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Determination of Residual Stresses in Plate Material by Layer Removal with Machine-integrated Measurement

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Abstract

Structural aircraft components are usually manufactured from rolled plate material. Despite a stress relief treatment residual stress remains in the plates. This can result in distortions of the workpiece after the final manufacturing step, which leads to time-consuming repair processes or even a scrap part. Using an FEM simulation, it is possible to predict distortions caused by residual stress and to avoid them by adjusting the manufacturing process. However, the known methods to determine the residual stress state in plate material are expensive in terms of time and material and require specially trained staff. This paper describes a novel method to measure residual stress in plates with little effort. The method is derived from the well-known Layer-Removal-Method and utilizes a machine tool with a standard probing device. The measuring task is fully automated and can be performed by untrained staff. No special preparation of the specimen is necessary. The paper describes the procedure and the results of residual stress measurement on samples of the material EN AW-7075 T651. The results are in line with values published by other authors.

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Keywords: structural components, residual stresses, layer-removal-method

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1. Introduction

The aircraft manufacturer Airbus forecasts that the worldwide fleet of civil passenger and cargo aircrafts will increase from 17,171 in 2011 to 35,489 in 2031 [1]. The demand for new aircrafts raises the challenge to increase productivity in all production stages. Modern aircrafts are designed in order to maximize energy efficiency. This denotes that low fuel consumption is in focus of the development of new aircrafts such as the Boeing 787 or the Airbus A320neo [2]. A decisive factor for the fuel consumption is the weight of the aircraft. In order to maintain low weight, the supporting structure components are designed in a way that a maximum rigidity is achieved with minimal residual material thickness. This results in parts with a thickness of only 2 mm. Such components can be up to 14 m long and additionally show complex shapes. These parts are typically manufactured from rolled aluminum plates. In addition, the chosen materials are difficult to machine and offer several challenges for the machining process. Especially, part distortions occurring after machining cause time consuming repair processes. During the machining process of structural components, up to 90% of the material is removed from the blank. Thereby, material inherent residual stresses are removed and additional residual stresses are induced into the subsurface of the machined workpiece by the machining process. Both effects cause distortions of the workpiece and lead to shape deviations, which cannot be repaired without damaging the aircraft component. By utilizing an FEM simulation with a custom preprocessor it is possible to predict the distortions caused by residual stresses and take appropriate actions to avoid it [3]. Yet, the quality of the prediction depends on the knowledge about the residual stress,

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which is induced by the process, and the residual stresses which exist in the rolled plate material.

2. State of the art: Measuring residual stresses in plate material

There are multiple different methods to measure residual stresses induced by manufacturing processes. The most common ones are by X-Ray-diffractometry and the hole drilling method. Both are limited to measurements of the subsurface up to a few millimeters. Hence, they are unsuitable to characterize the residual stress state of large plate material.

There are several different methods to determine the residual stress state in large parts. All of them remove material from the measured parts and observe the resulting deformation or strain. These measuring principles can be described as indirect and destructive. They can only determine relative residual stress inhomogeneity throughout the part but not absolute stresses.

Prime did extensive research in the field of these measuring methods. In 1999 he did a literature review on known publications about different measurement techniques based on successive extension of a slot by wire EDM or sawing [4]. In 2005 he described a generic inverse mathematical procedure to determine residual stress from strain or distortion measurements for achieving effective and reliable solutions [5].

In 2002 Prime determined the residual stress in rolled aluminum plates of EN AW-7050 in the state T74 and T7451. He used the crack compliance method by which a sample is split in half with a Wire EDM machine. The resulting strains on the part surface are detected with multiple strain gauges [6].

All existing methods depend on the usage of strain gauges and require special preparation of the samples by trained workers. Also for accurate results the splitting should be done by a wire EDM machine. As of this, the hurdles for a daily use are relatively high. Based on the work of Prime this paper describes a novel method to measure residual stress in plates with less effort and without special training.

3. Layer removal theory

Similar to the crack compliance method used by Prime et al. the layer removal method is based on removing material from a sample and measuring the resulting strain or distortion.

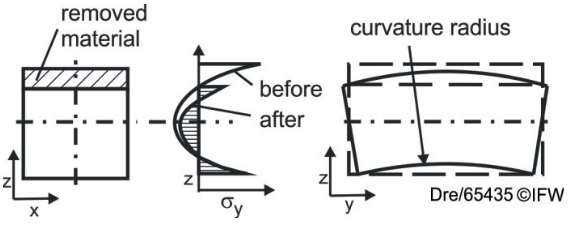

Fig. 1. Layer removal theory.

