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HOLE-DRILLING RESIDUAL STRESS METHOD PARAMETERS DETERMINATION

PARAMETRY MĚŘENÍ ODVRTÁVACÍ METODY PRO ZJIŠŤOVÁNÍ ZBYTKOVÝCH NAPĚTÍ

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The paper deals with some questions of residual stress and its determination by the hole drilling method. A more general problem of residual stress origin and measurement is considered in connection with related processes. The hole drilling method, its principles and effects that could influence the measurement are listed. Possibilities of numerical computations are presented for an experimental measurement support. Utilizing of other methods (thermography, electron microscopy, etc.) is mentioned. Experimental and numerical procedures for solving of some parameters influence are shown as examples of particular projects.

Keywords

residual stress measurement, hole-drilling method, finite element method, thermography measurement, electron microscopy

Introduction

Residual stress originates in consequence of material manufacturing and treatment processes, as well as its subsequent usage. Residual stress occurs in all technically important materials and represents one of material stage parameters together with microstructure and texture. It can beneficially or detrimentally influence material properties like toughness or fatigue and corrosion characteristics under both constant and cyclic loading. Residual stress is

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also a significant technical problem and its determination is getting important especially with new high-energy technologies development.

A number of residual stress measuring techniques exists based on different physical principles. The semi-destructive hole-drilling residual stress measurement method is one of most often used. It is very useful and direct method, however its usage is accompanied by some practical difficulties, for example material properties, drilling parameters, usability of hole drilling equipment components and others. The residual stress measurement by this method appears also as a very complex problem. Solving this could involve other analysis, like a structural, thermal or numerical computation. It requires performing many other experiments and co-work of different field specialist. It helps to understand the process of residual stress originating, measurement procedure improvement and also bring more reliable results.

Residual stress

Residual stress is defined as a stress occurring in material without acting of any external loads. It exists in materials of construction parts as well as whole assemblies and can influence their properties, depending on the stress type, magnitude and orientation.

The residual stress average value over the whole system is zero. Depending on the residual stress equalization volume it can be classified as *macroscopic (residual stress type I), microscopic (residual stress type II)* and *submicroscopic (residual stress type III)*. Macroscopic residual stress is quantitatively and directional homogeneous at volumes greater than grain size. Its changes cause macroscopic changes of a sample shape and its effect couples with an external loadings. It can be described as a stress average deviation at given place. Microscopic residual stress is related to local grain anisotropy-it equalizes at grain size volumes and submicroscopic residual stress is defined as a local deviation of microscopic residual stress. Type II and III residual stress is unable to determine by using the hole drilling method, therefore the macroscopic residual stress is only considered.

Residual stress originates as a consequence of inhomogeneous processes of material processing and using. Basics reasons can be defined as

- *Mechanical*-inhomogeneous plastic deformation due to mechanical treatment
- *Thermal*-inhomogeneous thermal field, different thermo-mechanical material properties
- *Chemical, structural*-material volume changes due to chemical reaction or phase changes
- *Others*-technologies based on thermo-mechanical non-equilibrium conditions material treatment

In some cases, the mentioned processes can act together. Residual stresses can also relax and change during material using. Also the residual stress originating during any technological operation is influenced of material history (residual stresses from previous operations, material structure, etc.) Full determination of residual stress originating process is a complicated problem [2]. However, understanding and determination of essential dependences relating to the residual stress can help to the control and optimize treatment processes.

Residual stress measurement

Residual stress measurement techniques can be divided based on their principle to *destructive* and *nondestructive* [5, 7]. The destructive ones are based on a destruction of the material and thereby relieving the original residual stress equilibrium state. A consequence of such relaxation (strain, displacement, etc.) is measured and residual stress is evaluated. Sectioning or layer removal (bending) techniques belong to these methods for example. Sometimes the material damage is not critical and can be removed or does not matter to material usage. In these cases, the method should be called *semi-destructive*. The hole-drilling method is an example. The nondestructive methods are based on material physical or crystalline properties dependence on its stress state. Diffraction, electro-magnetic or ultrasonic methods are the very frequently used techniques. Every technique has its advantages and disadvantages. Choosing the technique requires an analysis of the problem, possibilities of measurement and usability of given method.

Hole-drilling measurement method

The hole-drilling method [5, 8, 11, 12, 17] is a semi-destructive residual macro-stress measurement technique. It allows 2D dimensional residual stress determinations at surface plane at different depth.

