Concept to analyze residual stresses in milled thin walled monolithic aluminum components and their effect on part distortion

Konzept zur Analyse der Eigenspannungen in gefrästen, dünnwandigen, monolithischen Aluminiumbauteilen und deren Einfluss auf den Bauteilverzug

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Abstract. Thin walled monolithic components are applied in the aerospace industry because of their high overall-strength-to-weight ratio. The distortion of these components is a common problem and can lead to high costs due to remanufacturing or part rejection. The main drivers for the distortion are the stresses which occur during the machining process, so called machining induced residual stresses (MIRS), and the ones which are already in the material from prior processing including heat treatments, the bulk residual stresses (BRS). In this paper, a concept is introduced to analyze the effect of both MIRS and BRS on the distortion of thin walled monolithic aluminum components. Compensation techniques will be developed to avoid high costs, save time and improve part quality. The concept includes milling experiments as well as finite element method (FEM) simulations. The simulations incorporate a dynamic elastic-plastic process model of the milling process to predict the MIRS and a linear static, elastic model to forecast the part distortion. Before understanding the superposition of MIRS and BRS, the impacts of the individual aspects have to be investigated first. Milling experiments on stress relieved AA7050 parts with different machining parameters were carried out to identify their effect on MIRS.

Increasing feed per tooth was discovered to increase penetration depth of the MIRS. The cutting speed has no significant impact on the MIRS. MIRS are found to be highly linked to the forces acting while milling.

Keywords: Residual stresses, Distortion, Milling

Abstract. Dünnwandige monolithische Bauteile werden in der Luft- und Raumfahrt, aufgrund ihres hohen Verhältnisses von Festigkeit zu Gewicht, eingesetzt. Der Verzug dieser Bauteile ist ein häufiges Problem, welches zu hohen Kosten infolge von Nacharbeit oder gar Ausschuss führt. Der Hauptgrund für den Verzug sind Eigenspannungen (ES). Man unterscheidet zwischen prozessbedingten ES (PES) und initialen ES (IES). IES sind vorangehender Prozesse wie z.B. Wärmebehandlungen geschuldet. Ein Konzept zur Analyse des Einflusses von PES und IES auf den Verzug dünnwandiger monolithischer Aluminiumkomponenten wird vorgestellt. Es umfasst Fräsversuche sowie Finite-Elemente-Methode (FEM) Simulationen. Diese beinhalten ein dynamisches elastisch-plastisches Prozessmodell des Fräsvorgangs zur Vorhersage der PES und ein statisches, elastisches, lineares Modell zur Vorhersage des Bauteilverzugs. Es wurden Fräsversuche an spannungsarmgeglühten AA7050-Bauteilen mit unterschiedlichen Prozessparametern durchgeführt, um deren Auswirkungen auf die PES zu identifizieren. Dabei zeigte sich, dass ein erhöhter Vorschub zu einer erhöhten Eindringtiefe der PES führt. Die Schnittgeschwindigkeit hat keinen erkennbaren Einfluss. Zudem stellte sich heraus, dass die PES stark mit den beim Fräsen auftretenden Kräften verknüpft sind.

Keywords: Eigenspannungen, Verzug, Fräsen

1 Introduction

Thin walled monolithic aluminum components are applied in the aerospace industry because of their good properties, such as a high overall-strength-to-weight ratio [1]. For such rib type shaped geometries, up to 90 % of the material is removed during milling [2]. As these components typically are long, up to 14 m, and thin walled, down to 2 mm, the distortion is a common problem [2]. It leads to high costs due to remanufacturing or rejection of the parts [3]. The main reason for the distortion can be traced back to residual stresses (RS) [1]. Residual stresses are defined as the internal stresses locked in a body, where force and torque equilibrium prevail and no thermal gradients appear [3]. They are divided in three types. Type I are declared as macro RS, which are developed in several grains. Type II are defined as micro RS, which are developed in one grain. Type III are sub-micro RS, which are developed within several atomic distances of the grain. Type I RS are considered when it comes to distortion, because only these result in a change in macroscopic dimensions [4]. Furthermore, Type I RS can be categorized in two sorts due to their origin. One sort are the stresses driven into the material during the machining process, so called machining induced residual stresses (MIRS). The penetration depth of MIRS is limited to a shallow surface layer of the part. On the other side there are the RS, which are already in the material because of former processes like heat treatments (e.g. quenching). These are defined as bulk residual stresses (BRS), because they appear throughout the entire part-thickness [1]. The re-equilibration of the stresses causes the part to distort [5].

