CREEP ANALYSIS OF MULTI-PASS WELD AT MICRO AND MACRO SCALE LEVEL

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ABSTRACT: Currently welding is the most common way to create permanent connections in various constructions, which are operating at elevated temperatures. Power plant machinery is one of the industries in which the welds used in particularly critical structural elements. Large parts and component of steam generators, steam and gas turbines and nuclear reactors are all operate at high mechanical stress, under the heat and radiation effects. In the welded joints of these structures creep deformation appears and creep rupture strength of welded joints often determines the strength of the assembly. Different zones of welded joints are subjected to different temperature fields during the process of welding. Furthermore, in multi-pass welding heating and cooling cycles, which occur due to the overlap of the pass beads, form complex microstructure. Current work is devoted to the development of such approach. On the micro scale level creep and damage is modeled in separate areas of multi-pass weld metal, on micro scale level welded joint altogether is modeled, and on the macro scale level analysis of the whole welded structure is performed. For modeling of the weld metal creep-damage model of orthotropic material is used as an equivalent homogeneous medium. Creep-damage model of orthotropic material contains a large number of material parameters. To identify them, a special technique is introduced. It includes a procedure for finding the parameters of the isotropic model for multi-pass weld of separate zones based on the results of physical experiments. Identification of these parameters of the equivalent homogeneous orthotropic material model for weld metal performed numerically. Geometrical model of representative volume comprising a sufficient amount of recurring elements (individual passes) is made, and the finite element method is used to analyze creep and damage processes in it. The concept of effective stress of modern continuum mechanics of creep damage that allows to builds thermo dynamically consistent constitutive relations. Through a series of numerical experiments simulating all the necessary basic physical experiments, averaged parameters likes stresses & strain of creep-damage model of weld metal are calculated. Reliability of the averaging results was checked by calculations with different numbers of passes in representative-volume.
Keywords: Multi-pass welding, Creep-damage, Stresses & Strain, Orthotropic material and FEM.

I. INTRODUCTION

Currently welding is the most used way to create indecomposable joining in different branches of manufacturing and building. Appliance of welding for composing of the various metal constructional components has several advantages over the other types of connection. They include efficient material usage through the applying of the full cut surface for coupling; lower weight of components joined by welding; reducing the amount of failures and lowering the level of over measuring for additional processing when substituting casting with welding. Welding allows applying modern materials in constructions: highly durable and heat resistant steels, light alloys, pure metals etc. Welded joints have higher strength and reliability for constructional elements working under high temperatures. In power plant industry welded joints are used in the extremely important constructional elements.

Large details and junctions of steam generators, steam and gas turbines, nuclear reactors are all operating under high thermal and mechanical loads, and under influence of radiation. Creep deformation occurs and is observed in welding of these constructions, and long-term durability of welded joints often defines the life time of the construction itself. Steam and gas turbines are high temperature appliances. In modern steam turbines the temperature of steam can reach more than 560°C, and for the stationary gas turbines can exceed 850°C. For steam turbines it is common to use thick walled massive constructions made by casting and forging.

The use of welding can dramatically reduce the weight limit of forgings and castings to provide them better quality and lower the necessity of processing large work pieces on unique machines. The most critical turbine constructions are manufactured using welding: rotors, diaphragms, blades, body cylinders and valves and other components of alloy steels. Combined welding is widely used in constructions of dissimilar steels. Accuracy requirements for welded junctions in turbines are the most demanding among other welded construction. The world's leading manufacturers of power turbines in an effort to increase the power of their aggregates are producing welded rotors. In a review of Janssen [4] features of the welded rotor in steam turbines are considered. The combined intermediate and low pressure sections (IP/LP) of turbine rotor design 1.1 are based on the premise that steam pressure and temperature vary along its length.

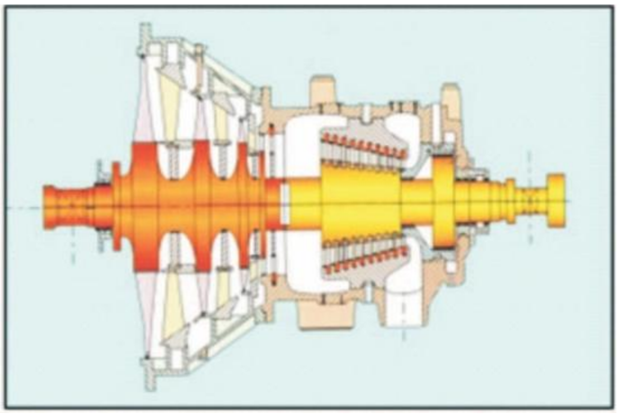

Figure 1.1 Welded rotor: schematic view and picture.

