Experimental methods of residual stress profile measurement

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Abstract

The contribution is dedicated to surface integrity assessment of components from the point of view of residual stress profile after machining and finishing technologies. Residual stresses play the key role for dynamic life and service reliability of the part, especially rotating aircraft airfoils made of titanium and nickel base alloys. Except a brief summary of measurement methods practical experience with application of Beam deflection method combined with electrolytic etching is published. Specific measurement results for real aircraft Ti6Al4V airfoils and Ti6Al4V plates following its manufacturing technology are the subject of experimental part.

Klíčová slova: measurement of residual stress profile; beam deflection method; electrolytic etching; airfoils, thumbling; laserpeening

1. Introduction

The properties of the surface layer have a major influence on service properties of machine parts. Assessment of surface integrity for particular application is not an easy task and requires comprehensive approach. Apart from routine dimension and roughness measurement great importance needs to be dedicated to defectoscopy methods, metallography, microhardness profile, residual stress investigation to avoid microcracks, surface burns, surface microstructural changes and also undesirable tensile stress, which significantly accelerates crack propagation and reduces fatigue properties [7]. Obtaining optimum condition in terms of roughness, dimensional stability during operation, residual stress distribution are the subject of intensive optimization of the machining process parameters and finishing technologies. Given the scope of the article only some measurements are published to highlight the differences in the state of residual stress profile in the surface after five different technologies. [4, 2, 7]

2. Residual stress

Residual stresses are internal and remain in the part even after removal of load, that caused them assuming local exceeding over yield strength [8]. In the simplest way tensile and favourable compressive residual stresses are differentiated. From the point of view of distances on which they can reach equilibrium microscopic and macroscopic residual stresses exist [10]. Intervention to macroscopic state of stress every time result in change of macroscopic dimensions. Loading of compressive layer of surface by external forces (e.g. from bending) are transmitted on the rest of the cross-section only after overcoming them. When part is operating real stress in particular point of cross section is result of superposition of operating load and residual stress [11]. In case of most types of loadings maximum tensile stress is placed in the surface layer (bending, torsion) and therefore this needs a lot of attention. Surface strengthening technologies enables to induce compressive residual stresses in the sur-face and prevent the part from exceeding ultimate tensile strength in the surface and creation of cracks. Compressive residual stress also tends to close grooves, indents and nicks that appears in service, for example creating foreign object damages on leading edges of turbine engine blades. [5, 3, 1].

The mechanisms and causes of residual stresses formation are nonuniform plastic deformation, nonuniform heating and cooling and phase transformation and absorption of elements into the surface layer [6].

3. Measurement methods

Due to the limited scope of the article only the most frequently used methods without more detailed descriptions and specifications are mentioned. The main attention is paid to the Beam deflection method (Method of electrolytic etching of layers) and its practical application and results on titanium parts measurement.

- **Magnetic methods** - Barkhausen noise – Evaluation of deformation on the hysteresis loop due to state of stress.
- **Ultrasonic method** - Residual stress measurements by ultrasonic methods are based on acoustoelastic effect. According to which the sound propagation (waves) in solids depends on the mechanical stress [9].
- **Brittle lacquers** - Method of brittle lacquers/coatings can receive the results of similar scope and quality as chemical methods. Brittle lacquer is applied on the part being investigated. Part is subsequently hole-drilled and the part tends to get into a new state of equilibrium, redistribute residual

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stresses, and deform its shape. This deformation brittle lacquer cannot resist and cracks. The size, density and direction of cracks in the lacquer serves to assess the magnitude and direction of the residual stress. [7]

