# RESIDUAL STRESS WHEN FACE MILLING ALUMINIUM ALLOYS

**JOSEF SEDLAK, PETR OSICKA, JOSEF CHLADIL**

**ALES JAROS, ALES POLZER**

Brno, University of Technology, Faculty of Mechanical Engineering, Institute of Manufacturing Technology

Brno, Czech Republic

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**e-mail:** sedlak@fme.vutbr.cz

The contribution analyzes the causes of the residual stress in the material during face milling. It focuses on characteristics of internal tension in materials (causes of occurrence, consequences), influence of cutting conditions, machining strategy and possibilities of removal / elimination of internal tension. The experimental section of this article deals with the measurement of internal stresses during face milling of samples (comparison of the aluminium alloys of groups 5th, 6th and 7th) before and after the heat treatment using the method of drilling holes using tensometric rosettes. Part of the contribution is also devoted to the comparision of milling tool diameter influence on the machined surface of sample flatness. The article ends with a discussion that evaluates the achieved results from a practical point of view, an overall conclusion of the results achieved with the problems that arose during the measurement and the final recommendation.

**KEYWORDS**

residual stress, internal tension, face milling, aluminium alloys, hole-drilling method

## 1 INTRODUCTION

Residual stresses are primarily detected by experimental methods that allow their direct or indirect measurement. The basic division of methods for measuring internal stresses is between destructive and non-destructive methods. The principle of destructive measurement consists of releasing original residual stresses by cutting material and evaluating the response, mostly deformation. The principle of non-destructive techniques is to find the relationship between physical or crystallographic properties of the material and residual stress. According to the principle tension measurement, resp. deformation, the methods can be divided into mechanical, diffraction and methods using the physical properties of the material [Lu 1996] [Osicka 2017] [Thermomechanics of technological processes].

One of the most used methods for measuring residual stresses that has been used to determine residual stress is the drilling method, sometimes called as the method of hole. The first proposal to measure residual stresses by releasing the borehole and recording the change of its radius was given in 1934 by Josef Mathar. In 1966, Rendler and Vignis developed a systematic and repeatable procedure for the application of a boring ethod for measuring residual stresses. In the following period, the method was developed in terms of hole drilling techniques, measurement of loosening deformations and evaluation of residual stress. A very important milestone was the use of the finite element method for calculation of the calibration coefficients and evaluation of the residual stresses from the measured relaxed deformations, which made it possible, in particular, to determine the depth-dependent internal stresses as well as other methods of application, for example for inhomogeneous materials, coatings, etc. [Lu 1996] [Osicka 2017] [Thermomechanics of technological processes].

In present time the boring method is one of the most widely used residual stress measurement methods. Modern computational methods are used for evaluation and the method is developed mainly from the point of view of hole drilling techniques and deformation measurement [Lu 1996] [Osicka 2017] [Thermomechanics of technological processes].

## 2 ORIGIN OF RESIDUAL STRESSES

When assessing the impact of technological processes on the quality of the surface layer of a workpiece during its production, it is possible to take into account the type and intensity of energies involved in its implementation. It is a mechanical, thermal and chemical energy. However, the effects of metallurgical, physical and material properties must also be taken into account [Bumbalek] [Forejt 2006] [Lu 1996] [Osicka 2017] [Prikryl 1982].

**Main cause of origin of residual stress** [Bumbalek] [Forejt 2006] [Lu 1996] [Osicka 2017] [Prikryl 1982]**:**

- uneven plastic deformation in the machined surface,
- uneven heating and cooling of the material causing it to expand and shrink,
- uneven changes in structure caused by heat and mechanical forces,
- chemical processes associated with the reaction of particles penetrating into the surface layer.

Each technological operation achieves the transformation of residual stresses in its own way only in such a volume of material where it is able to cause plastic deformation and thermally affect it [Bumbalek] [Lu 1996] [Osicka 2017].

Elastic-plastic deformation in chip generation area is the origin of residual stress caused by machining. An important factor is the time of influence of cutting conditions and the rate of change of the current conditions. This is evident, for example, in the case of grinding, where the heating is very rapid and short, the heating rate and the cooling time take place under extreme conditions [Bumbalek] [Lu 1996] [Osicka 2017].