Figure 1 shows the principle of the method using the example of a beam. Removing a layer of material from a sample also removes residual stress contained therein. In order to achieve an equilibrium the sample is distorted. These distortion corresponds to the Euler–Bernoulli beam theory. Based on the assumption of constant stress σ_y in direction of the y-axis the sample is evenly curved. With the current height h of the sample and the measured curvature radius ρ one can calculate the strain ε at the surface:

$$\varepsilon = \frac{h}{-2 \cdot \rho} \tag{1}$$

The bending moment which leads to this strain can be calculated based on the moment of inertia I and Young's modulus E:

$$M_b = \frac{2 \cdot \varepsilon \cdot I \cdot E}{h} \tag{2}$$

With the area cross-section A and the leverage to the neutral fiber k the bending moment leads to the corresponding stress in the removed layer:

$$\sigma = \frac{M_b}{A \cdot k} = \frac{2 \cdot \varepsilon \cdot I \cdot E}{h \cdot A \cdot k} \tag{3}$$

The removal of a layer has an influence on all successive measurements. This is caused by the shrinking moment of inertia during the measurement. Therefore, the determination of residual stress by removal of multiple layers must be done with the inverse solution of the following equation system [5]:

$$\mathbf{G} \cdot \boldsymbol{\sigma} = \boldsymbol{\varepsilon} \tag{4}$$

The calculation of four successively removed layers results in the following matrix:

$$\begin{bmatrix} G_{11} & & & \\ G_{21} & G_{22} & & \\ G_{31} & G_{32} & G_{33} & \\ G_{41} & G_{42} & G_{43} & G_{44} \end{bmatrix} \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \end{bmatrix} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix} \tag{5}$$

The kernel function G_{ij} for the present case is:

$$G_{ij} = \frac{h_i \cdot A_j \cdot k_{ij}}{2 \cdot I_i \cdot E} \tag{6}$$

The residual stresses σ_i for the corresponding layers can be calculated by solving the equation system (eq. 5).

4. Experimental methodology

4.1. Material

The experiments were done with standardized high strength aluminum material of the type EN AW-7075 in the state T651 (solution annealed, controlled stretched and artificially aged) from the manufacturer ALMET GmbH. The material was delivered as sawed plates of the size 720 x 250 mm and a thickness of 50 mm. The actual extraction position of these parts from the initial plates is unknown. The samples were 250 mm long and 30 mm wide with a height corresponding to the plate thickness of 50 mm. All were extracted from one plate next to each other. Samples 1 to 4 were extracted in rolling direction of the plates and samples 5 to 8 transversal to this.

4.2. Machine tool and machine probe

The machine tool used for the experiments is a DMG DMU 125 P with five axes and the numerical control Siemens 840D. The linear encoders for the linear axis have a resolution of 0.010 µm. The machine is equipped with the touch probe TS 640 from Heidenhain. According to the manufacturer the probe repeatability at 2σ is below 1 µm. In preliminary tests, the standard deviation for repeatedly probing the same point at a speed of 2 mm/min in positive x-direction of the machine tool was determined to 0.16 µm.

4.3. Milling process

To remove layers from the samples a flank milling process was used. The utilized tool was an end mill with three teeth, a flute length of 40 mm and a diameter of 25 mm (Garant 206260 20/4.0). A spindle speed of 20.000 rpm and a feed of 1000 mm/min was used. Preliminary this process was analyzed for process induced residual stress by an X-ray-diffractometry measurement. It induces tensile residual stresses of 95 MPa in feed direction and transverse to this into the surface up to a depth of 9 µm. The probe deformation caused by these stresses was determined by an FEM simulation [3]. At the beginning of the measurements the outermost point of the beam is deflected by 0.09 µm. Because of the reduced stiffness this value increases to 1.4 µm at the end of the measurement. These values are below 3% of the measured displacements from layer to layer. As the residual stress is induced into every layer, no influence on the actual characteristics of the measured initial residual stress distribution can be observed. However, it has an impact on the value calculated for the first layer. As of this residual stress, induced while removing the layers, applies a constant offset to the residual stress curve.

