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Experimental Stress Analysis

The study of the possibilities of residual stresses prediction in weld joint using the elastic-viscoplastic material model

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Abstract: This contribution is a study how to analyze the stress-strain responses to technological processes which are applied to special high-alloy steel with polymorphic behaviour for the energy industry. These are technological processes of welding and post weld heat treatment (PWHT) analyzed experimentally and by computational modelling. Residual stresses always arise during welding and PWHT in the weld joint and its surrounding. One of the requirements for the quality of weld joints of machine components is an adherence to a certain level of residual stresses especially for components in energy industry. The possibility of correct and effective prediction of residual stresses in the weld joint is the subject of this contribution. At present it is possible to computationally modelling the processes of welding and PWHT. The elastic-plastic material models are standardly used for computational modelling of these tasks. These constitutive models are not able to describe significant viscoplastic time-dependent deformation processes of material which occur during welding and PWHT. Exclusion of these processes during computational modelling can lead to unrealistically high values of predicted residual stress in weld joints and their surroundings. Therefore it is necessary to take into account these physical processes by appropriate application of the elastic-viscoplastic (EVP) material model. The aim of this contribution is to outline the possibilities of correct and effective residual stresses prediction in the weld joint and its surrounding via computational modelling in conjunction with experimental measurements.

Keywords: Residual stress, Computational modelling, Welding, Elastic-viscoplastic material model

1. Introduction

For creation of this study and subsequent usage for doctoral thesis was the following fact. The methodology of computational modelling of welding and PWHT is not so far sufficiently elaborated in practical calculations with inclusion of all physical processes, which proceed during high temperature. These calculations are consequently used for evaluation of residual stresses in welds and their surroundings. The courses and values of residual stresses magnitude can be

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significant input parameter for the following evaluation of welded constructions lifetime. Therefore it is important to computationally model the process of welding and PWHT as realistic as possible using the appropriate and correct description of the ongoing physical processes. At present two types of material models are used for calculations of residual stresses during and after welding and PWHT. The first type is the elastic-plastic material model with isotropic strain hardening and the second one is the elastic-plastic material model with kinematic strain hardening. Nevertheless the stress relaxation proceeds during the real welding process due to the effects of high temperature. That means that in reality the values of residual stresses are lower than those which are expressed by both elastic-plastic material models. The reason of this is that the elastic-plastic material model is not able to take into account the time-dependent elastic-viscoplastic material behaviour, which proceeds during the stress relaxation. This study should provide certain suggestions and ideas for the future objectives of my doctoral thesis. These are the proposal, ensuring and evaluation of experiments for the application of appropriate constitutive models for computational modelling. These constitutive models are able to take into account the time-dependent elastic-viscoplastic material behaviour ongoing in the material during the high temperature. Obtained results will be used for the application onto the real cases then.

2. Comparison of the elastic-plastic and the elastic-viscoplastic material model

The total strain of particular material models in notation for application in FEM software [1] is described by equations mentioned below.

The total strain - conventional models of plasticity

$$\varepsilon_T = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{th} + \varepsilon_{tp} \tag{1}$$

The total strain – the EVP material model

$$\varepsilon_T = \varepsilon_{el} + \varepsilon_{vp} + \varepsilon_{th} + \varepsilon_{tp} \tag{2}$$

ε_T – the total strain
ε_{el} – the elastic strain
ε_{th} – the (volumetric) thermal strain
ε_{pl} – the (deviatoric) time-independent plastic strain
ε_{vp} – the (deviatoric) time-dependent viscoplastic strain
ε_{tp} – the transformation plastic strain

Schematic representation of the physical principles of material models via simple rheological models [2] is shown in (Fig. 1) and (Fig. 2).

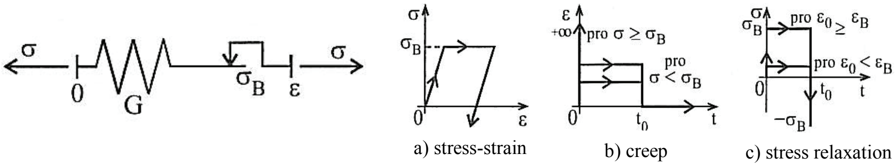

Fig. 1. Fundamental characteristics of the elastic-plastic material.