For these reasons, it is necessary to monitor and evaluate the residual stresses, for example, in the surface layer of hardened steel which will be used in the production of rolling bearings [Forejt 2006] [Lu 1996] [Osicka 2017] [Prikryl 1982].

Although the last operation has the greatest influence on the quality of the surface layer, it may, in an inappropriately chosen sequence of operations, remain in the surface layer affected by previous operations [Lu 1996].

In terms of conventional control methods, the surface layer may appear to be the same if hardness, roughness and shape deviation are measured. In this case, the residual stresses can vary in the surface layer, that holds for both direction and size [Bumbalek] [Forejt 2006] [Lu 1996] [Prikryl 1982].

A number of hypotheses have been published on the effect of residual stress on fatigue strength. Their conclusions, experience from the practice and the results of research experiments are consistent with the fact that the tensile residual stresses reduce the fatigue strength and the pressure residual stresses on the contrary increase. However, their effect is not equivalent and requires verification [Bumbalek] [Forejt 2006] [Lu 1996] [Osicka 2017] [Prikryl 1982].

In general, it is to be expected that during the operation of the component, especially at higher temperatures, residual stresses may be relaxed [Bumbalek] [Lu 1996] [Osicka 2017].

### 2.1 Method of drilling the hole

Method of drilling the hole is based on the redistribution of the strain and deformation caused by drilling the hole in the center of the strain gauge rosette. For this method rosettes with three windings with rotation 0°, 45° and 90° around the center were used, see Fig. 1 [Civin 2008] [Lu 1996] [Osicka 2017].

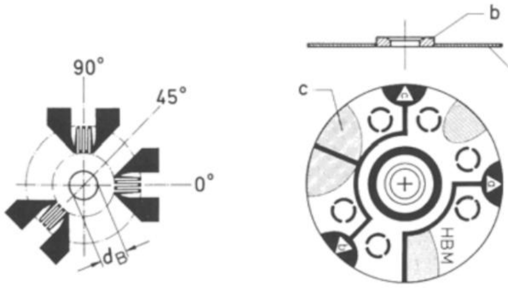



**Figure 1.** Tensometric rosette diagram for measuring biaxial strain by drilling the hole [Civin 2008] [Osicka 2017]

The hole drilling method requires drilling of a small hole with diameter 1 to 4 mm in the center of the strain gauge rosette to a depth corresponding to approximately the diameter of the bore [Civin 2008] [Lu 1996] [Osicka 2017].

Drilling is performed in steps and at the end of each step measurement of released deformations is made. This results in the distribution of residual deformations at a given location to a certain depth below the surface of the component. The obtained information is then evaluated according to various theories on the basis of determining the residual stress distribution in a given location [Civin 2008] [Lu 1996] [Osicka 2017].

### 2.2 Measuring parameters

The individual samples had an initial dimension of 100 x 50 x 20 mm. After roughing with removal of the 3 mm layer, the measured sample dimension was 100 x 50 x 17 mm and after finishing with removal of the 0.5 mm layer the final sample size was 100 x 50 x 16.5 mm. The rotor speed is between 20,000 rpm and 30,000 rpm while measuring [ASTM International 2002] [Beghini 2000] [Beghini 2010] [Osicka 2017] [Svaricek 2007].

Samples were measured by drilling to a depth of 1 mm in 0.067 mm increments. After each step, the voltamper characteristics of the individual strain gauges in the rosette are measured, from which the elongation of the individual strain gauges is obtained. On Figures, see Fig. 2, Fig. 3 and Fig. 4 there are photographs of actual measurements. On Fig. 2 and on Fig. 4 there is a boring device and on Fig. 3 there is the mill which was used for boring [ASTM International 2002] [Beghini 2000] [Beghini 2010] [Osicka 2017] [Svaricek 2007].