- **Chemical method** – Method based on hydrogen content pick-up principle. Atomic hydrogen diffuses into the base material, wherein is recombined to form of molecular hydrogen. Molecular hydrogen is preferably placed in submicroscopic cracks in the metal. Molecular hydrogen recombination increases its volume and induces stress field. This stress is added to the residual stresses in the surface e.g. after grinding, and if it exceeds locally ultimate tensile strength, creating the cracks. The larger the residual tensile stress, the sooner cracks occur. [7]
- **Hole drilling method** - Partial relaxation of residual stresses caused by hole-drilling and subsequent deformations of the hole are measured using strain gauges (usually 3 apart of 45°). Method is able to determine principle stresses. Ring-core drilling works on exactly the same principle.
- **X-ray diffraction techniques** – In x-ray diffraction residual stress measurement, the strain in the crystal lattice is measured, and the residual stress producing the strain is calculated, assuming a linear elastic distortion of the crystal lattice. Method is non-destructive in case of surface measurement up to the penetration depth in particular combination X-Ray tube and investigated material (units of microns). To get residual stress profile it is necessary to introduce electrolytic etching a remove material and measure the sample on multiple clamping. Residual stress profile determination by this method is very time-consuming and expensive. [8, 7]
- **Neutron diffraction** - The same physical principle as a diffraction X-ray diffraction also works neutron diffraction. Neutron radiation is not limited penetration depth as much as X-ray. Penetrating power of neutrons is significantly higher, since their attenuation coefficient is about 3 orders lower than X-rays. The basic limiting condition is a disposition of equipment and neutron source. [9]
- **Beam deflection method** – Technique measures macrostresses and determines residual stress profile. Subject of separate paragraph.

4. Beam deflection method

Beam deflection method is kind of mechanical method of measurement with long tradition on Faculty of Mechanical engineering of CTU. In 2015 method and the same computational processing went through significant development. Method is based on beam deflection after layer removal. Layer removal is realized by electrolytic etching.

Force-free and heating-free slow removal of material predestined this method for reliable measurement of residual stress profiles especially at shallow depths beneath the surface. In the literature, this technique can also be found under the names: Method of sequential electrolytic dissolution, Method of cantilever beam and Layer removal method. However, the practical implementation at Department of Machining of CTU (Fig. 2) has certain specific features and is designed to measure the blade components from advanced materials for aerospace industry (titanium, nickel-base alloys, stainless steels).

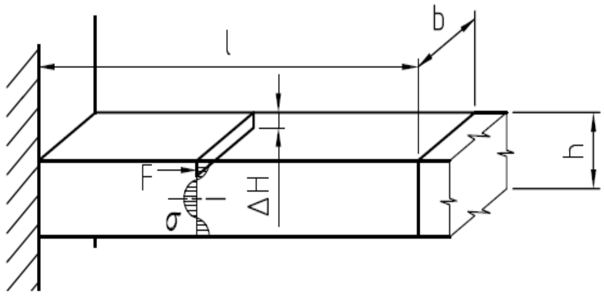

Fig. 1*. Equilibrium of residual stress across the beam*

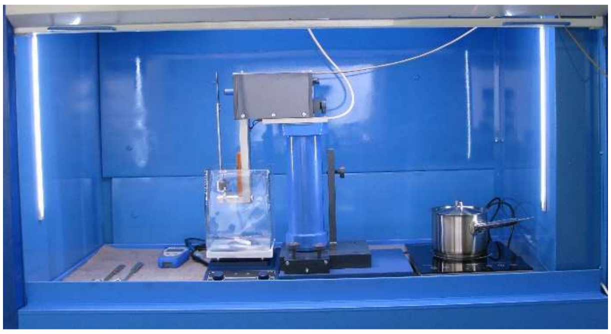

Fig. 2. *Residual stress measurement device, CTU*

Continuous measurement of beam deflection (e.g. strip, ring, coupon, or airfoil) is measured by proximity sensor with high resolution. Whole measurement cycle is performed in one clamping eliminating one of key source of error. As the deflection is continuous, the same removal of the material is continuous. Deflection is caused by breaching of static equilibrium through the electrochemical removal in certain strip or area. This forces the sample to deflect and establish in a new state of static equilibrium. Etched strip (Fig.3) is considered as restrained end of one-side cantilever beam. Removed depth is divided into layers and deformation increments are evaluated in those layers, in which residual stress is calculated. In other words in individual increment of depth ΔH is calculated such a value of stress, that would cause the same deformation in case of loading by external forces. This value of residual stress is an average on particular depth increment. Modern computational capabilities enables to calculate residual stress in such small increments, that we can assign the value of residual stress directly to depth beneath the surface. [12, 7, 6]

