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QUANTIFICATION OF RESIDUAL STRESSES IN THE WELD BY THE HOLE-DRILLING METHOD

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Residual stresses arise in the structures without loading during the technological processes, e.g. casting, rolling, welding, and pressing. In the paper is described the process of quantification of residual stresses by the hole-drilling method. For determination of residual stresses were used the procedures in which are supposed constant or linear distributions of stresses along the hole.

Key words: residual stresses, weld joint, hole-drilling method

Vrednovanje zaostalih naprezanja u zavaru metodom bušenja otvora. Zaostala naprezanja nastaju u neopterećenim izradcima tijekom tehnoloških procesa npr. pri odljevanju, valjanju, zavarivanju i prešanju. U članku je opisan postupak vrednovanja zaostalih naprezanja u zavarenom spoju primjenom metode bušenja otvora. Za određivanje zaostalih naprezanja rabljen je postupak u kojemu se predmnijeva stalna ili linearna raspodjela naprezanja duž otvora

Ključne riječi: zaostala naprezanja, zavareni spoj, metoda bušenja otvora (rupe)

INTRODUCTION

Many failures of supporting structures or machines are not caused only by stresses that are invoked by loading, but they often result due to residual stresses. Time needed for reparation of equipment and production losses are important factors, but much more serious are possible injuries or death of people. Residual stresses occur also in the structures without loadings. They arise mostly due to technological processes, e.g. casting, rolling, welding, pressing or forging.

Residual stresses are equally danger as are the stresses due to operational loading. They are undesirable from the following reasons: it is not easy to determine them, they are superimposed to the operational stresses.

Compressive residual stresses in surface layer of material are sometimes created deliberately, e.g. by shot peening, hardening, and so on and they have positive contribution to the strength properties of machine part. Residual stresses can be dangerous, because they can be relatively hard determined by non-destructive methods. We are not able to predict their magnitudes, type, nor direction. They are able to superimpose with stresses induced by corrosion, fatigue influences and it is very hard to remove them from the structure. Residual stresses should be known during operation of the equipment in order to determine their influence on functionality of machine part.

Although there were some attempts to model residual stresses, these models are not ideal. For the quality check during production of machine part it should be suitable to use the methods for determination of residual stresses at the same time. Although there was reached some progress in measurement of residual stresses to this time was not developed non-destructive, cheap and effective method. Regardless their occurrence and importance in determination of reliability of structures, the residual stresses are often not considered in practical computations. Residual stresses are one of the forgotten areas in designing of machine parts. The most spread method for determination of residual stresses is the hole-drilling method. It is based on change of stresses (or strains) after drilling the hole in specimen with residual stresses [1-5]. It is one of the methods based on the removing material from structure. Deformation change can be assessed by photoelastic coatings, brittle layers, or by strain gages. If we know magnitudes and directions of released strains, dimensions of the hole and material properties, we can determine residual stresses on the base of analytical or numerical analysis. This method is often considered to be semi-destructive, because drilled hole can be very small or it can be repaired by pin, bolt, or by welding. Of course, such reparation can change stress distribution. Sometimes are used blind holes although the assessment of residual stresses is rather complicated than for through holes.

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The hole-drilling method can be used for determination of residual stresses on the surface of big machine parts. Pattern gained by photoelastic coating or by brittle layers can be used for determination of magnitude and direction of two-dimensional stress state. Although this technique is used mainly on flat machine parts, it can be used also for grooves, welds and so on. For such measurements are available commercial equipments. Similarly as other methods for determination of residual stresses, it is a quantitative method. In comparison to other method of determination of residual stresses it is less destructive and the results can be gained relatively quickly and economically. The hole-drilling method can determine measurement of residual stresses only in one point. It was proposed several variants of hole-drilling method as well as several methods for the evaluation of results. Some of them are described in monograph [1]. In the paper is described procedure for quantification of residual stresses in weld by the hole-drilling method and by procedures developed on the workplace of authors [6-8].