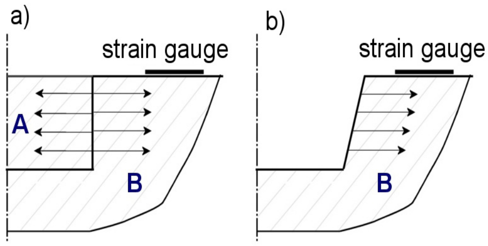


Fig.1: Principle of the hole-drilling residual stress measurement technique. a) before drilling; b) after drilling

This method is based on drilling a small hole (diameter~depth~1-4 mm) that causes the original residual stress relaxation, i.e. deformation of the material around the hole (see Fig.1). The hole is drilled by a conical shape mill. To avoid production of additional residual stresses during the drilling process, it is recommended to use high-speed drilling machine. Relieved strain is measured by strain gauge rosette mostly, other techniques are also usable, optical for example [16].

The basic equation of relieved radial strain and residual stress relationship is

$$\varepsilon_r = A(\sigma_x + \sigma_y) + B(\sigma_x - \sigma_y)\cos(2\theta) \tag{1}$$

where $\sigma_{x,y}$ is the main residual stress, θ is an angle of measured radial deformation (in polar coordinates) and A,B are calibration functions. Strain is measured at three known angles, allowing an evaluation of the main residual stresses values σ_x, σ_y and their direction. Calibration functions give relationship between the relieved strain and stress. These functions are dependent on material type, its state (isotropic, an-isotropic, etc.), hole and strain gauge rosette diameter, hole depth and depth (position) of determined strain acting. In some cases it is possible to determine these functions by help of experimental calibration. Generally, it is necessary to use numerical calibration (FEM computation) [6, 13, 14] and equation (1) has some more complex (integral) form, which can be schematically written

$$\varepsilon(h,H) = \int_0^h A(h,H) \cdot \sigma(H)\, dH \tag{2}$$

where h is actual hole depth and H is acting depth of stress $\sigma(H)$. Equations (1) or (2) are in the present form derived for homogeneous, isotropic material that behaves linear elastic during drilling of the hole.

The hole drilling method is frequently used technique for residual stress measurement of various materials. The equipment is mostly portable and measurement costs in wide range depend on drilling and strain measurement technique used. The Standard ASTM E837 [1] for the basic method concept has been adopted, however, many modifications and improvements exist [5]. Methods drawbacks are its destructive character, limited resolution and data interpretation in more complex cases.

Hole drilling method application

Specimen state

Knowledge of measured object (specimen) state knowledge is fundamental for applicability of the method and results accuracy. M*aterial properties* and *surface properties* are the main parameters. The sample should satisfy the conditions mentioned above - homogeneity, isotropy and linear plastic behavior. Elasticity modulus (*E*) and Poisson ratio (ν) values are the basic required mechanical properties. They are involved in the calibration functions. Material yield stress and surface hardness are other properties, that should be known.

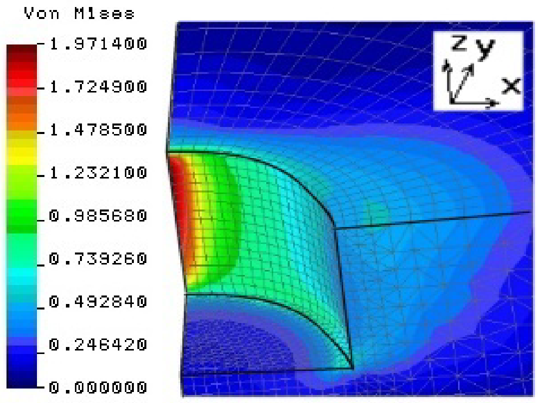


Fig.2: Relieved stress field near the hole (1/4 cut) after drilling - Von Mises stress relative to material yield stress.

The yield stress is an important property with regard to linear-elastic material behavior compliance. In some cases, when the residual stress does not reach the yield limit, plastic strain can occur near the hole (dependent on magnitude and orientation of the residual stress). This situation illustrates Fig.2. Relieved stress (strain) after hole drilling is computed using FEM analyses, for uniaxial residual stress state $\sigma_{res}=0.5\cdot\sigma_{yield}$ at *x* direction. Von Mises stress (shown in Fig.2 relative to yield stress) exceeds the yield stress in some points. That means, the plastic deformation can occur and the equation (1) and coefficients A, B should not be used.

Surface hardness is an important parameter with regard to drilling process. Drilling process possibility, parameters and drilling mill type should be decided depending on hardness and chemical composition of the material measured and drilling equipment.