5. Experimental measurement

Department of Machining, Process Planning and Metrology of Czech Technical University has been involved in research of surface integrity of titanium alloys in long term. Beam deflection method is key analytical tool for study of surface after different finishing technologies and study of theirs parameters on residual stress profile. For purpose of this publication residual stress samples were manufactured in shape of coupons of 4 mm thickness. Extracts of real titanium airfoils were manufactured as well (Fig.3). Residual stress distribution was studied after following technologies:

- Sample #1: thin airfoils – 5-axis surface contouring by ball mill
- Sample #2: thin airfoils – 5-axis surface contouring by ball mill + vibrational thumbling
- Sample #3: coupons– face milling
- Sample #4: coupons - face plane milling and subsequent laserpeening
- Sample #5: coupons – cut out by wire EDM

Fig. 3. *Thin airfoil segment measured close to the root*

5.1. Sample #1: thin airfoils – 5-axis surface contouring by ball mill

Residual stress measurement was performed in close proximity of leading edge of Ti6Al4V compressor airfoils. In order not to influence investigated area compressor wheel was cut radially by WEDM. In case of mechanical sectioning there is danger of thermal influence and also mechanical damaged due to small thickness of airfoil – approx. 1 mm.

5 axis finishing surface contouring by ball mill exhibits compressive residual stress profile. In the depth of 5 microns compressive stress of -205 N.mm^{-2} was measured. Compressive stress decreases almost linearly up to depth of 0,03 mm, followed by degressive decrease and transition to balancing residual tensile stresses in 0,045 mm. Sum of area under residual stress curve through entire cross-section equals to 0. Otherwise part could not be in static equilibrium. In other word: the higher and deeper compressive layer on the surface is, the higher is tension in the middle of the cross-section to balance the sample (Fig. 1).

In case of milling of titanium three main principles needs to be taken into consideration.

- Regarding the ratio of UTS/YTS (approx. 1.1), primary sheer zone tilts to the face of the tool and do not affect surface layer so much. Connection between chip and surface layer is being interrupted with high frequency.
- Specially, in case of small depth of cuts and thin airfoils, cutting edge of the ball mill tends to not only cut but also smear the surface layer. Surface layer is plastically deformed (elongated) but subsurface elastically deformed layer holds still the same length of the surface. Therefore compressive residual stresses are induced in the surface.
- Heat generating in cutting zone is undesirable and in vast majority of examples leads to tensile residual stresses or even microstructural changes on the surface. In this particular case this phenomenon didn't predominate.

5.2. Sample #2: thin airfoil – 5-axis surface contouring by ball mill + vibrational thumbling

Due to shallow depth of compressive layer after milling technologies of surface strengthening was taken into consideration. Even there is compressive residual stress layer in particular investigated area after 5-axis milling, surface contouring of thin airfoils tends to unstable process, because tilt angle of tool always changes, wrap angle changes (specially in roots of blades, corners), cutting speed, rigidity of the system tool-workpiece isn't still the same. Consequences of these phenomenon are very often observable on wavy surface, tool fluttering and sound expression of machining.

Surface of milling was finished by vibrational thumbling technology, that uses kinetic energy of steel balls of larger diameter (2 to 4 mm) to induce compressive residual stresses. Samples or airfoils are mounted in a cover making oscillating motion and giving kinetic energy to balls.

Larger diametr and weight has positive impact on surface roughness and primarily on the depth of compressive layer. Surface residual stress in the depth of 5 microns increased to -240 N.mm^{-2}, but subsequent decrease of compressive residual stress is not so steep and the depth of transition was significantly shifted to 0,12 mm. Tensile residual stresses deeper in core of the airfoil inevitably increased (Fig. 4).

