaction between cutting speed and cutting depth. The reason for the influence of the cutting depth can be explained by the fact, that two cuts with the same depth produce a higher heat quantity than one cut with double depth, which is probably caused by the friction between tool and surface of the workpieces.

In order to investigate the influence of a constant cutting depth on the workpiece temperature, additional temperature measurements were carried out without use of coolant. Fig. 4a displays the result of a constant cutting depth of a_p = 1 mm in overall 10 cuts. The maximum workpiece temperature was about 105 °C. It wasn't possible to point out a difference between the positions of the thermocouples, so the diagram shows the mean value of all four thermocouples.

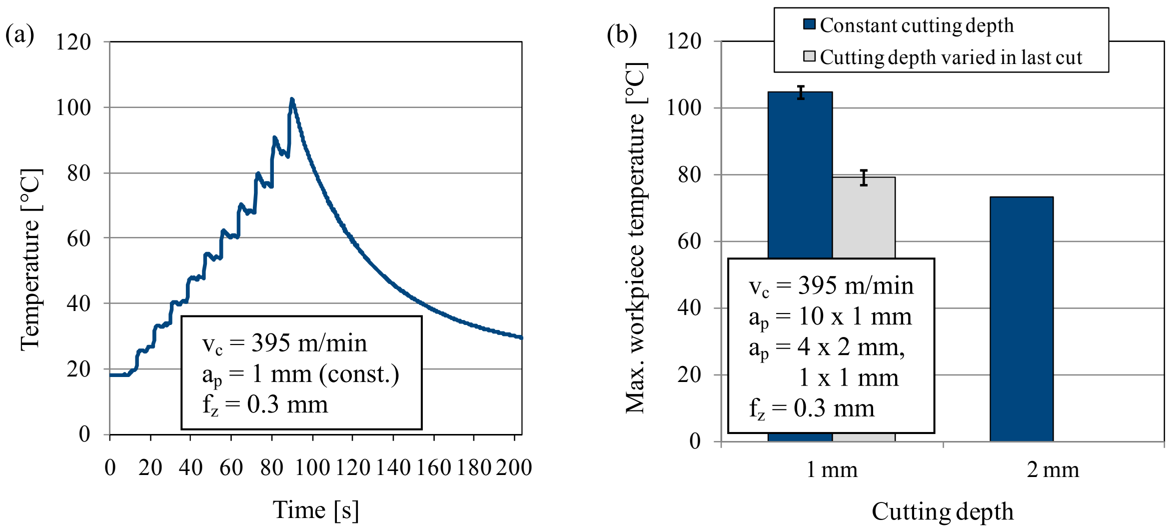

Fig. 4a: Temperature progression in milling of plate geometry
Fig. 4b: Maximum workpiece temperature at different cutting depths

The differences of the maximum temperatures for all three cutting strategies are shown in Fig. 4b. The replacement of a last cut with a depth of a_p = 2 mm with two cuts of a depth of a_p = 1 mm each leads to an increase of the workpiece temperature of about 6 °C. When the cutting depth is kept constant in every cut, the temperature increases about 25 °C. Shape deviation measurements after the milling of plane E2 (see Fig. 2) showed a significant increase of change in planarity of plane E1. This can be explained by significant higher temperature gradients when using the cutting strategy 10 cuts with each $a_p = 1$ mm.

Force measurements were carried out for both geometries (plate and frame). Concerning the plate model only the z-component F_z of the milling forces is relevant, which points towards the surface of the workpiece and so may affect the residual stress state. The measured forces varied from $F_z = 265$ N to $F_z = 436$ N at milling of lane 1 and from 151 N to 245 N at milling of lane 2. The influence of the cutting depth, the cutting speed and the coolant on the z-directional force was analyzed with DoE (Fig. 5). Only the cutting depth and the cutting speed have a high significant influence on the z-directional force. Besides the cutting depth shows an interaction with the milled lane which means, that its influence descends from an influence of the material removal rate. An increase of the cutting speed leads to a decrease of the milling force, which is commonly known [6]. However the effect of the milling forces on the residual stress state is much lower than the effect of the thermal influences, which is also confirmed by the temperature measurement.

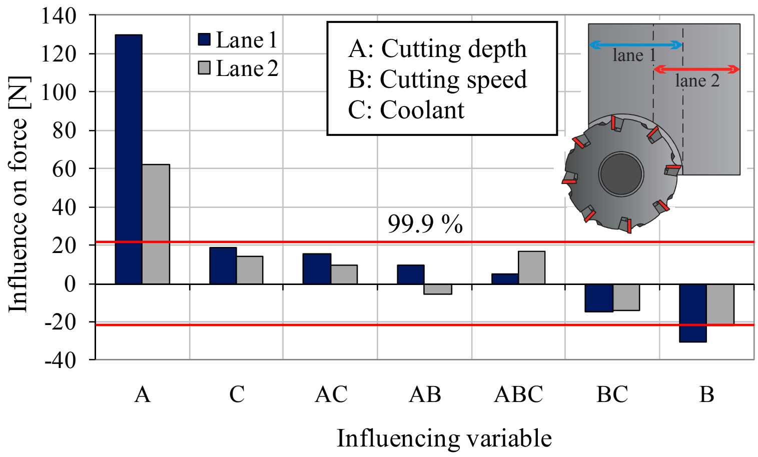

Fig. 5: Results of the DoE (milling forces in z-direction at plate model)

In case of milling the frame model the relevant force consists of the x-directional (F_x) and the y-directional (F_y) components of the milling force (Fig. 6).