Research was done focusing on the part distortion from RS. From the experimental perspective the effects of machining parameters on the MIRS were investigated. It was found that when milling aluminum alloys a root shaped profile (-√-) of compressive MIRS occurs near the surface [6]. Also, the distortion due to BRS of quenched aluminum was examined and a procedure to measure the distortion was defined [5].

Finite element method (FEM) simulations are often used to predict the part distortion. Wei et al. [7] was able to predict the distortion because of BRS. The Eigenstrain approach has been widely used to apply measured characteristic RS fields from numerous manufacturing processes to arbitrary geometries. DeWald and Hill [8] use the eigenstrain method to estimate residual stress fields from laser shock peening. Ribeiro and Hill use it to estimate residual stress at cold expended holes [9]. But the eigenstrain method is also useful in estimating distortions in elastic bodies, e.g. for nitriding [10]. Denkena et al. forecast the MIRS part distortion with FEM analysis and used MIRS measurement data from an empirical data base [2]. Ma et al. achieved a prediction of the MIRS by using cutting simulations [11]. In a second model the simulated MIRS are used to calculate the part distortion. No validation of MIRS in form of stress measurements is presented and a large simulation error is stated for the comparison of distortion measurement and simulation result. The prediction of the part distortion due to superposition of both RS was done by various researchers [12-14]. Madariaga et al. [12] could predict and validate the part distortion, but still MIRS measurements were required as an input for the simulations. Yang et al. [13] and Tang et al. [14] used a simplified model for simulating the distortion due to both sorts of RS. Only the temperatures and forces were considered to predict the part distortion. No prediction of MIRS is possible with this approach.

Although there are a lot of FEM approaches to tackle the problem of part distortion due to RS, there is still further research needed. It is necessary to understand and predict the impact of BRS and MIRS individually and their superposition on the part distortion with the help of experimentally validated simulations. In this paper a concept is introduced how to predict the part distortion due to both sorts of RS with the help of FEM simulations and experiments. In the end there will be a two step simulation model developed, which considers the machining parameters, workpiece geometry and BRS as an input and predicts the MIRS and the part distortion. These models will be validated once by experiments. The impact of further changes in input parameters can then be predicted without additional experiments. Which means no future cost and time intensive RS measurements are needed anymore. Besides introducing the concept, first experimental results, which show the influence of different machining parameters on the MIRS state and serve as validation for the process model, are presented.

2 Concept methodology

The main objective is to predict the distortion due to both BRS and MIRS and develop methods to minimize distortion. The concept contains a combination of experiments and simulation models. The experiments serve as a validation for each simulation model. In the end the models predict the part distortion based on information about machining parameters, tool and workpiece geometries, and BRS state of the material. As Figure 1 illustrates, this is done by considering each effect of BRS and MIRS individually before investigating the superposition of both. Following, the experiments are described first, which are divided in so called “plaque” and “feature” experiments. The plaque experiments deal with the influence of machining parameters and tool type on the MIRS in the workpiece. The feature experiments investigate the influence of BRS, MIRS and the superposition of both on the part distortion. Afterwards the simulation models are presented. A FEM process model to predict MIRS and an Eigenstrain model to predict part distortion because of both RS are introduced. Finally first results from plaque experiments are presented and discussed.

