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## Welding Damage Numerical Model of 15-5PH Stainless Steel

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### RESUME:

*For metal 15Cr-5Ni, a martensitic stainless steel, in the process of welding, it experiences the phase transformation of martensite to austenite during heating and the phase change to the martensite from austenite during cooling. Based on the study of damage concept in the multiphasic behaviour which occurs during welding process, a mesoscopic model is developed under phase transformation and damage condition. The constitutive equations of the model are coupling between ductile damage, small strain elasticity, finite visco-plasticity and phase transformation. The model uses the method of localization-homogenization to downsize to the single phase behavior and to combine to the macro behaviour. For the single phase behavior, it is based on the theory of thermodynamics and continuum damage mechanics (CDM). The constitutive equations are built to describe damage's growth and crack appearance during and after welding. In localization-homogenization processing, the TRIP (TRansformation Induced Plasticity) is taken into account.*

**MOTS-CLES :** *Welding Damage, Phase Transformation, Continuum Damage Mechanics(CDM), TRansformation Induced Plasticity(TRIP)*

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## 0 INTRODUCTION

Recently many efforts devoted on developing the numerical model to predict the residual stress induced by welding. Through homogenizing of material properties, quite a few macroscopic models are applied in the simulation of welding residual stress of phase-change materials. Further, some of such simulations are taken the volumetric change between  $\alpha$  phase and  $\gamma$  phase into account[1], and even some of models have considered the effect of phase-transformation induced plasticity[2-3]. With the development of the implementation of numerous experiments and further study of phase-transformation mechanism, several phase-change models were developed [4-5], and the applications of such models caused that the simulation of welding residual stress is more accurate and closer to the results of experiments. However, under certain conditions, damage and phase-transformation phenomenon exist simultaneously during welding process. Damage induced by welding usually happen during cooling stage of welding. It is obvious that mechanics properties of components or structures are affected by damage or even fracture induced by welding. Thus, it is really significant to use numerical modeling method to analysis and predict welding results including the distributing of residual stress and damage in many institutes and enterprises.

Although the achievement of damage mechanic provided various model to describe the damage evolution under different conditions [6-7], there is no evidence of a model with coupling of welding model considering TRIP and damage model. Such situations imply to cope with a diversity of damage models and add complexity to standard constitutive equations. The model contains three main ingredients, continuum damage mechanics, and transformation plasticity and multiphase behavior. The mesoscopic model was given briefly in the article [8]. However the description of model just used for the general metal materials with the feature  $\alpha$ -  $\gamma$  change, and did not mention the specific metal. As the further and supplementary of former study, here provide the specific metal of 15-5PH and also its identification is given in the study.

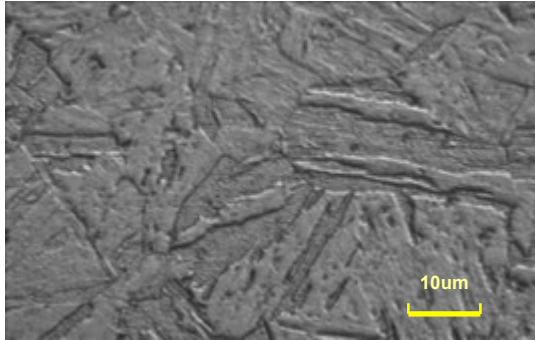
## 1 MATERIAL

15-5PH stainless steel is a martensitic precipitation hardening stainless steel offering high strength and common applications are components of aerospace including valves, shafts, fasteners, fittings and gears. The element compositions of 15-5PH (H1025) is shown in Tab.1. Welding of 15Cr-5Ni steel plays a significant role in the power and aeronautic industries. 15-5PH is quite different from austenitic stainless steel

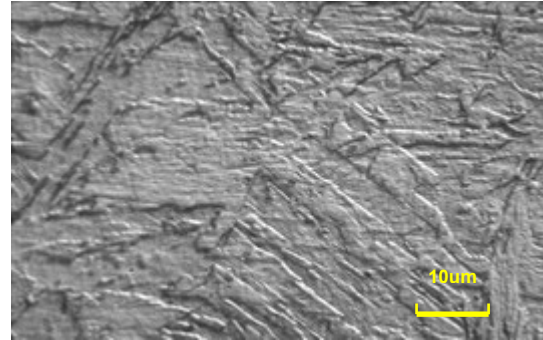
in that there are phase changes during heating and cooling phase. The microscopic observation of 15-5PH specimen were respectively done before and after welding (Fig.1).