Other properties of measured object could influence the measurement correctness as well. Concerning the material surface equality, applicability of strain gauges or sample dimensions for example. The method is arranged for flat surfaces, relative to the hole and strain gauge rosette dimensions. Non-planar surface shape, sample dimension changes or sample state changes can influence the calibration function and require a new calibration coefficients FEM computation [3].

Measurement

The measurement procedure consists of two basic steps:

- Surface preparation and strain gauge rosette bonding
- Hole drilling and relieved strain measurement

The measured material surface should be straighten and prepared for strain gauge bonding. Basic requirement for these operations is not to bring additional residual stresses to the material. Such procedure is not critical by flat sample surfaces [7]. If more aggressive surface treatment is necessary, it should be assumed that this operation influences the original residual stress in the material [10].

The conically shaped mill is used in the drilling hole-creation technology. The drilling procedure constitutes a fundamental step for the measurement accuracy. The hole should be drilled as close as possible to the strain gauge rosette center. Any eccentricity changes the assumptions of calibration coefficients determination and requires a *hole-eccentricity correction*.

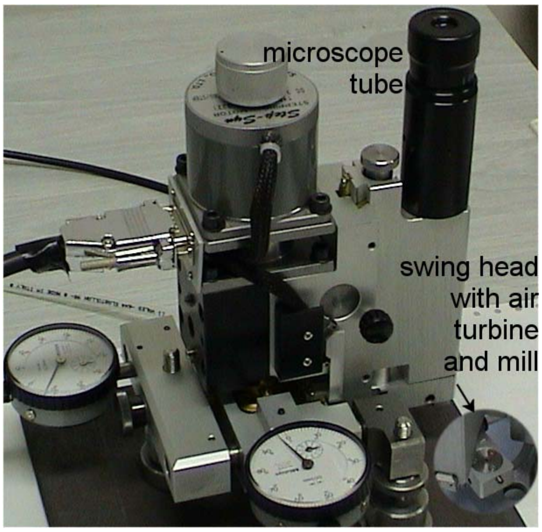


Fig.3: Residual stress measurement hole-drilling equipment SINT 3000.

The drilling procedure should not bring about additional stresses into the measured material as well. Therefore, so-called high-speed cutting (HSC) process should be utilized. HSC machining is based on a very high cutting speed and it is considered as additional residual stress free or negligible.

The available drilling equipment SINT 3000 (Fig.3) [15] allows very precise hole positioning, using the co-axial microscope - drilling mill set-up (microscope center cross in the drilling mill axis). The accuracy reached is about hundredths of millimeters.

A high-speed air powered turbine drilling machine with a rotation speed about 300 000 rpm and drilling mill radius 0.8 mm should satisfy the HSC conditions. Additionally, depending on drilled material the drilling machine drift speed has to be set according to cutting force minimization condition. If the cutting force is too high (due to the drilling conditions, sample properties or drilling mill wear) the air-powered system is unable to continue drilling process. In such case the system cannot be used.

Strong requirements are imposed to the mill at these drilling conditions. Drilling mill wear causes similar effect as the improper drift speed setting. It increases cutting force and changes drilling process conditions. These changes are accompanied by drilling process induced temperature increase. This results in decreasing of the material yield limit and higher temperature induced stresses occurrence. Both these effects can cause plastic deformation and additional residual stresses production near the hole. On the contrary, higher temperature can cause the original residual stresses thermal relaxation, if material drawing temperature is too low.

A tungsten carbide mill is usually applied for steel materials, but its wear rate is very high. Diamond mills used for hard materials cannot be used for steel, because of high carbon-iron affinity. Drilling is usually conducted in more steps, after each one the relieved strain is measured. It allows depth profile stress determination. Number of steps, i.e. depth per one step, and delay time between two steps should be a compromise between measurement time requirements, data requirements for given residual stress evaluation method and others, above all drilling induced heating of the material.

Relieved strain evaluation

Data measured evaluation represents solving of the linear equation system type (1) for a constant stress field or nonlinear integral equation system type (2) for a non-constant stress field. The solving methods are then based on discretisation (3) and numerical evaluation of the stresses at discrete points h_i.

$$\varepsilon(h,H) = \int_0^h A(h,H)\cdot\sigma(H)\,dH \Rightarrow \varepsilon_i = \sum_{j=1}^{i} A_{i,j}\sigma j \tag{3}$$

The basic method is so-called *integral method* [5, 6, 12], based on direct solving of the equation (3) by means of matrix $A_{i,j}$ inversion. Coefficients A or B compose a matrix and have to be computed (experimental calibration is quite difficult, mostly impossible) for each hole depth and acting stress position in the hole. A drawback of this method is its instability by greater number of steps and very high measurement errors sensitivity. This can be overcome by additional conditions imposing to the stress function σ(H), for example its limitation to any function type and solving of the equations by means of least square method. Such procedures are used by *power series method* [8] or *spline method* [9] for example. Other methods overcome theses problems by different simplifications (*incremental strain method, average stress method* and others), however, it restricts the real residual stress state determination possibilities.