4.4. Experimental setup

As described in chapter 3 the proposed method is based on removing layers from one side of a beam and calculating the residual stress contained in the layers using the Euler–Bernoulli beam theory and an inverse solution. The simplified experimental setup is shown in figure 2. The material sample is clamped in a cantilevered manner. For every analyzing step one layer of material is removed from the top side of the beam with the described flank milling process (step 1 in fig. 2). The milling starts at the loose end of the beam. In the performed experiments the layer thickness was 1 mm. Subsequently the machine tool performs an automatic tool change to prepare the machine probe. With the touch probe the machine measures the z-position of 20 equidistant points at the bottom side of the beam (step 2 in fig. 2). Like the milling process the measurement starts at the loose end. To achieve the maximum possible accuracy a slow probing speed of 2 mm/min is used. In the experiments the outermost measurement point of the beam changed by 3 to 5 µm from the first to the second layer and by 30 to 50 µm from the 34th to the 35th layer in measurement direction. This change in sensitivity results from the stiffness reduction during the experiments. For later evaluation the measured point data gets written to a protocol file by the machine control unit. For the removal of the followed up layer the milling path is adjusted according to the point measurements. This guarantees a constant beam thickness over the entire measurement. With the used machine tool removal and measurement of one layer lasted 155 sec. (milling: 20 sec., measuring: 50 sec., tool change: 120 sec.). Layers are removed up to a remaining material thickness of 15 mm. For the given sample further removal of layers results in an unstable milling process.

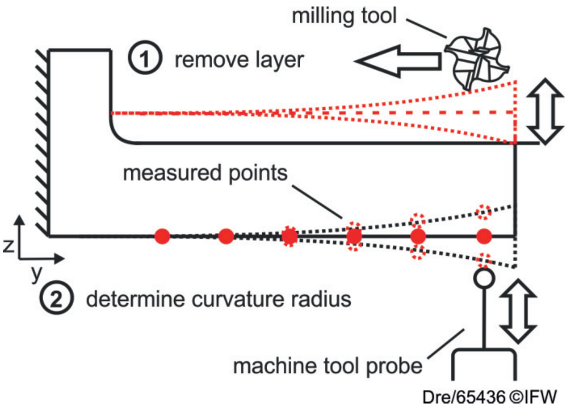

Fig. 2. Experimental setup

4.5. Calculation of residual stress from measured data

The calculation method described in chapter 3 depends on the curvature radius of the beam. The algebraic circle fit algorithm by Taubin is used to determine these curvature radii from the measured point data [7]. Creation of the system of equations (eq. 5) and solving of the inverse problem is done in MATLAB.

5. Results and Discussion

5.1. Residual stresses in EN AW-7075 T651

Based on measurements of four samples the residual stress in rolling direction for EN AW 7075 T651 is shown in figure 3. To characterize the residual stress throughout the entire plate thickness at samples 1 and 2 the material was removed from the top of the plate material and at samples 3 and 4 from the opposite side. The results from sample 1 and 2 show good correlation. This also applies to samples 3 and 4. In the overlapping area from 20 to 30 mm all four samples show similar calculated residual stresses. The calculated residual stresses extend over a range of -10 MPa to 14 MPa. Two local maxima can be clearly recognized at 20 and 30 mm. Local minima exist at 10 and 40 mm and in the center of the plate at 25 mm.

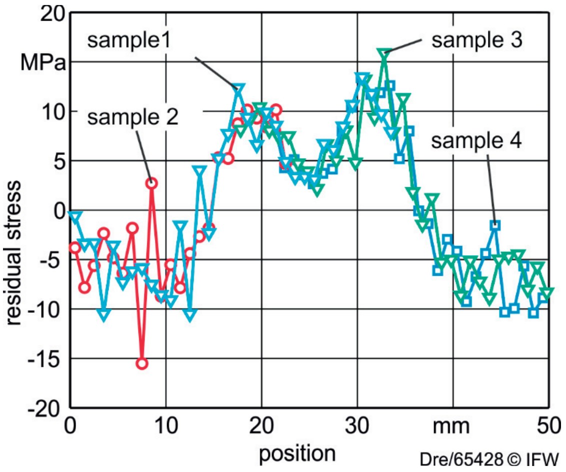

Fig. 3. Residual stress in rolling direction for EN AW-7075 T651

It is noticeable that in the marginal area from 0 to 15 mm and from 35 to 50 mm stronger fluctuations of the calculated residual stress values can be observed. This is due to the measurement principle. At the beginning of each measurement the stiffness of the beam is relatively high compared to the bending moment of the layer which gets removed. Thus, the change in shape of the beam is small. Because of the small strain the susceptibility to measurement errors is high at the beginning. As the measurement progresses the stiffness is reduced which leads to smaller fluctuations.

Due to the calculation method the observed measurement errors influence the layer where the error occurs and the following one as well. A measurement error at one probing position leads to an error in the determined curvature radius. The error affects the strain and thus the calculated stress in the current layer. If the next layer is without error the difference in strain between both is relatively high. The error is reflected in the opposite direction. This overshooting characteristic results in the observed peaks in one direction followed by a peak in the opposite one. Such a behavior can be observed in figure 3 from 8 mm to 9 mm at the determined residual stress from sample 2.