SYSTEM SINT MTS-3000 AND PROGRAM RESTAN FOR DETERMINATION OF RESIDUAL STRESSES

Mechanical and optical equipment SINT MTS-3000 in Figure 1, which is suitable for determination of residual stresses by the hole-drilling method, is a small workplace with three axes containing vertical head with microscope and high-speed turbine. It is used for drilling of precision holes with the help of optical centring system as well as for the measurement of diameter of the hole together with its position to referential points.

The equipment can rotate in three axes and it has three legs made of stainless steel. It contains magnets for its stabilization on flat surfaces and the legs can be tilted for their adaptation to equipment for non-planar surfaces. In such a case they are glued with special adhesive. The legs are joined to the body of equipment by rods with adjustable lengths for the positioning of vertical head perpendicularly to the surface of drilling. For such positioning is used L-shaped ruler. Base of equipment consists of two jointed moving parts. The radial movement is practically equal to null. Horizontal movements are manually adjusted by buttons and the deflections are measured. Precise movement in the direction of hole axis is controlled manually or by stepping motor controlled by computer. In both cases is the movement extremely precise.

Microswitch ensures determination of stability for controlling and automatic positioning. Switch is on if the vertical head reaches maximal upper position. The heart of the system is equipment consisting microscope and high-speed turbine.

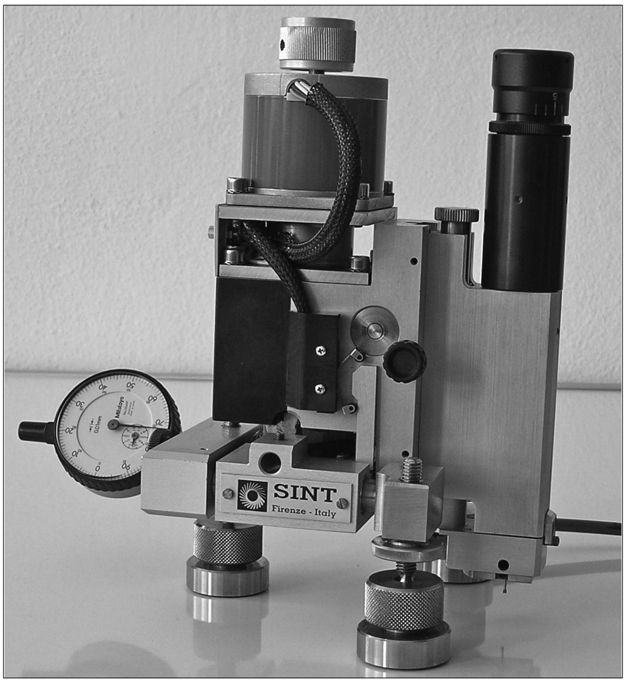


Figure 1. SINT MTS-3000

These two components are fixed to the body of system. During the drilling the turbine is exactly in the axial position with microscope. After optical centring and inspection it can rotate around their axes so the hole is visible by microscope. Air turbine with a spindle is installed such a way that it takes very small volume. It has approximately 300.000 rpm and it can drill holes of various diameters according to the drilling tool. Usually, hole cutter with diameter 1,6 mm with flat head and inverse cone is used. Turbine is jointed to air system by elastic rapid-clamping tube. System contains filter/reducer of pressure for regulation, manometer and electromagnetic piston controlled by computer.

Microscope has two functions – it allows adjusting cutter to referential points and at the same time to measure effective diameter of the hole. This procedure is possible due to movement along two axes, measurement of deviations and hair cross in ocular. Microscope has system for the change of ocular and hair cross position according to the axis of drilling.

Drilling can be with sequence step by step or with automatic sequence. Evaluation of stresses can be provided by optimization of data of measured deformations in relation to length of hole or by computation of residual stresses.

For every step there exists recommended procedure that software uses as default (if not specified other). System supports huge amount of drilling steps and accordingly description of graphs by many experimental points.

Optimization of data gained during drilling is very suitable and ensures high stability and quality of results. Minimal referential number of steps according to ASTM E 837-01 [9] is 8, but it is reccommended to use

20 or more steps. Due to high increments of stresses measured during individual steps of drilling it is suitable to drill in every step minimally 0,015 mm of hole depth.