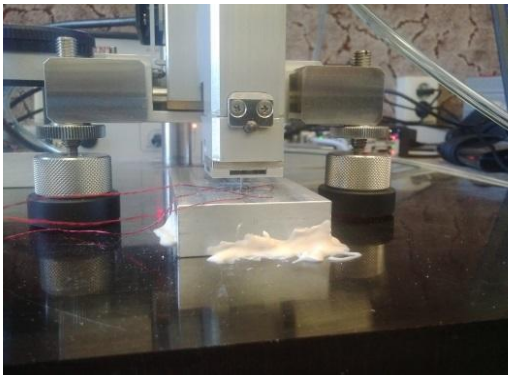


**Figure 2.** Drilling hole [Osicka 2017]

**Figure 3.** Used milling cutter [Osicka 2017]

**Figure 4.** Drilling device [Osicka 2017]

### 2.3 The procedure for measuring the residual stress

Samples must first be prepared for measurement. The surface should be stripped of coarse impurities and coatings with sandblasting followed by degreasing with petrol, toluene, acetone or ethyl acetate with cotton wool or pulp swabs. The tensometer and the molding bar are then stuck. After the glue is cured, the strain gauge contacts are welded to the contact wires from the control device [ASTM International 2002] [Beghini 2000] [Beghini 2010] [Osicka 2017] [Svaricek 2007].

The prepared sample is attached to the fixed support and the tool spindle is adjusted to the exact position of the target on the strain gauge using the optics on the boring device. After alignment of the measuring device with the spindle perpendicular to the measured sample area and input of all the necessary material parameters, everything is ready for measurement. After the measurement, the eccentricity is read at the four points of the drilled hole that the system uses to compensate for the calculation [ASTM International 2002] [Beghini 2000] [Beghini 2010] [Osicka 2017] [Svaricek 2007].

## 3 INFLUENCE OF MATERIAL AND CUTTING CONDITIONS ON FINAL INTERNAL TENSIONS

On the samples of three different aluminium alloys, which are largely used in aviation and space production, the residual stress was measured by the hole drilling method using strain gauge rosettes by HBP measuring technique, see Fig. 5 Ltd. [ASTM International 2002] [Beghini 2000] [Beghini 2010] [Osicka 2017] [Svaricek 2007]. The alloys were previously treated by roughing, annealing to remove internal tension and by finishing milling.

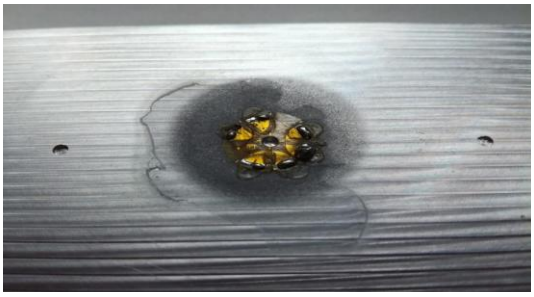


**Figure 5.** Detail of drilled tensometric rosettes with visible strain gauges

### 3.1 *Influence of material properties*

The residual stress was measured on three samples of different aluminium alloys after three technological operations. These were aluminium alloys 5083, 6082 and 7075. To calculate the residual stress in the samples, it was necessary to enter the material properties of the measuring device's software as shown in Table 1 [Dubovska 2015] [Osicka 2017].

**Table 1.** Material properties of measured samples [Osicka 2017]

| Sample | 1.1 | 1.2 | 1.3 |
|---|---|---|---|
| Material | 5083 H111 | 6082 T651 | 7075 T7351 |
| Young's modulus of elasticity E [GPa] | 70 | 70 | 71 |
| The yield strength $R_{p0,2}$ [MPa] | 100 | 240 | 434 |
| Poisson constant μ [-] | 0.33 | 0.33 | 0.33 |

To measure the residual stress of samples the hole drilling method using the 1-RY61-1.5 / 120S rosette strain gauge was used. The hole was drilled onto the SINT Technology MTS 3000 Drilling Kit using a TiAlN 1-SINTCTT / 1 cutter 1.6 mm diameter. The residual stress was measured at fifteen depths in a hole 1 mm deep [Osicka 2017].

*3.1.1 Residual stress after roughing*

The first measurement was carried out after the roughing operation, where chips with $a_p$ = 3 mm were taken. Samples were milled with a Gühring ø20 / 42 mm monolith carbide cutter, n = 120 $min^{-1}$, $v_f$ = 250 mm / min. The original sample sizes were then machined to 100 x 50 x 17 mm [Osicka 2017].

