Prediction of residual-stress depth profiles in turning of EN AW-2017 based on in-process measurements of machining forces and temperatures

T Mehner*,1, T Junge2, A Schubert2 and T Lampke1

1 Materials and Surface Engineering Group, Institute of Materials Science and Engineering, Chemnitz University of Technology, 09107 Chemnitz, Germany
2 Professorship Micromanufacturing Technology, Chemnitz University of Technology, 09107 Chemnitz, Germany

*e-mail: thomas.mehner@mb.tu-chemnitz.de

Abstract. The surface integrity of parts is strongly impacted by the surface-layer properties, which are modified by machining processes. In particular, it is advantageous if the finish machining process generates a resilient residual-stress state without additional post-treatment. Thus, this paper describes relationships between the forces and temperature which are measured in-situ/during the process and the residual-stress profile for the turning of the aluminum alloy EN AW-2017. The residual-stress depth profiles are measured by X-ray diffraction after electrochemical removal of material by means of jet-electrochemical machining. The characteristic features of the residual-stress profile (value and depth under the surface of the local minimum of the residual stress) are determined and modeled using multiple regression. The predictions of the models are validated by test samples. An excellent agreement between experiments and the model is achieved. Thus, the models can be applied to predict the expected residual-stress profiles during the machining process, which allows for an in-process adjustment of the machining parameters in order to generate an advantageous residual-stress state.

1. Introduction
Machining of parts affects the surface-layer properties. In particular, the residual stresses are impacted by the mechanical and thermal loads during machining. As a result, a characteristic residual-stress state occurs, which strongly influences the stress-corrosion cracking and fatigue behaviors, as well as the overall surface integrity. Thus, in addition to the generation of the final geometry, the finish machining process (e.g. turning) can be applied to tailor the residual-stress state, which could improve these very important properties. In general, compressive residual stresses are considered to be beneficial. While the residual-stress state at the surface is important, the residual-stress depth profile has to be considered as well. Crack growth can be initiated below the surface in regions with sufficiently high tensile residual stresses. However, the residual-stress profiles caused by machining processes were rarely considered and mostly investigated for steels. Only a small number of studies deal with other materials like titanium or aluminum. For the modeling of these profiles, different modeling approaches were used.

Jacobus et al. [1] developed a numerical model for the prediction of residual-stress profiles. The model includes thermomechanical coupling, plastic and frictional heating, convection, conduction, thermal softening and strain hardening. In turning processes of the steel AISI 4340 (1.6563), the model was calibrated and tested. In spite of the limited set of machining parameters (two feeds and two depths
of cut) used and the temperature measured optically in 5 mm circumferential distance behind the turning tool, a good agreement between the model and validation tests is achieved. Hua et al. [2] studied hard turning of the steel AISI 52100 particularly in regards to residual-stress profiles. They implemented a hardness-based flow-stress model into an elastic-viscoplastic finite-element model. The numerical investigation of different cutting-tool geometries allowed for a prediction of the residual-stress profiles, which were validated by face-turning experiments. Based on the good agreement between the experiments and the model, the conclusion was drawn that a high hardness of the material, a large hone radius as well as high feed rates cause higher compressive residual stresses at greater depths under the surface. The authors recommend that a low feed rate and high workpiece hardness should be used in order to keep both cutting-edge temperature and cutting force low and obtain higher compressive residual stress at the same time. Zhang et al. [3] modeled the residual-stress profile of a finish hard-turning process of AISI 1053 and AISI 1070 steels using neural networks and a regression model. The researchers included the type of cooling method, tool parameters like material, geometry, and edge preparation, as well as tool flank wear and cutting parameters. The model that is based on a neural network agreed well with the experimentally measured residual-stress profiles. Guo and Anurag [4] performed a finite-element modeling of the residual-stress profiles in hard turning of AISI 52100 steel. A coupled thermal-mechanical model without explicit chip formation was used to simulate the machining temperature and the material deformation for the prediction of the residual-stress profiles, and it was found that the plowed depth is the most important factor that causes the characteristic residual-stress profiles for the hard-turning process. Ordás et al. [5] investigated residual-stress profiles after hard turning of AISI D2 steel with tools of different wear states. They found sub-surface compressive residual stresses whose magnitudes are significantly lower, and depth is much shallower when worn tools were used instead of new ones. Thus, a strong impact of the tool wear state (i.e. the contact conditions during machining as well) is expected. Hence, the contact conditions have to be considered if residual-stress profiles are to be predicted.