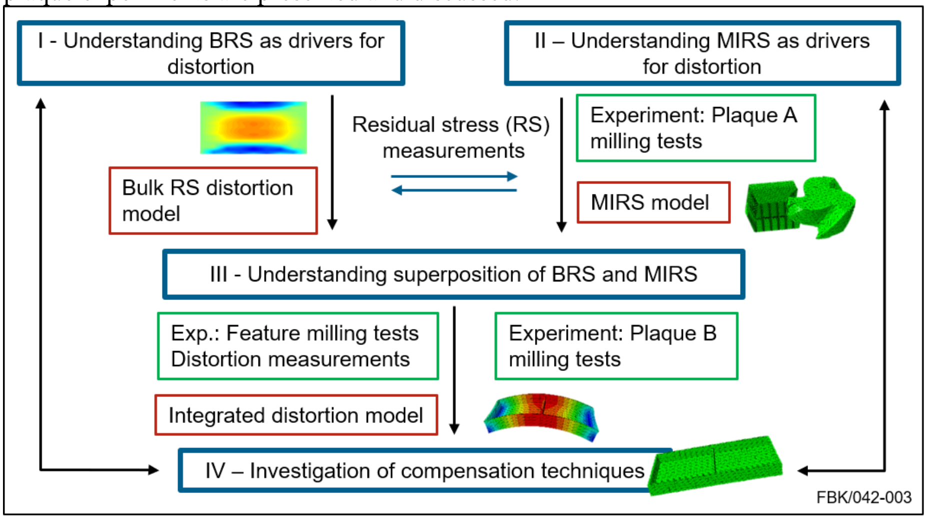


Fig. 1. Concept overview: Experiments highlighted in green boxes and simulation models in red

2.1 Experiments

Plaque experiments

The plaque experiments are designed to reveal the influence of machining parameters and tool type (end mill vs. inserts) on the MIRS in the workpiece. In part A (see Fig. 1) stress relieved aluminum parts AA7050-T7451 were chosen. The dimensions of the workpieces are 206x102x28 mm^3. They were face milled on the 206x102 mm^2 face with cemented carbide end mills of the type Kennametal[1] F3AA1200AWL. The tool properties can be found in Table 1.

Table 1. Tool properties

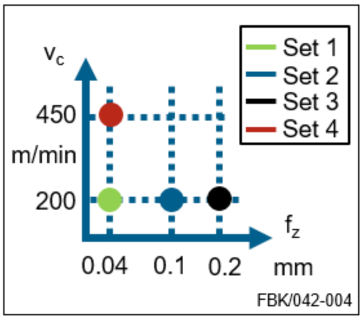
tool properties	Kennametal[1] F3AA1200AWL
diameter	12 mm
material	cemented carbide
number of flutes	3
helix angle	45°
cutting edge radius	-
length	76 mm
coating	-

Machining was carried out on a 5-axis DMG Mori DMU 70 CNC milling machine by down milling. The workpiece was clamped in a vice. The jaws of the vice were 125 mm long and 5.5 mm of the workpiece protruded prior to cutting. The feed direction is along the 206 mm dimension. Machining parameters are shown in Table 2. The feed per tooth f_z and the cutting speed v_c are varied. Three different feed per tooth and two different cutting speeds were investigated, which resulted in four parameter sets (see Fig. 2). They represent different load cases and were chosen by prior experiments because they showed less vibrations and no interference with the eigenfrequency of the set up. The process was monitored by recording forces using a piezoelectric dynamometer (Kistler Type 9255) with a sampling rate of 15 kHz. One surface layer was removed, which resulted in 25 paths with a constant width of cut of 4 mm. The last 2 mm were removed in an additional path. Later, in plaque experiments part B (see Fig. 1) machining will be done on parts which contain BRS (quenched material AA7050-T74) to see if or how the superposition effects the MIRS.

Table 2. Machining parameters

machining parameter	
machining strategy	down milling
cooling strategy	dry cutting
feed per tooth f_z	0.04 mm, 0.1 mm, 0.2 mm
cutting speed v_c	200 m/min, 450 m/min
depth of cut a_p	3 mm
width of cut a_e	4 mm
clamping strategy	vice

Fig. 2. Machining parameter sets



Feature experiments

The feature experiments are designed to show the influence of BRS, MIRS and the superposition of both on the part distortion. Stress relieved AA7050-T7451 and quenched material AA7050-T74 will be machined. Blocks of the same size as the plaques are going to be used and up to 90 % of the initial material will be removed, similar to industrial practice. The final geometry will be a small rib type component with one rib in the middle, surrounded by two pockets (see Fig. 3).