All the methods require knowledge of the *influence function*, i.e. calibration coefficients. In general case a 3D model has to be constructed (mesh is showed in Fig.2). In some cases (homogeneous isotropic material) using a special solver allows 2D solving of axially symmetrical geometry and non-symmetrical loads. The 2D model makes possible to significantly refine the mesh (fig.4 (a)) to improve the results accuracy.

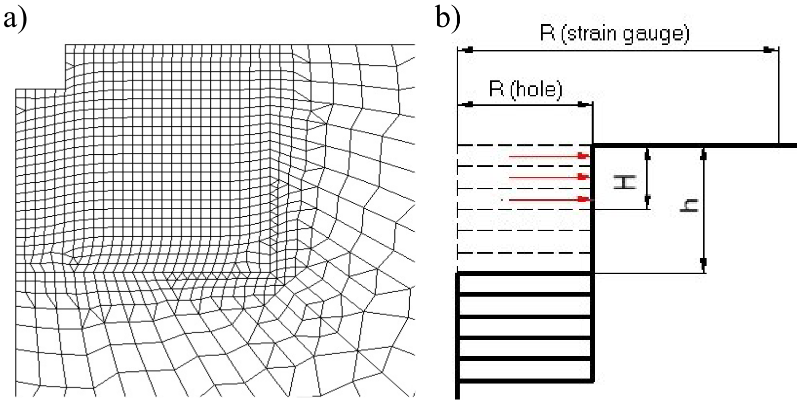


Fig.4: 2D mesh for calibration coefficients computation (a), calibration coefficients computation scheme (b).

Knowledge of calibration coefficients/functions is the basic assumption of method using. These are functions of material, hole and strain gauge rosette geometry, acting stress depth, but the measured sample geometry as well. Theoretically, for each measurement a new computation should be used. Practically, the coefficients are computed for various hole and strain gauge rosette diameters, hole depths *h* and stress acting depths *H* (by fixed depth *h*), as it is showed in fig.4 (b). The coefficients are then expressed in material independent non-dimensional form (it is proved, that only slight dependence on Poisson ratio exists [17]) and they are interpolated for similar problems group.

Direct residual stress originating estimation can play a significant role in results evaluation. Such process is a quite complicated problem, which cannot be fully solved. In some cases it can give us qualitative information of possible stress distribution or occurrence of stress peaks. It is important according to a local character of the experimental method. However, the computation is mostly considered as a rough approximation only, because of the problem complexity and material properties knowledge requirements.

Measurement analysis examples

Drilling mill influence - example 1

Heat/temperature during drilling is an important factor of hole-drilling measurement process (and machining processes generally). According to the HSC processes theory, most of the heat generated should move away by chips. However, some temperature raise is observed both in the mill and drilled material. Its magnitude can give evidence to some process features, drilling mill wear degree or improperly set drilling parameters. Moreover, it could be used for measurement errors estimation due to the thermo-mechanical (plasticity) processes.

Temperature measurement during the drilling process is performed by the thermography system Flir ThermaCAM SC 2000. Additional close-up lens 34/80 is used for enhanced resolution of small details of the mill and hole surroundings. Detailed description of