In the intermediate pressure inlet blades are operating under the temperatures up to 600°C which require to use creep resistant steel alloys, for example widely used CrMoV combinations. However in the low pressure area of the rotor one can say that creep is not of a significant importance. But since the length of the blades is substantial, it's more important to use materials with a high yield. For these applications forging NiCrMoV alloys are suitable. The 3.5% Ni steel forging has become the standard in industry for applications involving low pressure components. The joint welds are made with the multi-pass gas arc welding process in the narrow gap version. This process represents a variation of the conventional one, where the low weld metal sludge is offset by very narrow gap. Even for the wall of 180mm thick the gap width in the base area is in the range of 9mm and at the top only 11mm. As an example in junction of thick walled components, this multi-pass technology is very efficient compared to other welding processes due to the very high depth-width ratio. Two parts of IP/LP turbine rotor are welded in overhead position to in- crease productivity, Fig.1.1. Each part of a rotor is processed in a lathe to avoid unnecessary machine waste. After attachment welding, the gap is slowly filled by turning the rotor. After welding, various heat treatment procedures to handle the heat affected zones of IP and LP rotor parts without affecting the strength of both base metals.

In metals creep occurs mainly at high temperatures. For carbon steels creep is observed at temperatures of 450°C and higher. For nickel-chromium austenitic steels with high content of alloying elements allowable creep rate evolves at temperatures up to 600°C. In constructions with higher operating temperatures in order to avoid a catastrophic accumulation of creep strains commonly cobalt and nickel based super alloys are used. The simplest and the minimum required are experiments on uniaxial tension of samples at a constant load and temperature. In the course of the experiment is strain is read as a function of time. The corresponding graph is called the creep curve.

Typical creep curve is shown in Fig.1.2

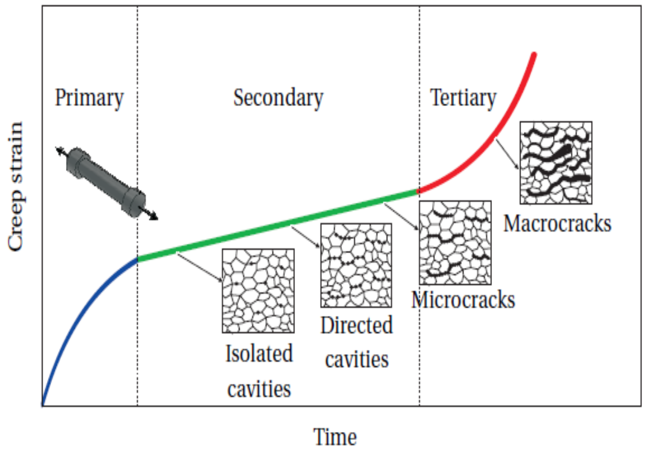

Figure 1.2 Typical creep curves.

II. MATHEMATICAL MODELING AND EQUATIONS

2.1. 2.1. Modeling of welded structures operating at high temperatures

Mathematical modeling of welded joints is caused by the necessity of designing welded structures with guaranteed parameters of long durability and reliability. The first step in such a simulation is the development of equations of state for the different zones of the weld. Because the weld structure is inhomogeneous, and some have small area size, difficulties arise in the procedure of experiments. It is practically impossible to make samples of the weld zone with homogeneous mechanical properties. In particular this applies to HAZ, which, despite its small size, may significantly affect the creep and rupture strength of welded joints. This features of the welds leads to the necessity to promote methods of mathematical modeling in the early stages of analysis of experimental results. In [6] to identify the creep parameters in the Norton law for HAZ, physical experiments for the base metal, weld metal and welded joint are combined with finite-element modeling of creep specimen. Respectively, Fig.2.1 shows comparison of specimen creep deformation between experiment, and bimaterial FE calculations with the width of HAZ= 4 and 2mm.