Figure 4 shows the residual stress transversal to the rolling direction for the tested material. For the measurement in rolling direction four samples were used. Samples 5 and 6 were measured from the upper side and 7 and 8 from the bottom. The repetitive measurements agree as with the previous measurements. In the overlapping area all calculated measurements are in-line. Two local minima at 10 and 40 mm with values of -8 MPa can be observed. In contrast to the measurement in rolling direction the middle area of the material shows a plateau with tensile stresses at 5 MPa. Measurement peaks can be observed especially at sample 7.

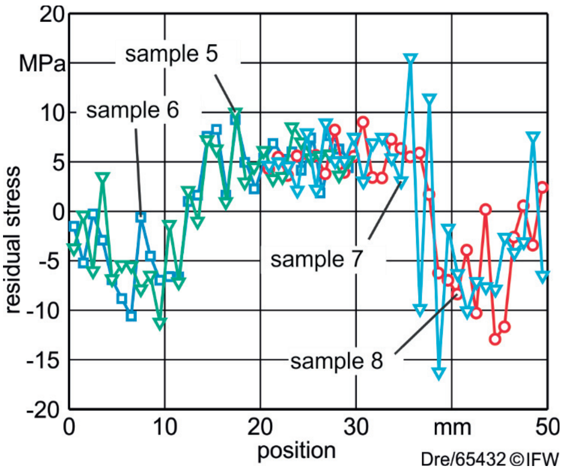

Fig. 4. Residual stress transverse to rolling direction for EN AW-7075 T651

5.2. Comparison to literature

The material EN AW-7075 T651 analyzed in this paper can be compared to EN AW-7050 T7451 examined by Prime [6]. Figure 5 shows his results for rolled plate material with a thickness of 80 mm.

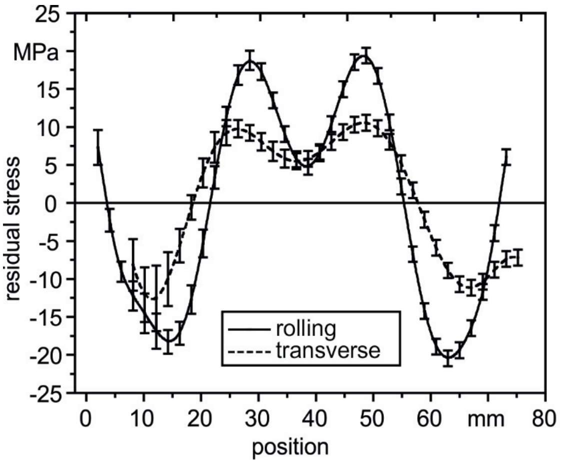

Fig. 5. Residual stress in EN AW-7050 T7451 [6]

The residual stress in rolling direction shows local minima at 15, 38 and 62 mm and two local maxima at 30 and 50 mm. This characteristic can be also observed in the residual stress curve of the material analyzed in this paper (fig. 3). According to figure 5 the residual stress in 7050 is in the range of -20 to 20 MPa and therefore higher as in 7075. This is in line with findings from Prime who detected lower residual stresses in plates with a thickness of 25 mm than in plates with 80 mm [6]. As the plates analyzed in the context of this work have a thickness of 50 mm the results are reasonable.

The residual stresses transversal to rolling direction in 7050 show similar characteristic to the ones in rolling direction. The minima and maxima exist at nearly the same positions but the absolute stress values are only in the range of -10 MPa to 10 MPa. In comparison to these results the measurements from 7075 reveal a different characteristic. A local minimum at the middle of the plate cannot be clearly recognized. This can be attributed to the lower absolute residual stresses.

6. Conclusion

This paper describes a novel method to determine the residual stress state in large solid parts like rolled plate material based on the layer removal theory. It is based on the crack compliance method described by Prime. In contrast to this, it detects the strain not by strain gauges but with the tactile probe of a machine tool. Due to this is limited by the linear encoders of the machine tool and the accuracy of the probe, where the crack compliance method is limited by the resolution of the used strain gauges. Another difference is the location at which the residual stress gets determined. Where the crack compliance method calculates the residual stress in the material that is removed in a small crack, the layer removal method considers the material removed in a large layer. It must be assumed that the residual stress is constant within the layer. The layer removal method is only suitable for material that is relatively long in comparison to its thickness.

In addition to this disadvantage the method described in this paper has the following advantages:

- It does not require strain gauges
- No special preparation of the samples like gluing of gauges
- Measurements can be carried out on common machine tools with probing devices
- The automated measurement can be performed by untrained staff

Thus, the measurements can be performed with existing equipment and staff without additional investment costs. This enables producers and manufacturing companies to implement a quality inspection of plate materials for only a small expense. By using advanced simulation techniques it is even possible to optimize the part placement in the plate material to minimize distortions and therefor reduce scrape production [3].

Acknowledgements

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