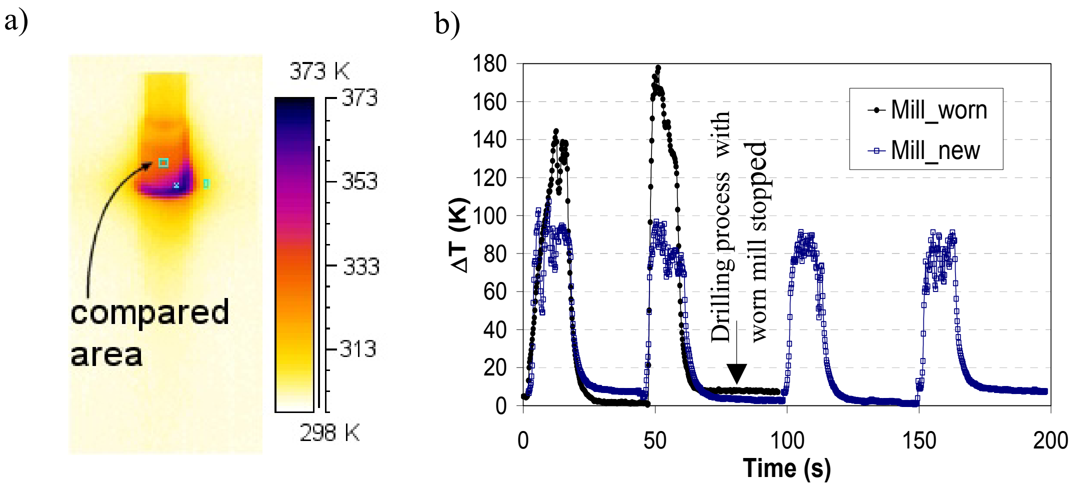


Fig.5: Drilling mill area to be compared on the recorded temperature field (a), temperature observed during drilling measured by thermography system at drilling mill - worn and new mill (steel specimen) comparison (b).

the drilling temperature measurement, measured objects (drilling mill, sample surface, strain gauge rosette) emissivity determination and data evaluation procedure can be found in [4].

Temperature is measured for different drilling procedure cases at drilling mill as a temperature average of small selected area shown in fig.5 (a) (because of measurement stability and accidental errors avoiding), approximately 1 mm from the hole-edge. Drilling procedure is carried out by shift speed of 0.1 mm/min and step-by-step system. One step is set to 0.025 mm, delay between two steps is kept long enough to measured objects cool down (delay times are not recorded in fig.5).

First, a comparison between application of a previously repeatedly used and new drilling mill is performed. A steel specimen (structural steel CSN 11 375/ISO 630-80) is used in both cases. From the results in fig.5 (b) one can see the temperature peaks (temperature difference from the working temperature) generated during drilling with a used mill are considerably higher than the peaks generated by the new mill. (Temperature rise at the mill-specimen contact is higher then the showed one in fig.5). Some mill damage thus can be assumed.

Both the further drilling process interruption due to the cutting forces increase and the drilling mill electron microscopy analysis verify this. Small sharp defects of a new mill due to manufacturing technology are shown in fig.6 (a). However, these are negligible compared with considerable wear of the used mill in fig.6 (b). Adhesive damage causes significant changes of the sharp shape and cutting features. This is accompanied by changes in drilling process and temperature increase during drilling.

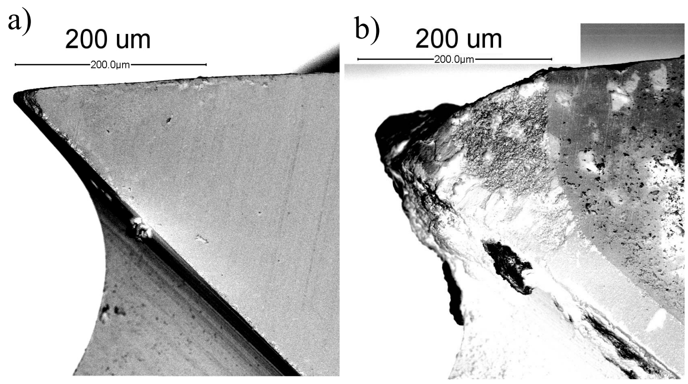


Fig.6: Detail of the mill sharp obtained by electron microscopy (secondary electrons). a) new mill b) worn mill.

Drilled material influence - example 2

Similar thermal effect like a worn drilling mill can be caused by material properties. The drilling device used and tungsten-carbide drilling mills are suited for steel materials or materials with similar or lower hardness. Harder materials can cause drilling process stop due to the insufficient air turbine power. Such increase of cutting forces is accompanied by increasing temperature generation as well.

Steel materials high temperature treatment is accompanied by an oxidized flake layer formation on its surface. The flake material has different thermo-mechanical properties, generally higher hardness than steel. An annealed steel sample (CSN 14220/ISO 683/11-70) with such a flake layer is used to a hole drilling experiment, when thermography measurement and strain measurement near the drilled hole are carried out during the drilling process. Parameters of drilling procedure and temperature measurement method are the same as used in previous example. New one drilling mill is used. Strain is measured by a strain gauge rosette for residual stress measurement HBM 1,5/120RY61S, data acquisition modules Advantech ADAM is used for full bridge strain measurement.