For the determination of residual stresses are used the following treatments: Standard ASTM E 837-01, Integral method, Method of Power Series, Kockelmann method, Program MEZVYNA.

All procedures have different areas of application:

Method according to Standard ASTM E 837-01 - It is a very stabile and reliable procedure considered to be as referential. Standard ASTM E 837-01 is the only one for the measurement of residual stresses by the hole-drilling method. However, it is limited, because it is based on the theory of proportionally distributed stresses along the hole depth. It means that it gives one couple of principal residual stresses for the whole hole depth.

Integral method - This method is often described in technical literature. It is applied for determination of residual stresses in the depth of the hole, especially in locations where the stress along hole depth varies due to different specimen thickness. This method makes possible to use constant amplitude, amplitude which growths with the depth of the hole, or variable stress distribution with optimisation of amplitude in depth and oriented to reduction of measurement errors.

Method of Power Series - The method is, in principle, simplified approximation of integral method. In comparison to integral method it allows to gain data from the depth of the hole (according to ASTM to 1.2 times of hole diameter). Software implements this method by using coefficients determined by Schajer.

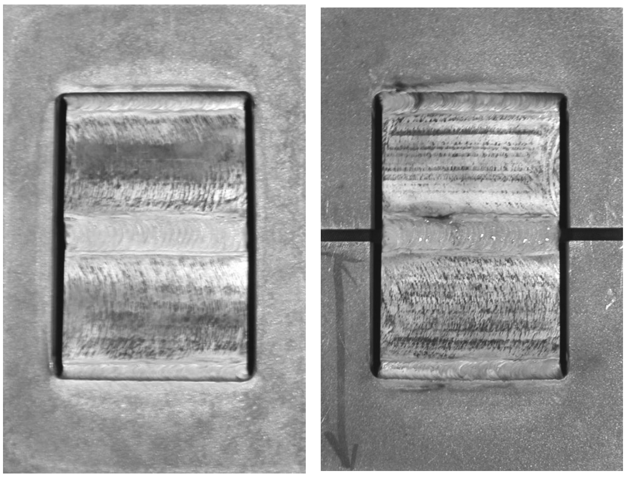
Kockelmann method - The method is considered to be an approximation of integral method and its advantage is based on determination of data in higher depth than are in integral method (hole depth can reach principal radius of rosette). The method uses numerical coefficients according to Kockelmann.

Program MEZVYNA - This product was developed in the workplace of authors and it is a complex and very detailed verified system removing the disadvantages of previous program products.

MEASUREMENT OF RESIDUAL STRESSES ON SPECIMENS WITH WELDS

Measurement of residual stresses was performed on the specimens designed and elaborated in Weld Research Institute – Industrial Institute, Bratislava. The specimens consist of two welded sheets of the thickness 10 mm that are welded to the closed frame (specimen CR – Figure 2a) and to the cutted frame (specimen RR – Figure 2b). Chemical composition of specimens is given in Table 1.

After delivery and visual control of specimens was discovered that due to welding there are relatively high



a) b)

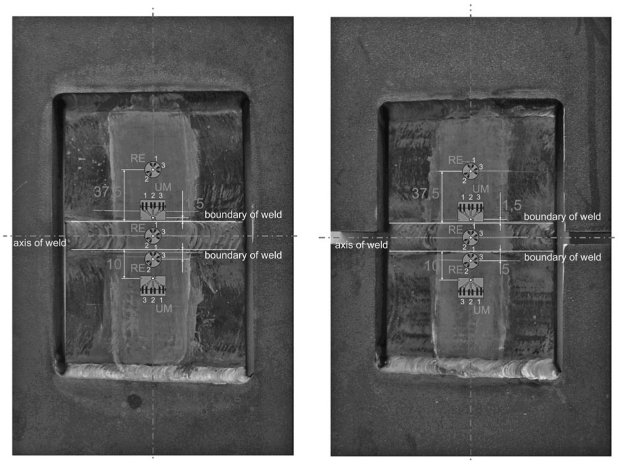
Figure 2. Specimens of sheets with welds. a) specimen CR in closed frame, b) specimen RR in cutted frame.