Bimaterial FE calculations gave useful information about constraint effects and especially allowed to determine the value of HAZ length well representing constraining effects in 9Cr1MoNbV steel weldments. It was also

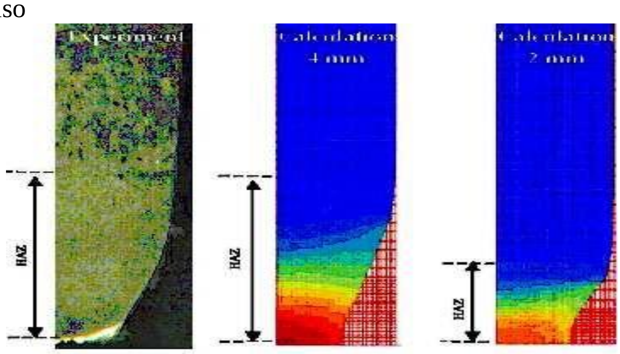

Figure 2.1. Weldment cut outs.

shown that the lower creep strength of the HAZ can mainly be attributed to its creep flow properties, whereas its intrinsic ductility is similar to that of the base metal.
A similar combination of physical experiments with numerical simulations used in [16]. ABAQUS finite element modeling (FEM) software is used to model the creep behavior and damage mechanisms of modified 9Cr1MoNbV steel weldments. Experimental creep results are used to identify parameters for a three-phase (base metal, welded metal and heat affected zone) creep models that includes the effect of damage. The influence of the thickness of the HAZ has been investigated, as it may vary according to the welding process. Three values of the thickness of the HAZ have been computed for a wide range of stresses.

2.2. Coupled creep-damage governing equations

Creep-damage constitutive equations of an isotropic material with isotropic damage are assumed in form:

$$\dot{\varepsilon}^{cr} = A_c \exp\left(-\frac{Q_c}{RT}\right)\frac{3\sigma_{vM}^{n-1}}{2(1-\omega)^n}S \qquad (2.1)$$

$$\dot{\omega} = A_d \exp\left(-\frac{Q_d}{RT}\right)\frac{\sigma_{eq}^{k}}{(1-\omega)^l} \qquad (2.2)$$

In Equations (2.1) and (2.2) $\dot{\varepsilon}^{cr}$ represents the creep strain rate tensor; $\sigma_{vM} = \sqrt{\frac{3}{2}s..s}$ is the Von Mises equivalent stress; S is the stress deviator; Ac, Ad, n, k, l are creep material parameters; is an isotropic damage parameter(0 < **ω** < **ω***), σeq is the damage equivalent stress, used in the form proposed by [17].

$$\sigma_{eq} = \alpha\sigma_{max} + (1-\alpha)\sigma_{vM} \qquad (2.3)$$

$$\sigma_{\max} = \frac{|\sigma_I| + \sigma_I}{2} \qquad (2.4)$$

By varying the parameter α one can generate different versions of the equivalent stress for better matching the predictions of theoretical models with experimental results on the long-term strength under complex stress state [7], [8],[9],[11].
To specify the different temperature effects on the creep and damage, we use two different functional relations: the first one is entered into the constitutive equation for creep strain rate and the second one into the evolution equation that determines the damage rate. The temperature dependence in relations (2.1),(2.2) is described by the Arrhenius function [15]. Here R - universal gas constant, Qc and Qd -the activation energies of creep and damage process, T - the absolute temperature, Ac , Ad - the material constants in temperature dependencies.
The most common methods of experimental investigation of the mechanical properties of materials at high temperatures are creep tests and long-term strength in uniaxial tension at constant stress and temperature. For such conditions system (2.1),(2.2) can be integrated. Taking notation σ11 = σ integrate the kinetic equation (2.2) with the initial condition ω = 0 at t = 0.

$$\omega(t) = 1 - [1 - Ad\exp\left(-\frac{Q_d}{RT}\right)(l+1)\sigma^k t]^{\frac{1}{l+1}} \quad (2.5)$$

The time to rupture t∗ can be defined with assumption ω∗ = 1 in the following form:

$$t_* = \frac{1}{A_d \exp\left(-\frac{Q_d}{RT}\right)(l+1)\sigma^k} \qquad (2.6)$$

By taking into account equation (2.5), the creep constitutive equation (2.1) is
integrated for ε_{11}^{cr} = εc r with the initial condition εc r = 0 for t = 0 as follows.