Residual-stress profiles of turned titanium have been investigated as well. For example, for the orthogonal turning of Ti-6Al-4V, Pan et al. [6] successfully predicted the residual-stress profile with good agreement using an analytical model. In the model, grain-size evolution and dynamic recrystallization are included.

For aluminum alloys, processes like milling, shot peening, and grinding have been investigated with a focus on residual-stress profiles [7–10], but no such investigations could be found for the turning of aluminum alloys. In this paper, the residual-stress depth profiles of samples machined by turning with different parameters are determined, and their characteristic features (value and depth of the minimum of the residual-stress profile) are predicted. For the first time, the prediction is based on a multiple regression model that uses the in-process temperature and forces as input values instead of machining parameters. Thus, the effects of tool wear do not need to be considered separately.

2. Experimental and materials
The material EN AW-2017 T4511 (extruded rods, supplier BIKAR-ALUMINIUM GmbH, Germany) was machined by turning on a precision lathe of the type PD 32 (Spinner AG, Switzerland). The rotationally symmetric specimens had a total length of 80 mm and were stepped. For a length of 60 mm, the diameter was 37 mm, and the remainder had the diameter of 25 mm. The shorter side was utilized for clamping using a dead-length collet chuck. In the finish machining experiments, uncoated cemented-carbide indexable inserts were used. The tools of the type CCGT 09T304-AZ (Mitsubishi Materials, Japan) were characterized by a tool-included angle of 80°, a clearance angle of 7°, and a rake angle of 26° near the cutting edge. In combination with the tool holder used, the nominal tool cutting-edge angle was 95°. During pre-machining, the feed (0.1 mm), the depth of cut (0.5 mm), and the cutting speed (150 m/min) were kept constant on a machining length of 50 mm while keeping a cylindrical section of 10 mm as the cold junction for the electrical brush contact for the in-process measurement of the temperature. After pre-machining, the specimens had a diameter of 31 mm. In the finish machining experiments, two different depths of cut (αp/mm = 0.4, 1.2) and five different feeds (f/mm = 0.04, 0.08,
0.12, 0.16, 0.20) at a constant cutting speed of 300 m/min were used. In addition, samples with three different cutting speeds ($v_c$/m m$^{-3}$ = 175, 425, 550) were machined with $f = 0.12$ mm and $a_p = 0.4$ mm. In total, 16 different tools were used for the machining of three samples per each set of parameters. One of these three samples was then selected for further investigations. The forces (cutting force $F_c$, passive force $F_p$, feed force $F_f$) were measured during machining by a three-axis dynamometer type 9257A (Kistler Group, Switzerland), which was connected to a charge amplifier type 5070A (Kistler Group, Switzerland). The in-process temperature was determined using a tool–workpiece thermocouple. The rotating workpiece was brought into electrical contact with a copper-graphite brush at the cold end of the workpiece (= cold junction). The thermoelectric voltage between the cold junction and the machining area (= hot junction) was recorded by a digital multimeter DAQ6510 with an integrated multiplexer card type 7700 (Tektronix, USA). The Seebeck coefficients of the workpiece and the tool were used to determine the temperature. Additional details are described by the authors in [11, 12]. Residual stresses were measured by X-ray diffraction (XRD) using a D8 Discover (Bruker, USA) with Co Ka radiation (point focus, irradiated area of approximately 0.7 mm in diameter) by application of the sin$^2$Ψ method. The {311} peaks of Al (elastic constants of the {311} lattice planes: Young’s modulus $E^{(311)} = 69$ GPa, Poisson’s ratio $ν^{(311)} = 0.35$ [13]) were measured along three rotation directions (0°, 45°, 90°) each in the positive and negative tilt direction using nine tilt angles ψ that are equally spaced on the sin$^2$Ψ axis from 0.0 to 0.8. In order to measure the depth profiles of the residual stresses, the material was removed in steps by electrochemical machining (ECM) using an electrolyte jet (NaNO$_3$, working gap 300 µm, voltage 56 V, 100 µm inner diameter of the nozzle, nozzle velocity 250–800 µm/s depending on the intended removal depth) on an area of about 5 mm × 5 mm [14, 15]. This process was chosen as it does not cause heating or mechanical deformation, and the removal of material by ECM mainly influences the residual stress in the normal direction, which cannot be measured by XRD in the used configuration. Thus, only a minor impact on the measured residual-stress profiles is expected. The intended removal steps were 10 µm, 25 µm, 45 µm, 70 µm, and 100 µm. The depths were measured by a stylus instrument T 4000 (Hommelwerke GmbH, Germany). The residual stresses were determined at the same position after each removal step. The residual-stress profiles $σ(x)$ were fitted using a sinusoidal decay function based on [16]:

$$σ(x) = C \cdot \exp(-A \cdot ω_0 \cdot x) \cdot \cos(ω_d \cdot x + φ) + σ_0$$

(1)

with

$$ω_0 = \frac{ω_d}{\sqrt{1 - A^2}}.$$

(2)

$C$ is the amplitude, $A$ the damping coefficient, $ω_0$ the undamped frequency, $ω_d$ the damped frequency, $φ$ the phase angle, and $σ_0$ a residual-stress offset. $σ_0$ serves the purpose of improving the quality of the fit, but it is usually fixed at zero. The absolute value of the depth under surface is denoted with $x$. Based on these fits, the depth and value of the residual stress at the minimum of the residual-stress profile were determined.

Correlations between the forces, the temperature, the depth below the surface, and the value of the local minimum of the residual stresses were determined by multiple regression using the analysis of variance (ANOVA) with a square model that includes interactions between the parameters. The parameters (i.e., $F_c$, $F_p$, $F_f$, and $T$) were normalized in order to limit their values to the interval [-1, 1]. The modeling was done on ten samples (hereafter called “calibration samples”) that were machined with constant $v_c$. The models were tested on four “test samples”, which were machined using different $v_c$ (table 1 in section 3). The model equations are independent of the machining parameters. This serves the purpose of validating it for varying cutting speeds.
3. Results and discussion

The forces and temperature that were measured in process during machining are summarized in table 1. 

\( N \) is the number of machining experiments which had been conducted with the same tool previous to the machining of the sample. Various different parameters have been used for these previous machining processes.

Table 1. Results of the in-process measurements of the forces and temperature during machining with different process parameters. The samples labeled as “test samples” will be used for the verification of the multiple regression model.