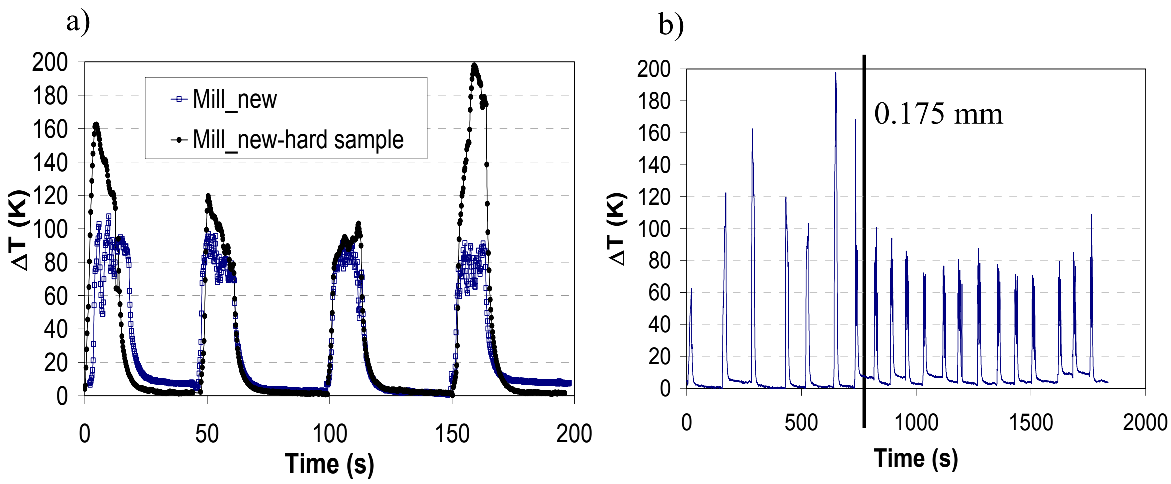
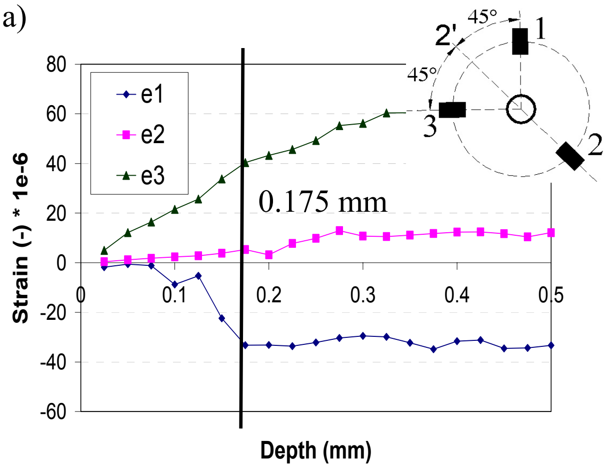


Fig.7: Temperature during drilling of a steel sample measured by thermography system at drilling mill (see fig.5); clean surface and surface covered by flakes (a), temperature peaks progress by flake-surface drilling (b).

The comparison of temperature peak generated by drilling to clear steel surface and by drilling to surface covered by hard oxidized flake-layer is in fig.7 (a). The figure shows, that even if a new drilling mill is used, the temperature can raise significantly, up to "worn mill" level. The drilling temperature evolution progress up to the last step (depth 0.5 mm, 20 steps) is showed in fig.7 (b). The record in fig.7 (b) includes delay times. A decrease of temperature peaks can be observed after 7-th step, at depth 0.175 mm. This decrease of maximum temperatures to values measured by new mill-steel drilling shows, that the flake layer is drilled out and drilling process continues to the steel.

a)



b)

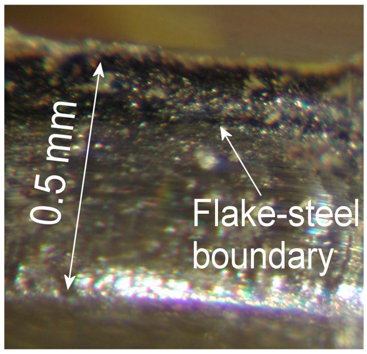


Fig.8: Relieved strain measured after stabilization delay during drilling of each step at three directions (a), microscopy picture of the hole-depth profile (b).

The above mentioned assumption is verified by strain progress records and microscopy pictures of the drilled hole in fig.8. In fig.8 (a) there is a record of the relieved strain after drilling of the each step (after delay time for strain stabilization). Strain is measured by a strain gauge rosette in three directions *1, 2, 3* (see scheme in fig.8 (a)). A sharp change of strain trend at direction 1 can be seen after 7-th step (0.175 mm). The flake layer lost its adhesion to the basic material in this direction probably. Thus, after drilling out of this layer and further drilling to the basic material, the relieved strain does not affect the sample (flake layer) surface. At the microscopy picture in fig.8 (b) the flake-steel boundary can be detected approximately at the one third of the hole depth.