Table 1. **Chemical composition of experimental materials / %**

Element	**C**	**Si**	**Mn**	**Cr**	**Mo**	**W**
Amount	0,12	0,29	0,86	9,14	1,47	0,03
Element	**Ni**	**Co**	**V**	**Nb**	**N**	
Amount	0,22	0,95	0,19	0,062	0,02	

protrusions on the surfaces. Smoothing the surface with strain-gage cement should decrease the sensitivity of strain-gages. This was tested on the specimen with artificially produced protrusions oriented perpendicular to one from principal strains. The roughness was abraded by grinding wheel using conditioner Vishay M-M and intensive cooling. The temperature increasing did not exceed 30°C. On such a surfaces were applied the strain-gages.

Application of strain-gages is shown in Figure 3a and Figure 3b, where depicted orientation of strain is gages is on the specimen with cutted as well as whole frame.



a) b)

Figure 3. Position, orientation, numbering and labelling of strain gages. a) closed frame, b) cutted frame.

For the measurements were used two types of strain gages Vishay M-M and SR-4: strain gages EA-06-062 RE-120/SE for determination of residual stresses with nominal grid resistance 120,0 Ω ± 0,4% and *k*-factor 2,09 ± 1,0%; strain gages CEA-06-062 UM-120 for determination of residual stresses with nominal grid resistance 120,0 Ω ± 0,4% and *k*-factor 2,08 ± 1,0%.

The system SPIDER8 uses half-bridge circuit. For chosen technology of drilling and range of temperatures was not necessary to use temperature characteristics of strain gages. Preparation of specimens for drilling was provided in accordance with technological procedures described in Standard ASTM E837-01. The materials used for the measurements were exclusively from Vishay Micro-Measurements. After controlling by equipment M 1300 were strain gages and joints isolated by coating M Coat A again made by Vishay Micro-Measurements. Application of strain gages as well as measurement on specimen was provided at three stages using the following procedure (numbering of strain gages are given in Figure 3).

At the beginning the strain gage was applied at the distance 37,5 mm from the boundary of weld (HZ) and this sensor was labelled as No. 1. The grid 1 of strain gage was perpendicular to weld axis and grid 3 was parallel to weld axis. Strain gage 3, at the distance 5 mm from the boundary of weld, was applied on opposite side of weld (Figure 4). After finishing measurements in locations 1 and 3 was applied strain gage No. 5 along weld axis, see Figure 5.

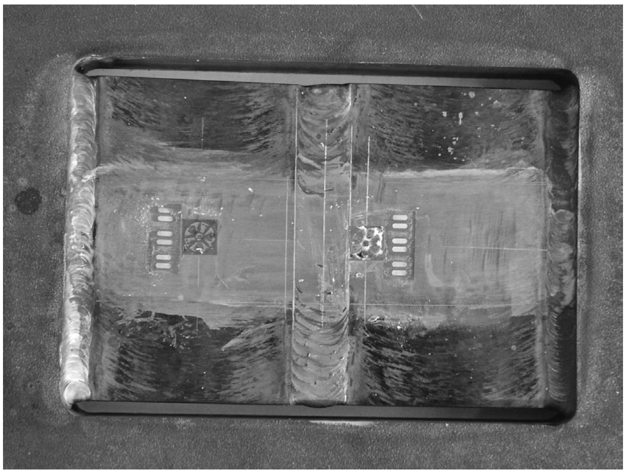


Figure 4. First stage of strain gage application.

MEASURED MAGNITUDES OF RESIDUAL STRESSES AND THEIR DIRECTIONS

For the evaluation of measured quantities were used program systems that allow assessment of residual stresses in accordance with ASTM E 837-01, Integral method and Method of Power Series. The magnitudes of stresses were determined from measured released deformations by using Young modulus E=2,17.10^5 MPa and Poisson ratio m=0,3 [10]. Results of evaluation are the

Figure 5. Second stage of strain gage application in the weld axis.

standard minutes developped by program for the chosen method. In Figure 6 are given charts of measured and interpolated values of strains for the specimen in whole frame in location No. 5. In Figure 7 are given the minutes of principal residual stresses in location No. 1 (whole frame) determined according to ASTM [8]. Because the Standard ASTM presupposes regular distribution of stresses along the hole depth, in Figure 7 is also given comparison of measured distribution of released deformations with the referential distribution of strains along the hole depth according to ASTM.