*3.1.2 Residual stress after annealing to remove residual stress*

Samples were heat treated after roughing. Annealing was used to remove internal tension. The 5083 alloy material was annealed at 380°C for 2 hours. Samples of alloy 6082 and 7075 were annealed at 160°C for 4 hours [Osicka 2017].

*3.1.3 Residual tension after finishing*

The samples were completed by face milling after measuring the stress after heat treatment. When finishing milling, a chip with a depth of $a_p$ = 1 mm was taken [Osicka 2017].

### 3.2 *Comparison of production operations*

For graphical comparison of the residual stress in the samples after individual technological operations, the measured data is inserted into the graphs for the individual measured alloys [Osicka 2017].

#### 3.2.1 Aluminum alloy 5083

The measurements in alloy 5083 in Fig. 6 show residual stress values after three test operations [Dubovska 2015] [Osicka 2017]:

- after roughing the sample, the highest tension 266 MPa was measured - (Roughing),
- after the sample has been annealed to reduce the internal tension, the maximum compressive stress has been reduced. Thus, the lowest maximum of the compared technologies was 225 MPa - (Annealing),
- after the finishing milling of the sample, the highest pressure stress was obtained from the comparative technological operations of 332 MPa - (Finishing).

Lower peaks at all measured values are caused by slipping of the material in the surface layer as a result of exceeding the yield strength during milling. Thus, plastic deformation occurred in the 0.1 mm surface layer [Dubovska 2015] [Osicka 2017].

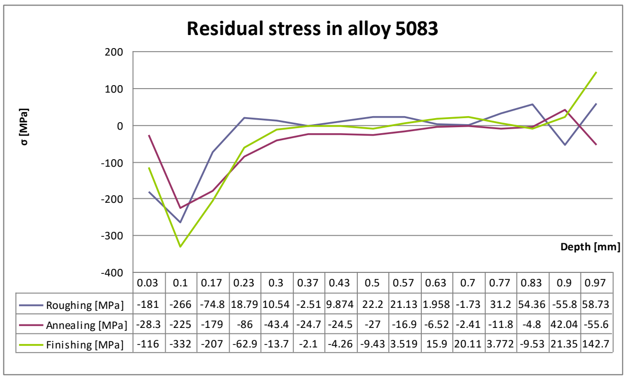



**Figure 6.** Graphical dependence of the measured residual stress on the drilling depth after three measured manufacturing operations on a sample of aluminium alloy 5083 [Osicka 2017]

*3.2.2 Aluminum alloy 6082*

The measurements in alloy 6082 in Fig. 7 show the values after the tested technological operations [Dubovska 2015] [Osicka 2017]:

- after the roughing milling of the alloy sample 6082, the maximum pressure of 200 MPa was measured. On the surface there has been a breakage in the stresses because of the "release" of the stress by exceeding the yield strength of the alloy - (Roughing),
- after annealing of the sample to reduce the internal stress, the highest tension of the used technological operations was measured. Out of an uncertain cause, in this case, plastic deformation in first measured layer did not occur. The highest measured pressure was 274 MPa - (Annealing),
- after the final milling of the sample, the highest pressure from the compared technological operations was 192 MPa - (Finishing).

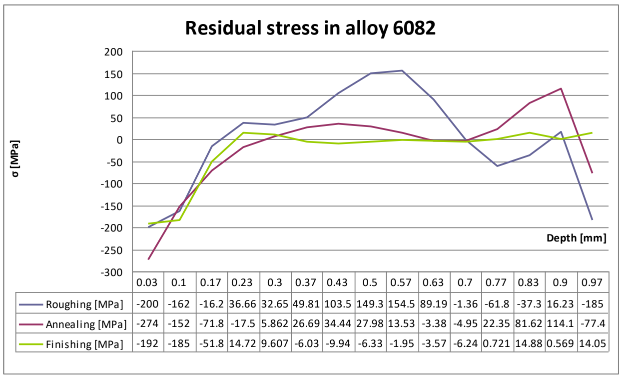



**Figure 7.** Graphical dependence of the measured residual stress on the drilling depth after three measured manufacturing operations on a sample of aluminium alloy 6082 [Osicka 2017]