$$\varepsilon^{cr} = \frac{A_c}{A_d} exp - \frac{Q_d - Q_c}{RT}\frac{\sigma^{n-k}}{l-n+1} X\left[1 - [1 - A_d\exp\left(-\frac{Q_d}{RT}\right)(l+1)\sigma k t]1 l+1\right. \qquad (2.7)$$

In the study of creep processes in the case of constant temperature, without loss of generality, we assume Qc = Qd = 0, and the constants Ac , Ac should be determined by the results of experiments at a given temperature. Then, Equations (2.5) and (2.7) take the form:

ω(t) = 1 − [1 − Ad (l + 1)σk t] l +1 (2.8)

$$\varepsilon^{cr} = \frac{A_c}{A_d}\frac{\sigma^{n-k}}{l-n+1} X\left[1 - [1 - A_d (l+1)\sigma^k t]^{\frac{1}{l+1}}\right] \qquad (2.9)$$

The time to rupture at constant temperature is determined by the dependence

$$t_* = \frac{1}{A_d(l+1)\sigma^k} \qquad (2.10)$$

III. PARAMETRIC STUDY OF CREEP EQUIVALENT CONTINUUM

To simulate the microstructure of multi pass welding as an equivalent continuum at the macroscopic level considered representative volume element was assumed prismatic body with a cross section:

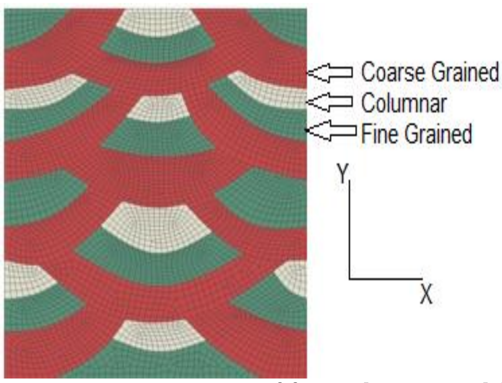

Figure 3.1 Cross section of finite element model of Volume Element

This section is considered as a repeating element is periodic in the plane OXY. Z axis is directed along the weld. Material properties of the weld metal zones are considered to be isotropic.
To describe the stationary creep of the weld metal zone Norton creep law for the incompressible material is used:

$$\dot{\varepsilon} = \frac{3}{2} S A_C \langle \sigma_{VM} \rangle^{n-1} \qquad (3.1)$$

where S is the stress deviator:

S = σ − σ0I

$$\sigma 0 = \frac{1}{3}\,\mathrm{tr}\sigma \qquad (3.2)$$

Two material constants, included in Eq.(3.1) are defined according to procedure described in Sect.2.1. Nowadays significant amount of experimental data is available for different materials. Examples of defining material parameters for Norton creep law can be found in [4], [7], [16], [17], [18], [19], [20].
Material parameters used for Eq.(3.1) are taken from [7] and are presented in Table 3.1. It should be noted that it is impossible to make the specimens directly from fine and coarse grained zones independently, that is why for these heat affected zones, material properties in them are

Table 3.1 Parameters of Norton law for weld metal zones

Zone Type	K MPa^{-n}/ sec	n
Columnar	$2.74 \cdot 10^{-21}$	7
Fine grained	$1.37 \cdot 10^{-20}$	7
Coarse grained	$1.37 \cdot 10^{-20}$	7

Section 2.2 outlined the sequence for determination of parameters characterizing the initial anisotropy of the weld metal, based on the basic physics experiments. Consider a procedure for performing numerical experiments for the theoretical finding these parameters.
The creep law for the homogenized continuum is presented by the averaged components in the volume V of the unit cell:

⟨ε˙i j ⟩ = Ac ⟨σvM ⟩n−1 bi j k l · ·⟨σk l ⟩ (3.3)

σvM = ⟨σ….B….σ ⟩1/2 (3.4)

where ⟨ε˙i j ⟩ and ⟨σk l ⟩ - averaged creep strain rates and stresses, which correspond to uniform macroscopic strain rate and stress:

$$(\sigma) = \frac{1}{V}\iiint_V \sigma\, dV \qquad (3.5)$$

$$(\dot{\varepsilon}) = \frac{1}{V}\iiint_V \dot{\varepsilon}\, dV \qquad (3.6)$$