5.3. Sample #3: coupon– face milling

Face milling represents initial state of the test coupons. Face milling by carbide inserts and productive cutting conditions was used to reduce coupons thickness to required 4 mm. Residual stresses on surface are almost negligible but increases to tensile with subsurface tensile peak of 100 N.mm^{-2} at 0,05 mm under the surface. Tensile stresses decreases gradually and they are fully compensated approximately 0,16 mm beneath the surface.

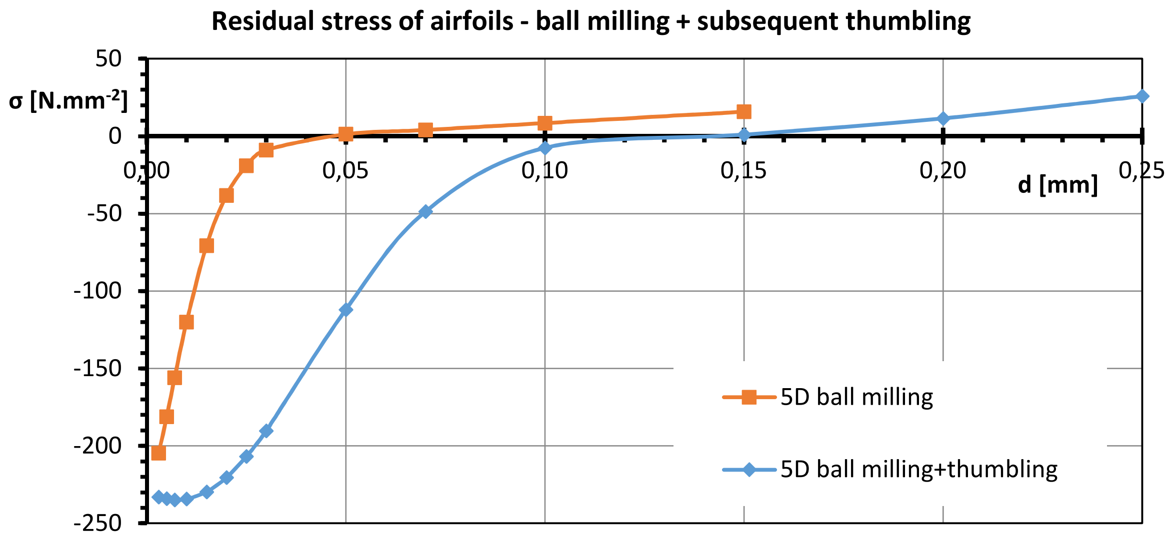

Fig. 4. Residual stress profile in Ti6Al4V airfoils

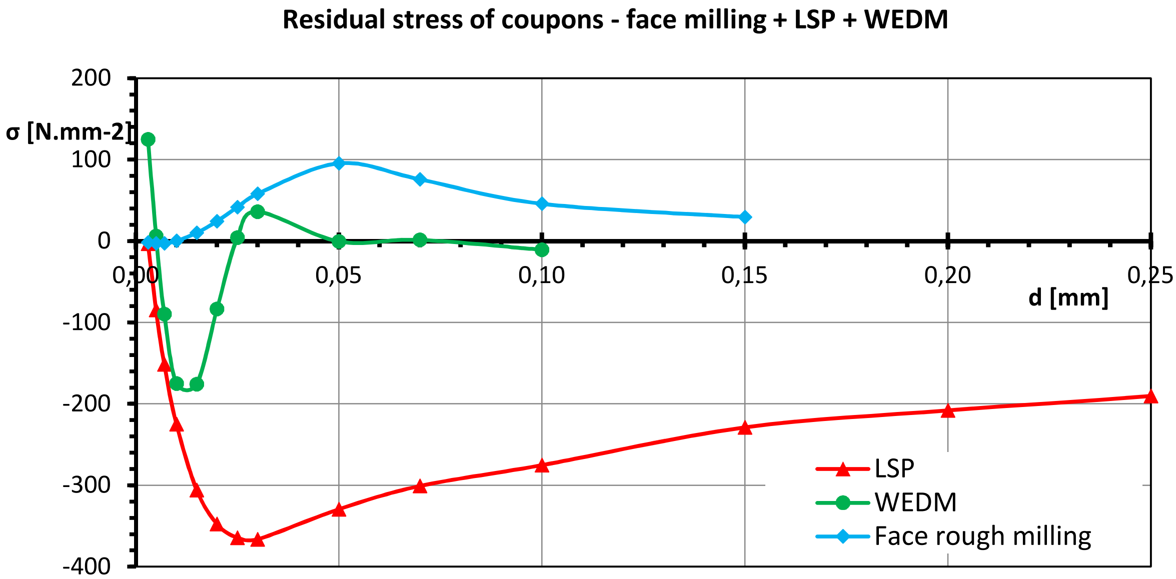

Fig. 5. Residual stress profile in Ti6Al4V coupons

5.4. Sample #4: coupon - face plane milling and subsequent laserpeening

Coupon manufactured by face milling, having residual stress profile acc. to sample #3, was subsequently laserpeened to induce compressive stress layer. Residual stress on the surface in the depth of 5 microns is -4 N.mm-2 and compressive residual stresses increases with steep slope to maximum value of -370 N.mm-2 in the depth of 0,03 mm. Exceeding this maximum residual stress curve turns back and from 0,15 mm up to the depth of transition to tensile 0,7 mm there is linear increase. Lasepeening technology provided highest residual stresses and incomparably deeper layer of compressive residual stress.

5.5. Sample #5: coupon – cut out by wire EDM

The surface manufactured by wire EDM cut exhibits tensile residual stress +130 N.mm^{-2} up to the depth of 5 microns under the surface. Beyond this depth compressive residual stresses increases with steep slope up to compression peak of -180 N.mm^{-2} in 0,15 mm followed by fast return back to tensile with transition at 0,025 mm. Second tensile peak is insignificant in the depth of 0,05 mm residual stress are balanced at 0 N.mm^{-2} with insignificant deviation in the order of unit of N.mm^{-2}, caused by external factors and measurement error.

6. Conclusion

Machining and finishing technologies has significant impact on parameters of surface layer of parts and theirs service properties. Summary of residual stress measurement techniques gives theirs principle and field of application.