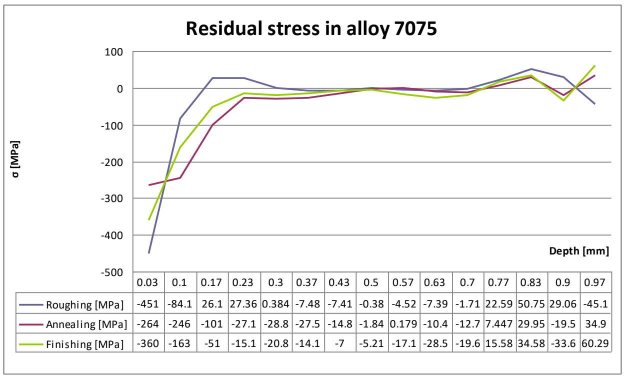
#### 3.2.3 Aluminum alloy 7075

The measurements in alloy 7075 in Fig. 8 show the values after the tested technological operations [Dubovska 2015] [Osicka 2017]:

- after the rough milling of the alloy sample 7075, the highest pressure of 451 MPa was measured. No curve fracture occurred in the area of measurement, suggesting that there was no plastic deformation from a depth of 0.033 mm, and there remained a high residual stress - (Roughing),
- after the annealing of the sample to reduce internal stress, a maximum pressure of 264 MPa was measured. At the drilling point, the plastic deformation was deeper than the other two

boreholes. The plastic strain extends to a depth of approximately 0.1 mm - (Annealing),

- after the finishing milling of the sample, the highest pressure of the compared technological operations of 192 MPa was measured. Again, the measured area shows it is clear that plastic deformation due to machining did not occur within 0.033 mm of depth - (Finishing).




| | 0.03 | 0.1 | 0.17 | 0.23 | 0.3 | 0.37 | 0.43 | 0.5 | 0.57 | 0.63 | 0.7 | 0.77 | 0.83 | 0.9 | 0.97 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Roughing [MPa] | -451 | -84.1 | 26.1 | 27.36 | 0.384 | -7.48 | -7.41 | -0.38 | -4.52 | -7.39 | -1.71 | 22.59 | 50.75 | 29.06 | -45.1 |
| Annealing [MPa] | -264 | -246 | -101 | -27.1 | -28.8 | -27.5 | -14.8 | -1.84 | 0.179 | -10.4 | -12.7 | 7.447 | 29.95 | -19.5 | 34.9 |
| Finishing [MPa] | -360 | -163 | -51 | -15.1 | -20.8 | -14.1 | -7 | -5.21 | -17.1 | -28.5 | -19.6 | 15.58 | 34.58 | -33.6 | 60.29 |

**Figure 8.** Graphical dependence of the measured residual stress on the drilling depth after three measured manufacturing operations on a sample of aluminum alloy 7075 [Osicka 2017]

### 3.2.4 Summary and comparison of manufacturing operations

These following properties are combined in these three graphical dependencies above [Osicka 2017]:

- the stress after roughing is steeper than the course of values after finishing milling. It follows that the residual stress after roughing does not extend to a lesser depth than the tension after finishing due to different cutting conditions,
- the residual stress is closing to zero for all alloys and technologies at a depth of between 0.2 to 0.3 mm.

### *3.3 The influence of cutting conditions*

To compare the influence of the cutter diameter on 5083 and 6082 alloys, flatness measurements were taken after milling a flat surface of samples measuring 133 x 103 x 15 mm. The final thickness of the sample after milling was 3 mm [Osicka 2017]. The finishing of the planar surface to be measured was done by spiral milling, see Fig. 9 and Fig. 10. Two different monolith cutters were compared on the samples, which differed by their diameter. In addition, two aluminium alloys were compared, see Table 2 [Osicka 2017].