For identification of 7 material constants in Eq.(3.3) 7 independent numerical tests should be executed. For these purposes 3-D finite element model of VE are created in the finite element code ABAQUS 3.2.
At first it is necessary to determine the conditions of reaching steady state stage for the strain rate. Series of creep analysis of VE were performed under the constant uniform stress ⟨σ11 ⟩ for different time levels.
From the results of numerical experiments one can extract the set of strain rate ε˙11 values for the different moments of time ti (i = 1, ..., N). In Figure 3.2 we can observe the creep strain redistribution during creep, with a visible first stage and

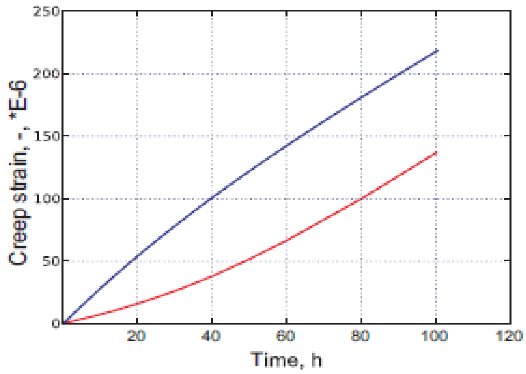

Figure 3.2 Creep strain in columnar zone and HAZ

On the figure 3.3 one can observe stress redistribution process under different stress levels in the different zones of the VE. It is clear that the higher the applied stress is, the more significant is the stress redistribution. We can observe the stress concentrating in the columnar zones and the HAZ is relaxing.

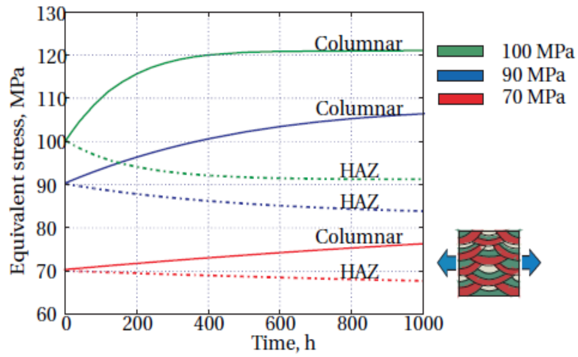

Figure 3.3. Equivalent stress redistribution in time for different zones

However to perform qualitative evaluation of the influence from the in homogeneity of the weld metal, we can take creep curves Fig. 3.19 of the columnar zone and fine-grained zone in HAZ of the base metal from [17], and assume that the relation between time to rupture would be the same as for the columnar and HAZ of the weld metal.

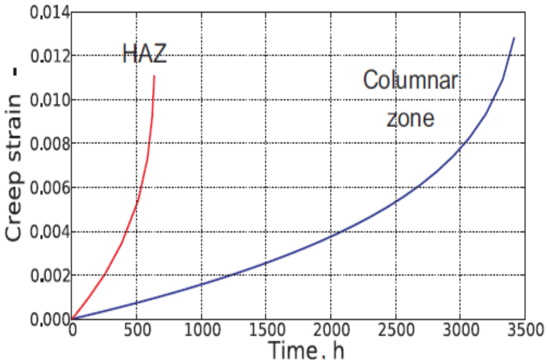

Figure 3.4 Creep curves assumed for columnar zone and HAZ

To model the creep damage behavior of the equivalent homogenous material for weld metal, VE from the previous analysis was used and the same set of numerical experiments was performed. As results of this numerical experiments damage parameter distribution on the VE and its evolution during time was obtained. In Figure 3.5 one can see the difference in the damage

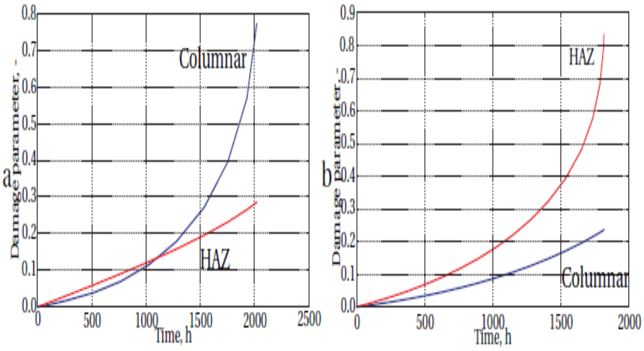

Fig 3.5 Damage parameter ω in tests on (a) longitudinal (b) transverse directions