Temperature influence - example 3

Increased temperature decreases material yield stress, produces thermally induced stresses and can cause thermal stress relaxation. Thus, the temperature and induced stress/strain distribution in a material during drilling is an important question.

It is assumed, that the highest temperature, i.e. heat source, is at the drilling mill-measured sample contact. Special methods using thermocouples are developed for this temperature measurement, but these cannot be applied in this particular case not to disturb the sample and relieve strain measurement. Thermography is not capable to measure this temperature directly and indirect problem has to be solved. In terms of the experiment described in example 1 the temperature progress is evaluated at points 1, 2 and 5 mm (T1, T2, T3) from the hole edge. A numerical model (FEM) of the hole as an axially symmetric problem is created in Cosmos/M system (similar mesh as the one showed in fig.4). The computed temperature at the hole bottom during drilling process is fitted to the measured temperature at check points 1, 2 and 3. Subsequently, thermally induced strain evolution without other loads is simulated. Constant material properties are used for the simulation, hole-depth change during computation is not considered.

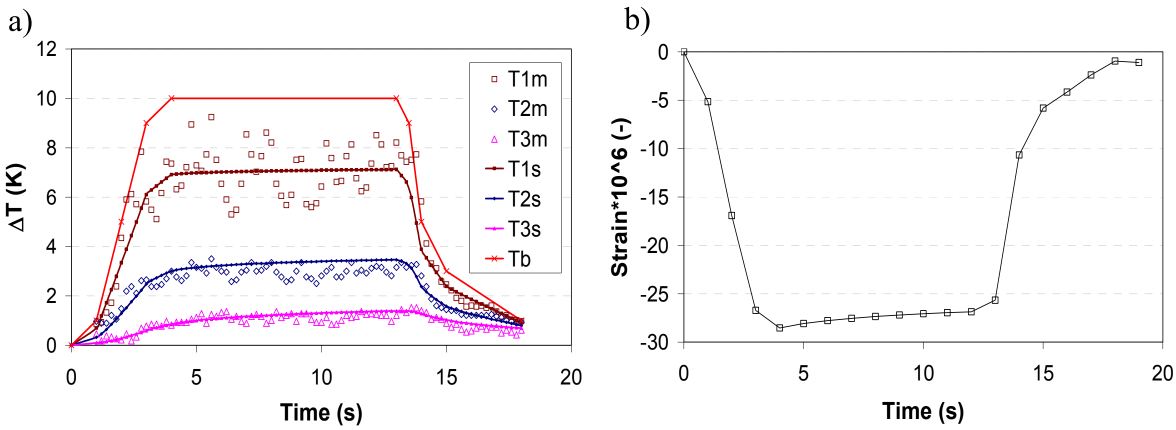


Fig.9: Measured (m) and computed (s) temperature increase during one drilling step at points 1 (1), 2 (2) and 5 mm (3) from the hole edge, entered boundary temperature at the hole bottom Tb (a), computed thermally induced strain at strain gauge rosette sensor position (2.55 mm from the hole center) (b).

In fig.9 (a) there is shown measured and computed temperature time path (difference from the initial temperature 299 K) for the hole depth 0.19 mm at check points and the entered boundary temperature at the hole bottom. The thermally induced strain at the place 2.55 mm from the hole center (strain gauge rosette mean radius, i.e. sensor positions) is then showed in figure part (b). The maximum temperature growth at the hole bottom about 10 K for this case is simulation result. This temperature increase does not cause significant thermal stresses even relaxation processes in the material. However, thermal induced strain near the hole reaches values comparable to the relaxation strains.