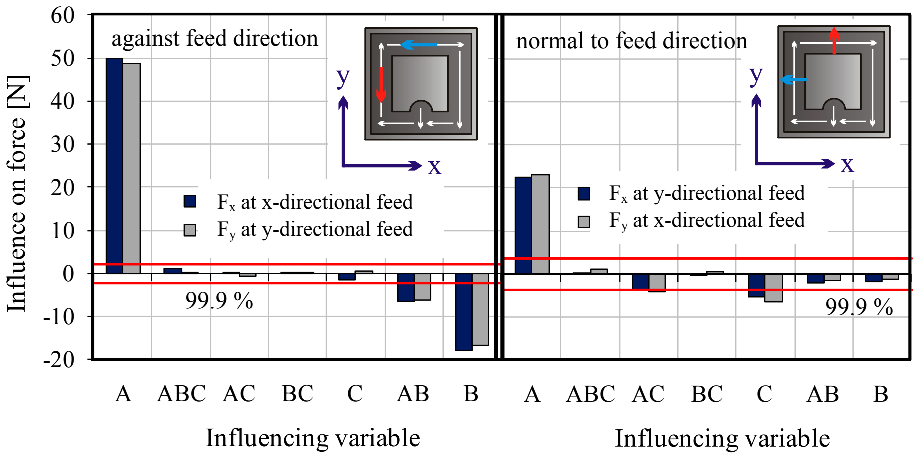

Fig. 6: Results of the DoE (milling forces at frame model)

The force measurements indicate the effective force direction to act from right of the feed direction and against it. The part acting from right is caused by down milling at the right side of the feed direction and up milling at the left side. As down milling causes a force towards the tool and up milling causes an opposite directed force both forces add up [7]. The force acting against the feed direction and the force acting normal to the feed direction were separately analyzed with DoE. As expected the values for F_x and F_y are similar. The minimal values of high significance against the feed direction are 2.2 N for F_x and 1.8 N for F_y. Normal to the feed direction the values are 3.6 N for F_x and 3.0 N for F_y. The cutting depth has a high significant influence on both parts of the milling force. The force against the feed direction is also significantly influenced by the cutting speed and a cutting depth - cutting speed interaction. However the force normal to the feed direction is significantly influenced by the coolant and a cutting depth - coolant interaction. The increase of the milling forces with increasing cutting depth is expected due to higher material removal [8]. The influence of the coolant on the force normal to the feed direction can be related to the lubricating effect which is only effective at the left and right side of the tool. The influence of the cutting speed on the force against the feed direction was also observed by Schulz [6].

4. Conclusions and Outlook

Investigations were carried out concerning shape deviations before and after final milling of aluminum EN AW-7022 T652 plate and frame geometries. Results showed no significant influence of the analyzed machining parameters cutting depth and cutting speed on the planarity and parallelism of the workpieces. Implication of this observation is that distortion was driven through thermal loads. Temperature measurements indicated an influence of the cutting depth and the use of the coolant on the temperature rise in the last cut and especially on the maximum workpiece temperature in dependence on processing. Force measurements proved the fact, that mechanical loads within the investigated parameters have less influence on distortion due to their magnitude. As a conclusion the residual stresses and distortions are mainly influenced by thermal loads. Further investigations will be focused on the development of the residual stresses and strains during milling, thermal loads during machining with minimum cooling lubricant and time stability of residual stresses. In future the investigation of the history of the workpieces within the process chain will be a major task. Within the analyzed machining parameters an optimized processing can reached by a consequent observance of the thermal loads, which can be influenced by the cutting strategy and effective use of the coolant.

5. Acknowledgement

The research work (AiF 15867 N) was assisted by budget funds of Bundesministerium für Wirtschaft und Technologie (BMWi) in the context of Arbeitsgemeinschaft industrieller Forschungs-vereinigungen “Otto von Guericke” e.V: (AiF), wherefore explicit thank is given.

6. References

[1] B. Denkena, B. Breidenstein and L. de Léon-Garciá: CIRP Intern. Conf. on High Perf. Cutting 2 (2006) 1-8.
[2] S. Nervi, B. A. Szabó and K. A. Young: AIAA J. 47 (2009) 1635-1641.
[3] E. Brinksmeier and J. Sölter: CIRP Annals – Manufact. Techn. 58 (2009) 507-510.
[4] F. Hoffmann, O. Keßler, T. Lübben and P. Mayr: HTM Z. Werkst. Waermebeh. Fertigung 57 (2002) 213-217.
[5] W. Kleppmann: *Taschenbuch Versuchsplanung*, 4. Aufl. (Carl Hanser Verlag, München, Wien, 2006) pp. 94-108.
[6] H. Schulz: *Hochgeschwindigkeitsbearbeitung – High-Speed Machining*, 1. Aufl. (Carl Hanser Verlag, München, Wien, 1996) pp. 46-58.
[7] H. Braun: *Fachkunde Metall*, 53. Aufl. (Verlag Europa Lehrmittel, Haan-Gruiten, 1999) pp. 169.
[8] X. P. Li, H. Q. Zheng, Y.S. Wong and A.Y.C. Nee: J. Manufact. Process. 2 (2000) 225-240.