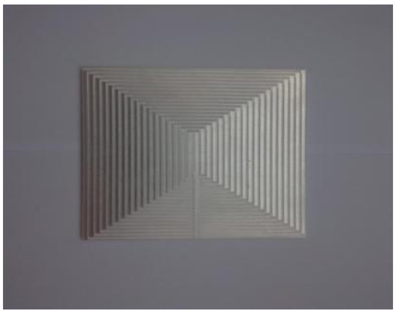


**Figure 9.** Milling by monolith cutter ø4 mm [Osicka 2017]

**Figure 10.** Milling by monolith cutter ø20 mm [Osicka 2017]

**Table 2.** Flatness measurement of machined surface of samples [Osicka 2017]

| Sample number | Dimensions | Material | Cutting conditions | Milling tool | Measured flatness |
|---|---|---|---|---|---|
| **4.1** | 133 x 103 x 15 | 5083 H111 | $a_p$ = 2 mm<br>$a_e$ = 2 mm<br>$v_c$ = 120 m/min<br>$f_z$ = 0.1 mm | Milling cutter ø4 mm JABRO TORNADO | 0.046 mm |
| **4.2** | 133 x 103 x 15 | 6082 T651 | $a_p$ = 2 mm<br>$a_e$ = 2 mm<br>$v_c$ = 120 m/min<br>$f_z$ = 0.1 mm | Milling cutter ø4 mm JABRO TORNADO | 0.199 mm |
| **4.3** | 133 x 103 x 15 | 5083 H111 | $a_p$ = 2 mm<br>$a_e$ = 10 mm<br>$v_c$ = 400 m/min<br>$f_z$ = 0.2 mm | Milling cutter ø20 mm JABRO TORNADO | 0.068 mm |
| **4.4** | 133 x 103 x 15 | 6082 T651 | $a_p$ = 2 mm<br>$a_e$ = 10 mm<br>$v_c$ = 400 m/min<br>$f_z$ = 0.2 mm | Milling cutter ø20 mm JABRO TORNADO | 0.217 mm |

## 4 DISCUSSION

As a result of the comparison of aluminium alloys, see Fig. 11, Fig. 12 and Fig. 13 in terms of residual stress after face milling, the 5083 alloy has the lowest stress value on the machined surface. From practice, as well as from flatness measurement on samples indicates that flatness is the most important for the resulting surface quality. However, it is important to take into account the high pressure value that has been measured 0.1 mm below the surface, which can cause a material defect [Osicka 2017].

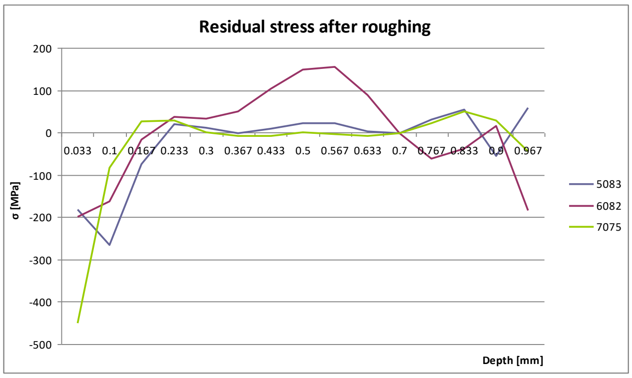



**Figure 11.** Graphical dependence of residual stress after roughing on the depth in the material [Osicka 2017]

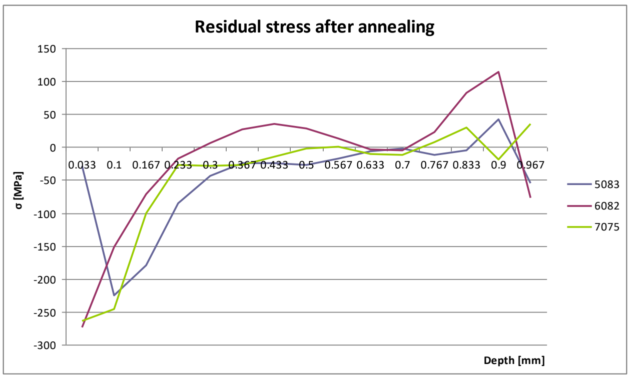



**Figure 12.** Graphical dependence of residual stress after annealing to remove internal tension on the depth in the material [Osicka 2017]