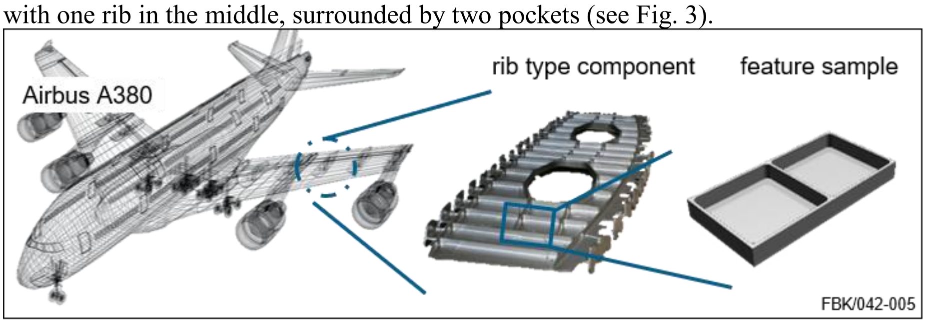


Fig. 3. Feature sample design in comparison to real components [15,16]

Different wall thicknesses will be manufactured in order to differentiate between the influence of BRS and MIRS on the part distortion. Because it is expected that the effect of MIRS will be neglected, if a certain wall thickness is reached. The distortion of the bottom surface will be measured by means of a coordinate measuring machine. This experiment also serves as a validation for the integrated distortion model.

2.2 Simulation models

Machining induced residual stress (MIRS) model

The MIRS model is a FEM process simulation. Its purpose is to predict the MIRS in the shallow surface layer. An explicit, dynamic, elastic-plastic approach is chosen in ABAQUS[1]. An explicit solver is used, because large strain rates and high deformations occur. As input data the machining parameter feed f and rotation speed n are given. The tool is assumed as a rigid body, neglecting wear. The material behavior is described via Johnson Cook material model [17]. Damage of the material happens when the Johnson Cook damage initiation criteria is met [17]. Its evolution is described by a damage evolution law based on the linear displacement of the elements. Final failure is defined when a specific value of displacement is reached. At this point element deletion takes place and allows for the separation of the material, respectively the chip formation. Element deletion is realized by setting the stiffness matrix at the affected element to 0. A fine mesh in the near surface region is needed to detect the MIRS profile. One rotation of the tool will be computed due to large computational times. Temperature-displacement coupling is used to consider thermal effects. Material parameters are defined by literature values.

Bulk residual stress (BRS) model & integrated model

The bulk residual stress (BRS) model is an Eigenstrain model developed using BRS measurement data in quenched AA7050-T74 plaques. The BRS distribution in the plaques is measured using a series of slitting measurements as described by Olson and Hill [18]. This provides a two-dimensional map of the in-plane components of BRS throughout the 206 mm and 102 mm plaque area. An eigenstrain field is derived from the BRS measurement data using an inverse analysis. The integrated model is an extension of the BRS distortion model. It combines eigenstrain fields found for BRS and MIRS and is used to predict distortion expected in parts machined from the plaque materials.

3 Experimental Results

Plastic deformation, thermal stress gradients, phase transformations and the superposition of these effects cause MIRS. Therefore, the monitoring of the mechanical loads, i.e. force measurements during machining is important. In the following sections, forces and stresses are analyzed exemplary in y-direction (perpendicular to feed direction). As down milling was used, these forces predominate the machining process.

3.1 Force analysis

Every fourth path out of 25, beginning with the second, was measured. The root mean square (RMS) of the force signal during the stable phase (beginning and end of each milling path are not considered) of each path was calculated. The arithmetic mean over all measured paths F_y was calculated to allow for comparison of all machining sets (see Fig. 4.)

Increased forces are the result of an increased feed per tooth due to a higher chip thickness and higher material removal rates. A maximum value of approximately 330 N is reached for the highest feed per tooth. Slightly decreased forces F_y could be observed for the variation of cutting speed from 200 m/min to 450 m/min. According to literature this is due to the decreased strength of the material for higher temperatures, which are typically reached for higher cutting speeds [19].