| \( f \) (mm) | \( a_p \) (mm) | \( v_c \) (m/min) | \( N \) | \( F_c \) (N) | \( F_p \) (N) | \( F_l \) (N) | \( T \) (K) |
|-------------|-------------|-------------|------|-----------|-----------|-----------|-------|
| Calibration samples |
| 0.04        | 0.4         | 300         | 6    | 20.6      | 5.1       | 8.7       | 386.7 |
| 0.08        | 0.4         | 300         | 6    | 39.9      | 7.0       | 13.5      | 390.1 |
| 0.12        | 0.4         | 300         | 6    | 46.9      | 4.7       | 9.0       | 388.6 |
| 0.16        | 0.4         | 300         | 6    | 53.7      | 7.6       | 7.5       | 456.6 |
| 0.20        | 0.4         | 300         | 6    | 68.0      | 8.5       | 9.3       | 407.0 |
| 0.04        | 1.2         | 300         | 5    | 55.5      | 10.3      | 25.0      | 415.3 |
| 0.08        | 1.2         | 300         | 2    | 94.8      | 18.3      | 36.4      | 454.7 |
| 0.12        | 1.2         | 300         | 2    | 130.4     | 20.7      | 36.4      | 455.8 |
| 0.16        | 1.2         | 300         | 4    | 163.2     | 26.1      | 43.6      | 477.2 |
| 0.20        | 1.2         | 300         | 4    | 196.1     | 29.6      | 42.2      | 430.0 |
| Test samples |
| 0.12        | 0.4         | 175         | 0    | 46.4      | 8.1       | 10.7      | 384.0 |
| 0.12        | 0.4         | 300         | 0    | 45.7      | 6.2       | 8.97      | 425.1 |
| 0.12        | 0.4         | 425         | 0    | 42.2      | 4.5       | 6.5       | 452.1 |
| 0.12        | 0.4         | 550         | 0    | 44.7      | 4.1       | 6.7       | 479.7 |

The temperature actually reached and the required forces depend strongly on the contact conditions between the tool and the specimen, which are influenced by built-up edge formation and tool wear. For various tools, cutting-edge breakage occurred, which strongly affected the contact conditions [12]. Thus, the regression model will be applied using the forces and the temperature instead of the machining parameters. In addition, the forces and the temperature are the more relevant parameters as they affect the development of the residual stresses. Outside of some deviations that are caused by the different tool contact conditions due to built-up edge formation and tool wear, the forces rise with increasing feed and depth of cut. The cutting speed influences the forces only slightly, but the temperature is severely impacted. The slight reduction of the forces is caused by the increased temperature that improves the machinability of aluminum (e.g. decreased flow stress with rising temperature).

A typical profile of the area of ECM material removal is shown in figure 1. While not even in their entire, the middle portions of the profiles, in which the XRD measurements were done, were sufficiently even for all samples.
Figure 1. Typical profile after ECM material removal measured along the axial direction. In the center of the area, the residual stresses were measured. This part was flat for all the samples and removal steps. The profile that is shown corresponds to the second removal step with a depth in the center of -22 µm relative to the surface.

The fitting function (equation (2)) describes the course of all residual-stress profiles well. At the surface, tensile residual stresses can be measured for all samples except for low feeds (0.04 mm and 0.08 mm) in the axial direction. At the first removal step (around 10–15 µm), a steep decrease of the residual-stress value can be observed – compressive residual stresses are present in all samples in the axial direction. In the tangential direction, the tensile residual stress is reduced, but no compressive residual stresses are generated for most of the samples. At higher depths after its minimum, the value of the residual stress increases only slightly (typically about 10–30 MPa). The depth of the minimum in the residual-stress curve and the value of the residual stress in the axial direction are shown in figure 2.

Figure 2. Value and depth under the surface of the residual stresses in the axial direction (left) and corresponding residual-stress depth profiles (right).

In the axial direction, the residual-stress value at the minimum is almost constant for each of the depths of cut (about -24 MPa for $a_p = 0.4$ mm and -47 MPa for $a_p = 1.2$ mm). Thus, the larger depth of cut increases the compressive residual-stress value by more than 20 MPa. However, the depth of the...
minimum decreases steadily with increasing feed. It should be noted that the sample that was produced with \(a_p = 1.2\) mm and \(f = 0.16\) mm has significantly different residual stresses. This is most likely caused by a local anomalous increase of the forces during machining. The compressive residual stresses below the surface at the curve’s minimum are about 100 MPa lower than expected from the tendencies that can be observed in the other samples. As it can be seen in figure 2 (bottom right), this value is not caused by an outlier, as high compressive residual stresses were measured in three depths between 15 µm and 40 µm. The values in figure 2 (left) of this sample could be caused by a local difference at the measurement position in that particular sample. Thus, this sample is not considered in the further analysis. The results of the tangential direction are shown in figure 3.