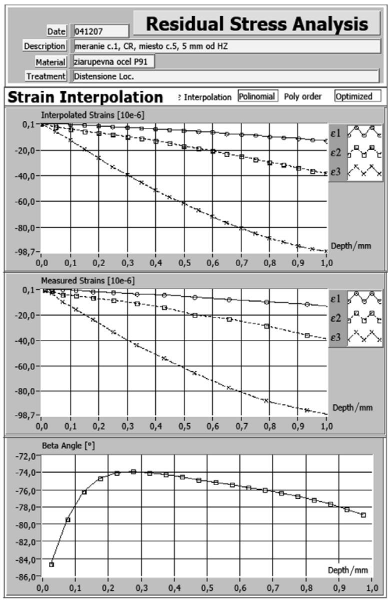


Figure 6. Charts of measured and interpolated magnitudes of strains – closed frame, location No. 5

In Figure 7 are given the minutes of computed equivalent residual stresses by the Method of Power Series in the location No. 4 and the specimen with cutted frame. In the Table 2 are given the values of maximal and minimal principal normal stresses determined by program systems according to ASTM E837-01 for the specimen included in the whole as well as in cutted frame for individual locations of measurements.

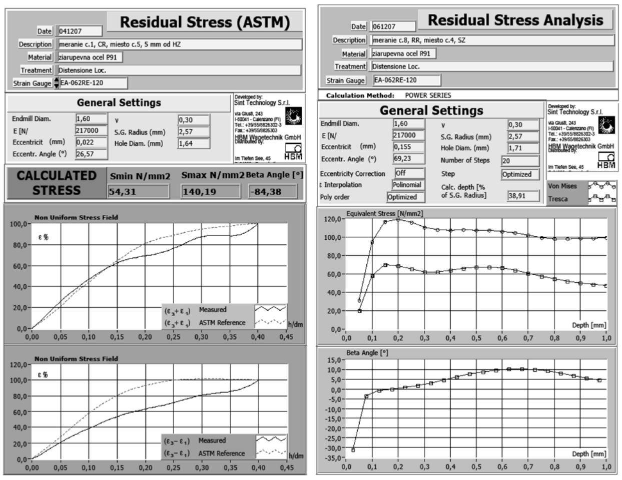


Figure 7. Magnitudes of principal residual stresses in location No.1 (closed frame) determined according to ASTM and equivalent residual stresses determined by the Method of Power Series in location No. 4 – cutted frame

Table 2. **Magnitudes of residual stresses determined by ASTM**

Location Type of strain gage	Closed frame			Cutted frame		
	σ_{max} / MPa	σ_{max} / MPa	φ / °	σ_{max} / MPa	σ_{max} / MPa	φ / °
1 - RE	211,3	-120,6	+10,0	159,7	-46,8	-16,8
2 - UM	180,9	36,4	36,7	82,0	34,3	39,3
5 - RE	140,2	54,3	-84,4	99,1	37,8	-85,6
3 - UM	109,7	25,1	48,9	110,3	8,3	51,0
4 - RE	88,6	68,8	-8,7	104,3	77,6	7,3

CONCLUSION

Application of the hole-drilling method for the determination of residual stresses in welded joints (in weld, in the transition area and in base material) can be considered as extraordinary suitable and the measured results are relevant. Especially, using of special strain gages with the drilled hole diameter from 0,8 to 1,6 allows, for the welded sheets with the thickness more than 2 mm, to quantify not only magnitudes and directions of principal residual stresses, but also their distribution along the depth of the hole. Design of equipment SINT-MTS 3000 in contrast to system RS-200 allows drilling not only in butt welds, but also in fillet welds that are more frequently used in the structures. The measurements have showed that the levels of residual stresses reach magnitudes 100 MPa and for positive signs of stresses their superposition with operational stresses can substantially decrease the lifetime of the structure.

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