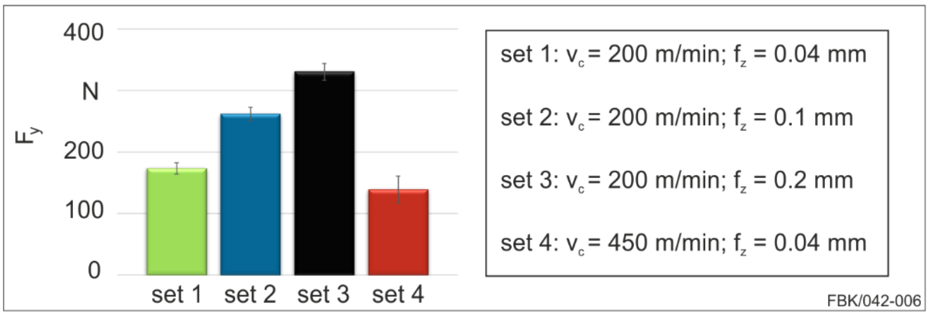


Fig. 4. Forces F_y of different machining sets

3.2 Machining induced residual stress analysis

MIRS measurements were performed using the slotting technique, a uniaxial near surface RS measurement technique similar to the well-established hole drilling technique [20]. A slot, instead of a hole, is cut into the workpiece surface in a series of depth increments. The local deformation caused by redistribution of RS is observed by a strain gage adjacent the slot. Residual stress perpendicular to the long direction of the slot is calculated by an inverse analysis using the strain versus depth data.

For all machining parameters the typical root shaped compressive stress profiles were measured (see Fig. 5) [21]. Higher feeds result in increased depths t_{max} of the maximum compressive residual stress and in an increased penetration depth t_p of the whole profile. This is due to the higher forces for increased feeds, which lead to larger plasticly deformed areas. There is no systematical trend recognizable for the amplitude of maximum compressive MIRS. A maximum compressive RS of -200 MPa was measured at a depth t_{max} of 60 µm for the highest feed. The penetration depth t_p was 150 µm. The variation of cutting speed seems to have no influence on the MIRS profile (see Fig. 5b) although a slightly decrease of forces was measured.

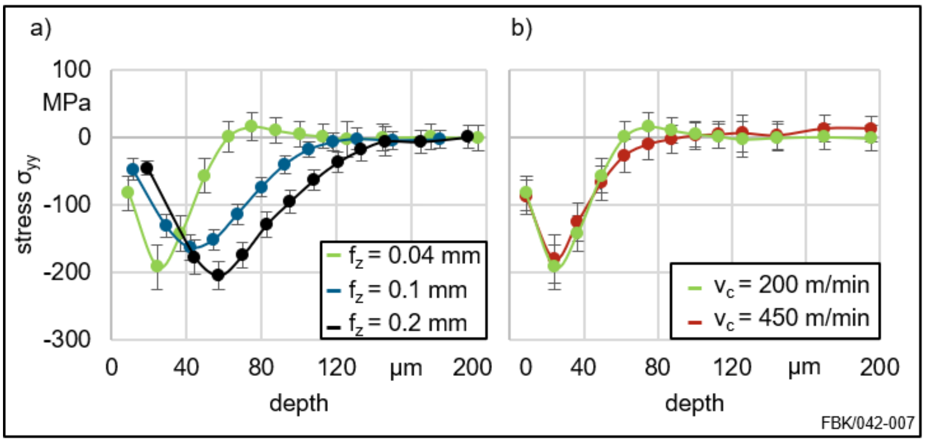


Fig. 5. Residual stresses σ_{yy} perpendicular to feed direction for constant $v_c = 200$ m/min and different f_z (a), and constant $f_z = 0.04$ mm and different v_c (b) (adapted from [21])

4 Conclusion and Outlook

A concept to analyze the effects of both MIRS and BRS on the part distortion was introduced. The concept includes experiments and simulation models. Before understanding the superposition of MIRS and BRS, the impacts of the individual aspects have to be investigated first. Milling experiments on stress relieved AA7050 parts with different machining parameters were carried out to identify their effect on MIRS. An increased maximum compressive residual stress depth with increased feed was found. To get more reliable information, e.g. about the maximum residual stress, a statistical validation is needed. In addition to the forces, temperatures will be considered in the future based on measurements. Finally, the simulation results will be compared to the experimental results.

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[1]Naming of specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.

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