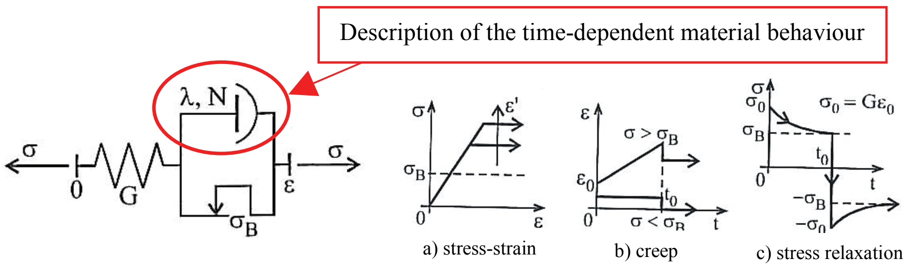

Fig. 2. Fundamental characteristics of the elastic-viscoplastic material.

G – modulus of elasticity in shear
σ_B – locking stress, the value of locking stress is equal to yield stress
λ, N – parameters describing the Norton nonlinear fluid damper
σ_0 – initial stress, relaxation of initial stress to magnitude σ_B = Re

3. Relevance of using of the EVP material model for computational modelling of welding and post weld heat treatment (PWHT)

The stress and strain behaviour of steel under welding and PWHT conditions should not be assessed only on the basis of usually used plasticity laws. It should be also evaluated by characteristics, which take into account the time-dependent elastic-viscoplastic material behaviour (stress relaxation, creep). That results in necessity to use the EVP material model to achieve of reliable results obtained by computational modelling of welding (single-pass, multi-pass) and PWHT (annealing after welding). The importance of the EVP material model application is described in the following subsections.

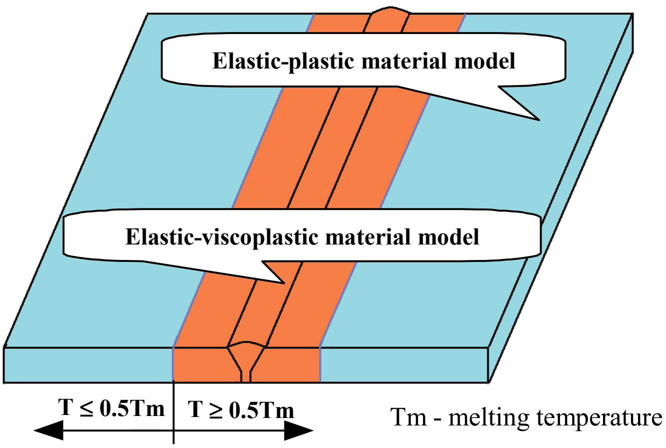

Fig. 3. Areas of application of material models for computational modelling of welding - depending on temperature.

3.1. The description of stress and strain material behaviour during single-pass welding

Computational modelling of single-pass welding is the first case of application of the EVP material model. In this case the EVP material model describes the reduction of residual stresses due to the stress relaxation at high temperatures T ≥ 0.5Tm [3] (orange area in Fig. 3). It could be stated that only temperature T ≥ 0.5Tm is sufficient reason for application of the EVP material model during computational modelling of single-pass welding.

3.2. The description of stress and strain material behaviour during multi-pass welding

In the case of computational modelling of multi-pass welding the high temperature T ≥ 0.5Tm (orange area in Fig. 3) is not the only factor, which should be taken into account using the EVP material model. The second significant factor is consideration of the time-dependent elastic-viscoplastic material behaviour during computational modelling of multi-pass welding of steel with polymorphic behaviour, during which the following processes occur. In general, the phase transformations occur during welding of steel with polymorphic behaviour. The result of phase transformation could be the basic structures as ferrite, pearlite, bainit and martensite. Beside the structures mentioned before it is also possible to achieve the other structures by appropriate heat exposure onto the basic structures. It could be for example tempered martensite - sorbite, top bainit, bottom bainit etc. Each structure of the material described before has different mechanical properties. The subsequent weld bead has heat-effect onto the previous one during multi-pass welding. It means that the harder and more brittle structure (e.g. martensite) of the previous weld bead is being changed by heat exposure of the subsequent weld bead onto the softer and tougher structure (e.g. sorbite). This will reduce the hardness and strength and increase the ductility and toughness. This transition from the harder and more brittle structure onto the softer and tougher structure causes the change of mechanical properties. This will lead to the reduction and partial homogenization of the residual stresses due to the stress relaxation in area under the individual weld beads. These processes should be also described by using the EVP material model either for particular structures of material or in the presence of one dominant structure just for this dominant structure.