Parameter evolution between a) longitudinal tension test and b) test in the transverse direction. In case of the longitudinal direction damage parameter increases faster on the columnar zone, despite the fact that HAZ is more prone to damage according to the material parameters. This happens because of the stress redistribution due to creep in the longitudinal tension test. In Figure 3.6 one can see that stress this numerical experiment concentrates in the columnar zone, and the in some time points equivalent stress in columnar zone may reach twice the value compared to HAZ. On the other hand,

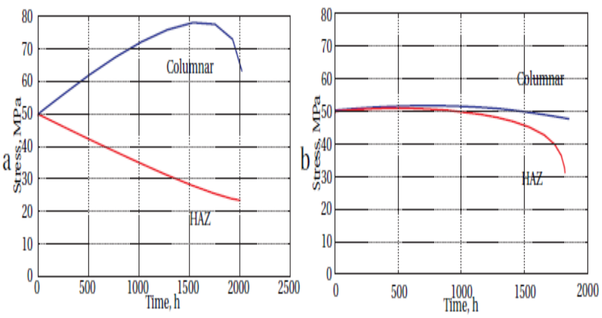

Figure 3.6 Stress redistribution in time for tension tests in 33 and 11 directions

in numerical experiments on tension in one of the cross-section directions, stress redistribution between the zones not so essential, however still been higher in columnar zone. This is why damage parameter in these tests reflects material parameters better, and increases faster in more damage prone zone - HAZ.

IV. RESULT AND DISCUSSION

In Fig.4.1 one can see the averaged equivalent creep strain redistribution over time for three numerical experiments on uniaxial tension in longitudinal, and two cross-section directions. As one can see, curves that reflect the behavior

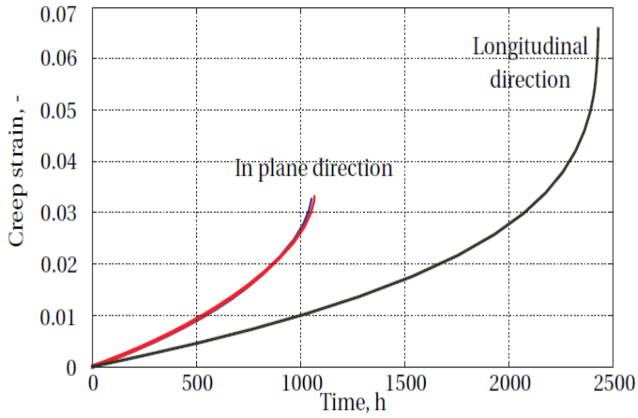

Figure 4.1 Equivalent creep strain in tension tests for different directions

of the VE in tension tests on the cross-section directions almost coincide, and the longitudinal tension test curve has lower creep rate and has higher time to rupture value. Based on this result one can assume that creep damage material properties of the equivalent material for multi-pass weld metal are transversely isotropic. To describes such anisotropy in the equivalent material response, the model of creep with damage for transversally isotropic material described in 2.2. was used.

Table 4.1 Time to rupture , h

-	16-pass	8-pass	4-pass
$t_*(1111)$	1740	1821	1899
$t_*(2222)$	1735	1837	1926
$t_*(3333)$	2342	2493	2614
$t_*(1212)$	891	956	1001
$t_*(1313)$	989	1032	1103

Multi-pass welds are commonly used when it is necessary to make a joint of thick-walled constructional elements, for example thick-walled tubes. To make such welding joints operators usually make an angle cut on the joining surface . This leads to difference in number of passes between the

areas close to the top and bottom surface of the constructional elements. As a result, this will cause the difference in the properties of top and bottom layers of weld metal. One of the ways to take this kind of operational features into account in modeling a real construction is to create a model with the each and every pass including the heat affected zones. However this will lead to non-reasonable computational costs. The way that is proposed in this work is to substitute this kind of complex inhomogeneous structure with three layers of homogenous equivalent materials, the properties of which will differ accordingly to number of passes.
Typical microstructure of the welded joint consists of base metal, weld metal and the heat affected zone (HAZ) that is formed from a part of a base metal as a result of a heating and cooling processes appearing during welding. In figure 4.2 one can see two model types of welded joint - one with the passes and one with the equivalent material layers. The material properties of the base metal and the HAZ used for analysis are taken from , and the properties for the equivalent material layers are taken from the analysis of VE's on a micro scale.