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Practical experience in the application of beam deflection method in connection with electrolytic etching for measurement on different samples is mentioned.

In case of titanium alloy airfoils vibrational thumbling exhibits significant improvement in absolute value of compressive residual stress, but first of all in higher depth of the layer. Mechanism of inducing surface compressive residual stresses after 5–axis milling was discussed on the basis of general known phenomenon.

Titanium alloy coupons were measured in 3 different conditions. Face milling represent initial status before application of finishing technologies and exhibits low tensile residual stress up to the depth of than 0,1 mm. Residual stress profile of surface manufactured by wire EDM showed surface tensile stresses and subsurface compressive residual stresses. Depth of transition (10 microns) in this particular case correlates with the thickness of recast layer measured on metallographic sample. Initial annealed stress-free state is reached in 0,05 mm beneath the surface and this depth also represents a stock, that should be removed before application of strengthening technologies in case of surface preparation for experiments by wire EDM cutting.

Laserpeened sample exhibited noticeable compressive peak -370 N.mm^{-2} in the depth of 0,03 mm and incomparably deeper compressive layer with the transition to tensile balancing stresses in 0,7 mm. Such a depth isn't achievable by strengthening technologies of shotpeening and thumbling working on the principle of impact energy.

Beam deflection residual stress measurement method has been tested on different surfaces of Ti6Al4V alloy and it was considered as productive and cost efficient technique for residual macrostress profile determination.

Acknowledgement

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List of symbols

d depth (mm)
σ residual stress (N.mm^{-2})
UTS Ultimate Tensile Strength (N.mm^{-2})
YTS Yield Tensile Strength (N.mm^{-2})

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