3.3. The description of stress and strain material behaviour during post weld heat treatment (PWHT)

The third case of the EVP material model application is computational modelling of PWHT (annealing to reduce of residual stresses). The reduction of values and partial homogenization of residual stresses is achieved by PWHT in the weld joint. The processes which proceed while PWHT are similar to the processes ongoing during multi-pass welding among particular weld beads. However, there is a specific difference with regard to the appropriate application of the EVP material model. The time-dependent elastic-viscoplastic material behaviour during PWHT proceeds at longer time and at lower temperatures than during welding. A general example of residual stresses distribution which is obtained from computational modelling is stated in (Fig. 4). Only the elastic-plastic material model was used in area of the weld joint (Fig. 4) on the left (welding). The distribution of residual stresses after PWHT is stated in (Fig. 4) on the right. There was used the EVP material model on a certain distinctive level.

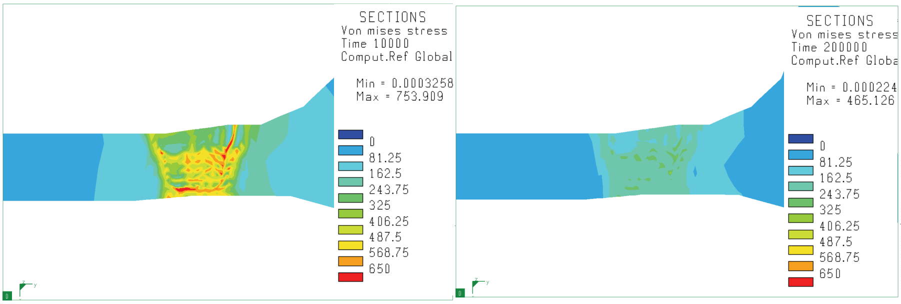

Fig. 4. Distribution of residual stresses after welding (left) and after PWHT (right).

It is clear that the EVP material model must be applied in all three mentioned cases (single-pass welding, multi-pass welding, PWHT) for the correct prediction of residual stresses by numerical way as mentioned above. Exclusion of the time-dependent elastic-viscoplastic material behaviour in computational modelling in one of those cases leads to higher value of residual stresses. The EVP material model should be applied at the first stage for computational modelling of welding. It will take into account the temperature influence $T \geq 0.5Tm$ and the influence of structural changes caused by multi-pass welding among particular weld beads. The EVP material model should be also applied for the second stage of computational modelling. It will take into account the influence of structural changes caused by PWHT.

4. The types of EVP material models and their application

The problems of application importance of the EVP material model during computational modelling of welding and PWHT was outlined in the text mentioned above. It is necessary to distinguish two types of EVP material models [1]. The first EVP material model is described by four parameters. This EVP material model should be applied for description of rapid thermal processes, which means welding. The second EVP material model is described by five parameters. This EVP material model should be applied for description of slower thermal processes, which means PWHT. The appropriate experimental measurements must be performed for determination and debugging of particular parameters of EVP material models. It is necessary to perform the experimental measurements of creep (primary part of creep curve) and stress relaxation characteristics for the EVP material model which is described by four parameters. For the EVP material model which is described by five parameters, it is necessary to perform the experimental measurements only of creep characteristics (primary and secondary part of creep curve). The stress relaxation tests need not be performed in this case. In order to make a valuable prediction of residual stresses in the weld joint and its surrounding by computational modelling, the EVP material model should be applied in accordance with schema which is stated in (Fig. 5).

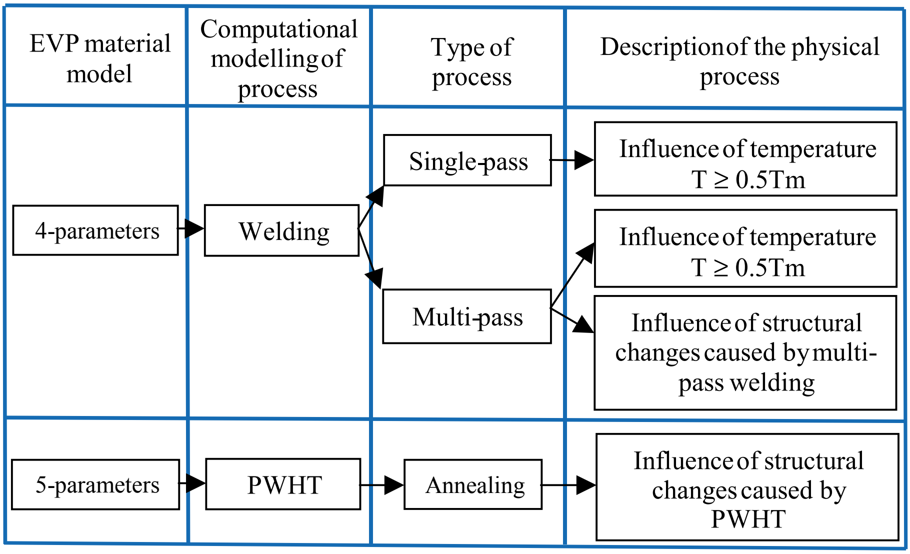

Fig. 5. Description of application of EVP material models for computational modelling of welding and PWHT.