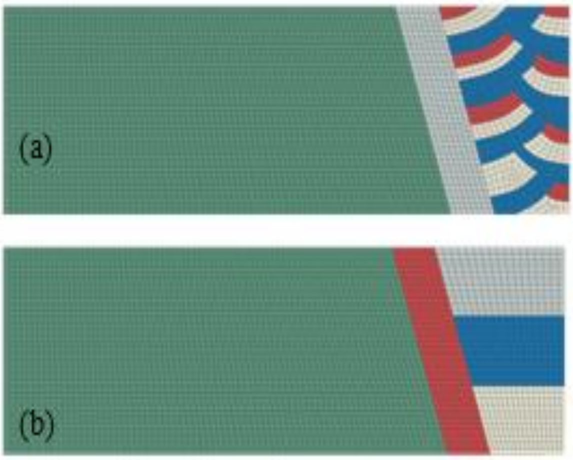

Figure 4.2 Finite Element Model of a welded joint (a) with passes and (b) with equivalent material layers

Table 4.2 Equivalent stress and creep strain response difference between models

	σ_{eq} (in plane)	σ_{eq} (longitud.)	ε_{eq} (in plane)	ε_{eq} (longitud.)
Top layer	2.4%	1.82%	1.7%	0.92%
Middle layer	0.83%	0.76%	0.69%	0.54%
Bottom layer	1.85%	1.3%	1.5%	1.47%

Comparing average equivalent stress response of each layer with the corresponding area of the model with passes one can see that the difference in response between two models is at maximum less than 2.5% (Table 4.2).

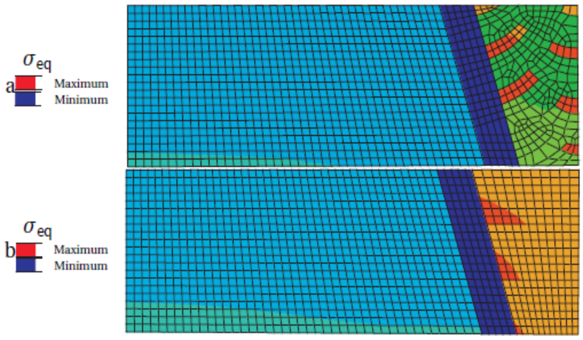

Figure 4.3 Equivalent stress redistribution after 1000 hours of creep (a) model with passes (b) model with equivalent material layers

V. CONCLUSIONS

A new micro - macro approach to the analysis of creep and creep rupture of structures with multi-pass welds is introduced. Theoretical basis of this approach is the modern advances in the theory of creep and continuum mechanics of damage. The proposed approach uses the results of metallographic examination of the microstructure of the welded joint. Essential novelty of the proposed approach is the consideration of the anisotropy of the creep properties and the development rate of damage in multipass welds. Practical implementation of the micro-macro approach required the use of known numerical methods in mechanics of deformable bodies and the development of new special algorithms.
Investigation of creep and fracture of welded structural elements approach proposed in the work has a potential for the development and improvement. This applies to modifications of creep-damage model for materials, as well as to developing more effective ways of homogenization of structurally inhomogeneous media. To achieve these objectives, the following tasks are planned:

- Defining relations for the creep strain rate (2.23) can be improved to reflect the process of hardening in the first stage of creep. Various forms of such ratios for the isotropic material are known. In the case of anisotropic models its necessary to overcome the problem of ensuring the continuity of theoretical creep curves for different directions.
- For structural elements of nuclear plant it is relevant to incorporate effect of radiation on the creep processes. In such operating conditions one can observe swelling of the material over time. Account of such phenomena in anisotropic materials creep models is a promising task.
- To use the proposed approach in the structural analysis of design elements the user-subroutine was developed and implemented in the software package ABACUS. Numerical experiments were performed on structural elements of power machinery, which confirmed the suitability of the proposed approach in design practice.
- Reduction of computational cost in defining material parameters of equivalent homogeneous materials is possible by the development of algorithms that use dual periodicity

conditions of representative volume.

• For typical forms of multipass welds it would be suitable to develop soft- ware of computer-aided design and analysis of the welds oriented for use in commercial software products.

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