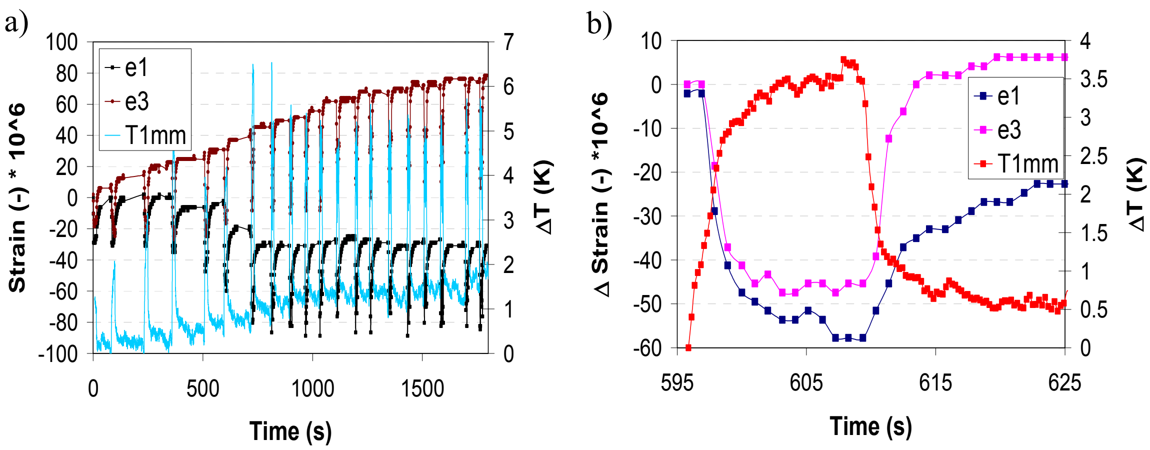


Fig.10: Temperature difference T1mm (at 1 mm from the hole edge) and strains e1, e2 time path during drilling (a), detail of the temperature and strain differences (strain difference to the state before the 6-th step drilling) time path at 6-th step (b).

This simulation results are not too far from strain measurement described in example 2. In fig.10 (a) there are both measured temperature and strain time paths. Fig.10 (b) then shows a detail of temperature-strain time path in 6-th step, where the strain is plotted as a difference to the state before the 6-th step drilling. Differences are caused by different material properties-the strain is measured on the oxidized flake-covered sample. It can be seen, that although the measured drilling mill temperature by this sample is higher than by the experiment with clean steel surface (comparison in fig.7 (a)), the flake-sample temperature is lower (see fig.9 (a)-clean steel surface and fig.10 (b)-flake covered surface). On the other hand, the strain peaks are higher by the flake layer. This is caused by different thermo-mechanical properties of the steel and oxidized layer.

The case of sample covered by flakes is not modeled, because the thermo-mechanical properties of the oxidized layer and properties of basic material-flake layer interface are not known. However, the simultaneous temperature-strain measurement verifies, that the thermally induced strain is comparable to the measured strain. Moreover, whole sample can be slightly heated (several K - dependent on sample dimensions, material properties and drilling regime), how one can see in fig.10 (b).

Conclusions

The basics of residual stress characteristics, classification and measurement methods are introduced in the contribution. The hole-drilling residual stress measurement method is described in relation to its practical using. The basics steps of the problem analysis are defined as:

- material measured thermo-mechanical properties and its composition
- drilling of the hole and relieved residual stress recording
- measured data evaluation

Determination of some analysis problems is shown as practical examples. The example 1 gives care to the whole drilling procedure in connection with drilling mill quality. The mill state appears as a very important measurement factor. Based on results presented the usage of worn drilling tool can change the drilling process characteristics. These changes are detectable by temperature measurement and the drilling mill damage can be fully evidenced by electron-microscopy measurement. The effective temperature measurement method is IR-thermography. Both drilling mill and sample temperature changes during drilling process can give useful information. However, the measured material properties should be considered as well and the temperature should be evaluated relatively with regard to actual measurement conditions.

Measured material surface properties can significantly influence the measured process, as it is shown in example 2. If the drilled material has too high cutting resistance, it causes drilling forces increase and then temperature generation increase, similar as by using of a worn drilling mill. Furthermore, the measured material surface and subsurface structure should be known. By the residual stress evaluation the homogeneous isotropic material is assumed. If this condition is not fulfilled, the calibration coefficients changes or new evaluation formulaes should be derived. In case of this application example, an additional problem with surface layer adhesion occures. Evaluation of the residual stresses both in flake layer or basic steel material (that differ due to the different thermo-mechanical properties) is thus very problematic or quite impossible.

In connection to the performed temperature measurement the temperature increase influence during drilling process is determined in example 3. Simulated and measured temperatures and strains verify, that the temperature raise during drilling (about 10K by given conditions at the hole bottom) should not cause significant thermal stresses and subsequent plastic deformation or relaxation processes. However, the thermally induced strains $\varepsilon \sim 10^{-5}$ around the hole are comparable with the measured one. Further, it can be seen, that the whole sample temperature can slightly increase (several K). Both these findings lead to the requirement of longer delay times between two drilling steps, that should exceed the whole drilling process several times.

It is shown, that detailed knowledge of the problem solved in consequence to method possibilities is fundamental for the reliable measurement. Above all the measured material properties and drilling conditions can significantly influence the measurement and a great care should be given to its determination.

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