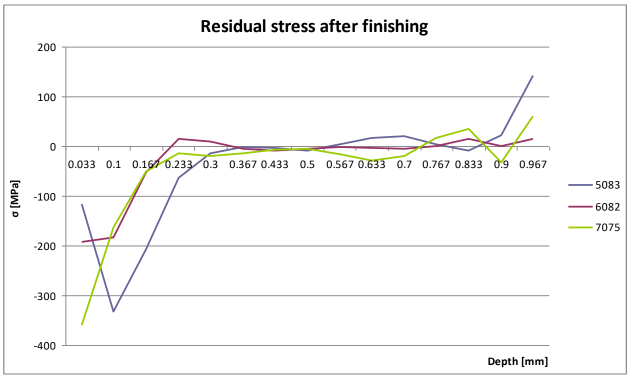



**Figure 13.** Graphical dependence of residual stress after finishing on the depth in the material [Osicka 2017]

The comparative method compared the flatness of four samples that were machined by two different cutter diameters. This parameter while machining influences residual stress and it is in practice regarded as the major factor effecting the tension. The measurement showed the predominant influence of the material on the resulting value of the residual voltage. However flatness appeared worse for samples machined by larger diameter cutter [Osicka 2017].

- a flatness of 0.046 mm was measured when machining a material sample of 5083 with a 4 mm diameter cutter,
- when machining material sample 6082 with a 4 mm diameter cutter, a flatness of 0.199 mm was measured,
- a flatness of 0.068 mm was measured when machining a material sample 5083 with a 20 mm diameter cutter,
- a flatness of 0.217 mm was measured when machining a material sample of 6082 with a 20 mm diameter cutter.

From the results above, the face milling using the larger diameter of the milling cutter results in a lower quality surface than when using the smaller diameter of the milling cutter. However, it is for consideration of how small the diameter of the milling cutters is worth, while to use in terms of surface quality, as using a smaller cutter diameter increases machining time and increases the wear of the tool [Osicka 2017].

## 5 CONCLUSIONS

The drilling method was used to measure the stress in three samples of three aluminium alloys 5083, 6082 and 7075. Individual samples of these materials were measured after roughing, subsequent annealing to remove internal stress and after finishing [Osicka 2017].

- for the aluminium alloy with the lowest yield strength of 100 MPa of the measured samples - EN AW 5083, the area of plastic strain reached a depth of up to 0.1 mm. However, the value of the residual stress below this depth was up to 332 MPa after finishing [Osicka 2017].
- for aluminium alloy with a yield strength of 200 MPa - EN AW 6082, the lowest tension of the three alloys compared was measured. The highest value was 274 MPa of pressure. However, the plastic deformation only reached a depth of 0.033 mm [Osicka 2017].
- the aluminium alloy EN AW 7075 with a yield strength of 434 MPa measured the highest tension of 451 MPa. There was almost no plastic strain in the measured area [Osicka 2017].

Measurements showed that machining was influenced by subsurface stress up to a depth of 0.3 mm of material for all samples and processes. Only the stress after roughing reached just 0.2 mm depth. By simply comparing the measured flatness, a common sign of the influence of the material is visible. The flatness of the material samples EN AW 6082 was measured approximately 4 times higher than the measured material sample values EN AW 5083 [Osicka 2017].

Finally, the influence of the cutter diameter can be compared, the flatness machined by the 20 mm diameter cutter is approximately 20 µm higher than the area machined by the 4 mm milling cutter. In conclusion, the larger the diameter of the cutter used, the worse the accuracy of the workpiece will be. If material selection is possible in the part manufacturing, the material with a lower yield strength is suitable for the resulting surface flatness quality. From the materials compared, the material of the EN AW 5083 was the best in this respect [Osicka 2017].

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**CONTACTS**

Assoc. Prof. Josef SEDLAK, Ph.D., MSc.
Assoc. Prof. Josef CHLADIL, CSc., MSc.
MSc. Ales JAROS, Ph.D.
MSc. Ales POLZER, Ph.D.

Brno University of Technology
Faculty of Mechanical Engineering
Institute of Manufacturing Technology
Department of Machining Technology
Technicka 2896/2, 616 69 Brno, Czech Republic,
tel.: +420 541 142 408, e-mail: sedlak@fme.vutbr.cz,
http://www.fme.vutbr.cz/prdetail.html?pid=16690
tel.: +420 541 142 557, e-mail: chladil@fme.vutbr.cz,
http://www.fme.vutbr.cz/prdetail.html?pid=660
tel..: +420 541 142 404, e-mail: jaros.a@fme.vutbr.cz,
http://www.fme.vutbr.cz/prdetail.html?pid=76390
tel.: +420 541 142 545, e-mail: polzer@fme.vutbr.cz,
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