5. The proposal of verification assignments for computational modelling and experimental measurements

In the next step it is necessary to define the appropriate verification assignments which will be identical for computational modelling and experimental measurements of residual stresses. In order to verify all particular influences (the effect of temperature $T \geq 0.5Tm$, structural changes caused by multi-pass welding and PWHT) and thus confirm the necessity of the EVP model material usage, the following verification assignments are defined:

1. Single-pass welding of two plates => the verification of temperature influence $T \geq 0.5Tm$
2. Single-pass welding of two plates + PWHT => the verification of temperature influence $T \geq 0.5Tm$ + the influence of structural changes caused by PWHT
3. Multi-pass welding of two plates => the verification of temperature influence $T \geq 0.5Tm$+ the influence of structural changes caused by multi-pass welding

4. Multi-pass welding of two plates + PWHT => the verification of temperature influence $T \geq 0.5T_m$ + the influence of structural changes caused by multi-pass welding + the influence of structural changes caused by PWHT

It should be emphasized that application of the EVP material model for computational modelling should lead to more realistic description of residual stresses values. Furthermore the application of the EVP material model should take into account the process of residual stresses homogenization in cross section of the weld and its surrounding. This means that the practical output will not only be the final value of residual stress for subsequent evaluation of welded constructions lifetime, but also the level of residual stress homogenization in the weld and its surrounding. This is important for optimisation of the dwell time during PWHT from the practical point of view.

6. The division, the causes of rise and the problems of residual stresses experimental measurement in welding

Residual stresses are stresses acting in body permanently, without external loading as result of the previous time-independent or the time-dependent deformation processes in material. The reasons of residual stresses rise in body are force, deformation or heat actions which can be caused by various technological processes. Internal forces are in equilibrium with applied residual stresses and their resultant is generally nonzero.

Residual stresses can be classified according to various points of view. The significant viewpoint of residual stresses classification, which acts in the polycrystalline materials, is size of volumes, where the stresses are not changed from the viewpoint of size and direction [4]:

1. Residual stresses of the first kind (σ^{I} - macroscopic) – these are approximately homogeneous in the macroscopic area (in many grains) of the material [mm]
2. Residual stresses of the second kind (σ^{II} - microscopic) – these are approximately homogeneous in areas comparable to the size of individual grains
3. Residual stresses of the third kind (σ^{III} - submicroscopic) – these are inhomogeneous even in areas comparable with interatomic distances

Residual stresses in the specific point of body are always superimposition of all three kinds mentioned above. The important fact which must be taken into account is that the residual stresses of the first kind are the average value of residual stresses acting in many grains. The decisive dimension for classification of residual stresses mentioned above is grain size of material [4].

The classification of residual stresses mentioned above was stated as general division of residual stresses which can arise by specific technological process or loading. However, among the causes of rise of residual stresses after welding should be included the following causes of rise [3]:

1. Change in volume - as a result of thermal expansion, chemical conversion, microstructural transformation or change in state
2. Change in shape - as a result of (time-independent) plastic and (time-dependent) viscoplastic deformation

Before performing the experimental measurements of residual stresses it is undoubtedly important to realize, through which available experimental method, in which area and how credibly it is possible to determine the residual stresses after welding and PWHT. The available experimental methods for determination of residual stresses in welding is the hole drilling method, the magnetic method, the X-ray diffraction method and the neutron diffraction method. Schematic division, description, advantages and disadvantages of these methods are stated in the table (Table 1) [4], [7].

Table 1. Division and description of chosen experimental methods

Method	Hole drilling	Magnetic	X-ray diffraction	Neutron diffraction
Applicability	homogeneous plane stress on the surface	ferromagnetic material, plane stress	isotropic homog. material, polycrystalline, plane stress	isotropic homog. material, polycrystalline, spatial stress
Kind of analyzed residual stress	I. kind	I.+II.+III. kind	I. and II. or III. kind	I. and II. or III. kind
Measured parameter	surface deformation	amplitude of Barkhausen noise	change in interatomic distance	change in interatomic distance
Depth of investigation	0,02 - 15 mm	0,1 - 1 mm	1 - 50 μm	to 100 mm
Problems with coarseness and textures	no	yes	yes	yes
Where it is possible to measure	IAM Brno Brno UT	Brno UT VŠB TU Ostrava	FNPE Praha Brno UT VŠB TU Ostrava	NRI Řež