![Figure 3. Value and depth under the surface of the residual stresses in the tangential direction (left) and corresponding residual-stress depth profiles (right).](image)

As with the axial direction, the tangential direction shows almost constant values of the residual stress (about 10 MPa for \(a_p = 0.4\) mm and -4 MPa for \(a_p = 1.2\) mm). The larger depth of cut causes the residual stress at the minimum to become smaller or even slightly compressive. The same sample described above, which was produced with \(a_p = 1.2\) mm and \(f = 0.16\) mm, deviates from these trends as it was observed for the axial direction.

For both directions, the residual stress rapidly approaches values below 10 MPa, i.e. almost free of residual stresses, for depths above 60–80 µm – despite the presence of high tensile residual stresses at the surface in the tangential direction. No clear correlations between the results in figures 2 and 3 and the feed could be identified. This is caused by the differences in the tool-wear state, which varied by machining processes. Thus, the forces and the temperature are considered in the following.

Using multiple linear regression and ANOVA, the results from the calibration samples were modeled. The normalization of the parameters as well as the relevant coefficients of the underlying equations are shown in tables 2 and 3.
Table 2. Normalization of the parameters that are used in the multiple-regression model.

| Term | Normalization                  |
|------|--------------------------------|
| $F_c$ | $(F_c - 108.36 \text{ N})/87.77 \text{ N}$ |
| $F_p$ | $(F_p - 17.18 \text{ N})/12.44 \text{ N}$ |
| $F_t$ | $(F_t - 24.85 \text{ N})/17.32 \text{ N}$ |
| $T$   | $(T - 421.69 \text{ K})/34.95 \text{ K}$ |

Table 3. Results of the multiple-regression model. The $p$-value corresponds to the error probability of the related term.

| Term | Coefficient | $p$-value |
|------|-------------|-----------|
| Axial residual stresses at the minimum |  |
| $F_c$ | -17.34 | < 0.001 |
| $F_t^2$ | 23.00 | < 0.001 |
| Constant | -54.92 |  |
| Tangential residual stress at the minimum |  |
| $T$ | 11.42 | 0.006 |
| $F_p$ | -16.57 | < 0.001 |
| $T \cdot F_c$ | 16.89 | 0.006 |
| $F_t^2$ | 9.48 | 0.012 |
| Constant | -12.81 |  |
| Depth of the minimum (axial) |  |
| $T \cdot F_c$ | 22.22 | 0.176 |
| $T \cdot F_t$ | -14.62 | 0.144 |
| $F_p \cdot F_t$ | -58.77 | 0.057 |
| $F_t^2$ | 74.55 | 0.026 |
| Constant | 7.62 |  |
| Depth of the minimum (tangential) |  |
| $F_p$ | 14.21 | < 0.001 |
| $F_p \cdot F_c$ | -14.59 | 0.003 |
| Constant | 35.07 |  |

The experimental and calculated results are compared in figures 4 and 5.
The residual-stress values at the minimum of the residual-stress profile can be fitted very well using only three (axial direction) or five (tangential direction) terms. The $R^2$ values are very high ($> 0.960$) and the error probabilities $p$ very low ($<< 0.05$). For the axial direction, only $F_c$ and $F_t$ have a significant impact on the residual stresses. When the cutting force is above 108.36 N (table 2), the residual-stress value at the minimum becomes smaller (or more compressive), whereas an increase of the feed force always increases the tensile residual stresses. In the tangential direction, $F_p$, $F_t$ and the temperature as well as its interaction with $F_c$ have an influence on the residual-stress values. As for the axial direction, an increase in the feed force causes more tensile residual stresses. Only temperatures above 421.69 K would increase the compressive residual stresses, but due to the interaction with $F_c$, the interaction term of almost all machining processes is positive. The effects of both terms combined lead to the conclusion that only high temperatures and low cutting forces would increase the compressive residual stress. This is not a typical combination of these two parameters, which leads to the conclusion that high temperatures have a negative impact on the residual stress at the minimum of the depth profile. High passive forces favor compressive residual stresses.