Experimental methods for determination of residual stresses are credibly applicable in standard realisation only in specific area where the certain conditions are met. These conditions are for example homogeneous plane stress on the surface, homogeneous and inhomogeneous stress through the thickness, values of residual stresses which do not exceed the required multiple of the yield stress and experimental measurements which are performed in area of linear elastic strain where the Hooke´s law is valid. Such area can be considered only the area sufficiently far away from the weld. But for verification of the correct application of the EVP material model, which application is especially significant in the weld and its surrounding where the plastic strain rises (further only as WIS - Weld and Its Surrounding), it is necessary to have possibility of residual stress measuring just in area of WIS. In this area a general triaxial stress is rising, values of residual stresses have already been exceeding the required multiple of the yield stress, material has undergone plastic strain and therefore it is not possible to calculate the residual stresses from measured strain by Hooke´s law. This means that in standard performance of experimental measurements by mentioned methods it is not possible to determine credibly enough the level of residual stresses in WIS.

Under certain assumptions, there is possibility of performance of the measurement in WIS by mentioned experimental methods. If the hole drilling method is used on the basis of [5] it should be possible to determine the macroscopic residual stresses above yield stress level, in elastic-plastic area and in tenths of mm below the surface. The author of this article [5] deals with determination of residual stresses in elastic-plastic area by the hole drilling method with help of FEM iterative solution. Nevertheless the author did not deal with measuring directly in the weld joint, where the whole cross section of material has already undergone plastic strain. This means that for experimental determination of residual stresses in WIS will be necessary to perform the testing assignment. This assignment would consist in creation of larger plastic area in whole cross section of specimen by mechanic loading. Further the measurement of strain and the attunement of calibration coefficients using FEM would follow for material which has undergone plastic strain and with residual stresses over yield stress. If it is proved that the hole drilling method used in this way [5] provides the credible results, this method could be applied for determination of residual stresses in WIS.

The second possible method is the determination of residual stresses in surface layers (0,01 – 1 mm) in area of WIS using the magnetic method (magnetoacoustic Barkhausen noise effect). This method could be probably used on the assumption of the appropriate attunement of the calibration curve in area of the elastic-plastic strain. Thus tuned calibration curves could be used to convert magnetic parameter into values of residual stresses in particular directions [6].

The third method which could be used under certain conditions for determination of residual stresses in part of WIS area, is the X-ray diffraction method. It should be possible to determine the macroscopic and microscopic residual stresses by this method in surface layers (1 – 50 μm) in the vicinity of weld, strictly speaking in heat affected zone (HAZ) of weld joint. The possibility of residual stresses determination only in HAZ should still be sufficient for verification of usability of the EVP material model. In accordance with [7] the certain number of repeated measurements of residual stresses in HAZ of weld joint was performed with good agreement. Nevertheless the determination of residual stresses directly in the weld is problematic.

The fourth method is the neutron diffraction method. This is the only method which is able to determine the residual stresses in the relatively large depths of material (approximately 100 mm). Nevertheless the application of this method for the determination of residual stresses in area of WIS or directly in the weld is problematic as well. Another aspect which complicates the application of the neutron diffraction method is particularly high price as well as availability of this method.

7. Conclusion

The possibility of development of computational modelling of welding and PWHT by appropriate application of the EVP material model was discussed in this contribution. The first type of the EVP material model which is described by four parameters should be applied for computational modelling of welding (single-pass welding, multi-pass welding). This type of material model describes the reduction of residual stresses values due to the stress relaxation at high temperatures T ≥ 0.5Tm and the structural changes caused by multi-pass welding. The second type of the EVP material model which is described by five parameters should be applied for computational modelling of PWHT (annealing to reduce of residual stresses). This type of material model describes the reduction of residual stresses values due to the stress relaxation during the structural changes caused by PWHT. The appropriate application of both EVP material models will lead to improvement of the resulting values and distribution of residual stresses. These improved values and distribution of residual stresses could be used for evaluation of limit states of welded constructions. Nevertheless in order to confirm the sufficient credibility of residual stresses values it is necessary to have the possibility of experimental verification. Generally the problems of residual stresses measurement (chapter 6) in WIS which was discussed with experts in the measurement of residual stresses is highly demanding. If the conditions mentioned in chapter 6 are met the hole drilling method, the magnetic method and the X-ray diffraction method could be applied for verification of the EVP material model. This means that it will be probably possible to compare only residual stresses in surface layers (µm – mm) of material in WIS without the possibility of residual stresses comparison in larger depths of the material in WIS. Nevertheless even such measurements of residual stresses will be beneficial to verification of the EVP material model application.

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