The model shows a very good agreement with the experimental data. When the test samples are taken into account, their deviations from the line $y = x$ are small. Thus, both model equations can be used to predict the residual stresses at the minimum of the residual-stress profile with high accuracy. The calculated depth of the minimum of the residual stresses is shown in figure 5 in comparison to the experimental values.

The depth of the minimum of the residual stresses can be calculated with the models with high accuracy. The $R^2$ in the axial direction is the lowest of the four models, but the value is still high (0.874). For this model, the depth increases with increasing feed force. There are three relevant interactions for this direction, namely the interactions between temperature and cutting force, temperature and feed force, and passive and feed forces. Thus, the resulting depth of the minimum is a complex interaction between all parameters. The $p$-values are comparably high for the temperature-related interactions ($> 0.10$), but these interactions are necessary in order to predict the depth values of the test samples. In the tangential direction, the $p$-values are very low ($<< 0.05$). Only the passive force and its interaction with the cutting force influence the depth of the minimum. High passive forces ($> 17.18$ N) in combination with low cutting forces ($< 108.36$ N) would increase this depth, but this combination cannot be realized by the parameter sets that have been investigated in this study.

Figure 4. Comparison of the measured and calculated residual-stress values at the minimum of the residual-stress profile in the axial (left, $R^2 = 0.967$) and tangential (right, $R^2 = 0.975$) directions. The modeling was done using the calibration samples only. The lines correspond to $y = x$. 
Figure 5. Comparison of the measured and calculated depths of the minimum of the residual-stress profile in the axial (left, $R^2 = 0.874$) and tangential (right, $R^2 = 0.949$) directions. The modeling was done using the calibration samples only. The lines correspond to $y = x$.

For both of the models in figure 5, the test samples show an excellent agreement. Thus, the general validity of all four models was shown by using test samples that were machined with a variation of $v_c$. No such variation was done for the calibration samples. Hence for the modeling, the approach to use $F_c$, $F_n$, $F_t$, and $T$, which were measured in process, was proven to be applicable to predict the relevant features of the residual-stress profiles in the turning of EN AW-2017.

4. Conclusions

The characteristic features of the residual-stress profiles generated by turning of the aluminum alloy EN AW-2017 were determined by XRD after stepwise removal of material through the application of jet electrochemical machining. On the surface, tensile residual stresses were present in most of the samples regardless of the machining parameters used. The residual stresses decline quickly and a typical local minimum was measured. At the minimum, mostly tensile residual stress were measured in the tangential direction, whereas compressive residual stresses were detected in the axial direction.

The multiple-regression models, which use the parameters measured in process, describe the experimental observations with excellent agreement, which is also true for the test samples. Thus, the models allow for the prediction of the aspired-to temperature and forces during the turning process in order to achieve an advantageous residual-stress profile (e.g. for improved fatigue strength). Due to the inclusion of test samples with varying cutting speed, the models were validated for a wide range of processing parameters. Hence, the approach to model the in-process temperature and forces (instead of processing parameters) has been proven to be suitable as the impacts of the tool wear on the residual-stress profile are implicitly included in these models. Time-consuming measurements of residual-stress profiles can be omitted. The models allow for an in-process control of the expected residual-stress state. Thus, despite tool wear, the turning process can be used to adjust the surface integrity robustly during machining.

Acknowledgments

The scientific work has been supported by the German Research Foundation (DFG) within the research priority program SPP 2086 (SCHU 1484/26-1, LA 1274/49-1) grant number 401805994. The authors thank the DFG for this funding and intensive technical support.

The support of Franz Pfaffendorf (ECM), Marc Pügner (XRD measurements), Claudia Albero Rojas (depth measurements), and Morgan Uland (English proofreading) are gratefully acknowledged.
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