**Table 1** Chemical compositions of 15-5PH stainless steel

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	N	NB
0.030	0.40	0.66	0.020	0.001	15.44	0.05	4.50	3.16	0.013	0.0247	0.292



Before welding



After welding

**Fig. 1** Microscopic observation (100 X) of 15-5PH steel

## 2 MESOSCOPIC MODEL

### 2.1 CONSTITUTIVE EQUATIONS

The mesoscopic model, which we introduced, is developed through the method of localization-homogenization. The homogenizing procedure used is the Taylor's approximation, which assumes homogeneous deformations in a heterogeneous medium with nonlinear behavior. This law provides the closest possible match with Leblond's theoretical case for elastoplastic phases. Such approach, called micro-macro, consists of starting from the behavior of each phase and working back to the macroscopic behavior of the material. After the localization, the behavior of each phase can be treated respectively, without coupling. Thus, the model can provide the freedom to choose the behavior type of each phase.

The approach was based on the Voigt model with equal repartition of strains in all phases of the multiphase composite.

$$\varepsilon = \varepsilon_i \quad (i = \alpha, \gamma) \quad (1)$$

Based on the principle of localization mentioned above, we split the total strain rate into two parts, one coming from the total microscopic strain rate of the phases, and the other representing the plastic transformation strain rate. Thus:

$$\dot{E}^{tot} = \dot{E} + \dot{E}^{pt} \quad (2)$$

In the model, classical plasticity and transformation plasticity are assumed to be uncoupled, which is true for small strain. Thus, the homogenization law for stress is:

$$\Sigma = \sum_{i=\alpha, \gamma} z_i \sigma_i \quad (3)$$

Such modeling scheme provides great flexibility in the calculation. Arbitrary constitutive laws, including different models of transformations plasticity rates and damage governing equations can be selected for each phase. Therefore, the equations of the mesomodel can be developed as follows.

The strain equations are

$$\dot{E}^{tot} = \dot{\varepsilon}_i + \dot{E}^{pt} \quad \forall i \quad (4)$$

$$\dot{\varepsilon}_i = \dot{\varepsilon}_i^e + \dot{\varepsilon}_i^{thm} + \dot{\varepsilon}_i^{vp} \quad \forall i \quad (5)$$

The transformation plasticity strain rate guided by Leblond's transformation plasticity model is presented to further explain the TRIP as follows:

$$\dot{\varepsilon}^{pl} = \begin{cases} 0 & \text{if } z \leq 0.03 \\ -\frac{3\Delta\varepsilon_{\gamma-\alpha}^{th}}{\sigma_{\gamma}^y} \cdot S \cdot (\ln z) \cdot \dot{z} & \text{if } z > 0.03 \end{cases} \quad (6)$$

where,  $\Delta\varepsilon_{\gamma-\alpha}^{th}$  is difference of thermal deformations between two phases, and  $\sigma_{\gamma}^y$  is limited stress of phase of austenite.  $z$  presents volume proportion of phase  $\gamma$ .  $S$  is deviator of the macroscopic stress.

For each phase's behavior, in order to focus on the interpretation of various coupling behavior clearly, it is reasonable to choose the same type of plastic hardening model (including isotropic and kinematic hardening) for two phases, although applying different models for each phase is closer to the reality. Material properties, including the damage parameters, should choose different data according to the various phase materials.

The elastic and thermo metallurgical strains are

$$\varepsilon_i^e = H^{-1}(T)\underline{\sigma}_i + [\varepsilon_i^{thm}(T) - \varepsilon_i^{thm}(T_{ref})] \quad (7)$$

with  $\varepsilon_i^{thm} = \alpha_i(T) \cdot Tl$  for  $\alpha$  phase,  $\varepsilon_i^{thm} = \alpha_i(T) \cdot Tl - (1-z_{\gamma})\Delta\varepsilon_{\alpha-\gamma}^{T_{ref}}$  for  $\gamma$  phase.

The coupling model for each phase is developed on the base of method of local state in the thermodynamics of irreversible process.<sup>1-2</sup> The various states' laws of the phases can deduced from the state potential of each phase and the partial differentials of each phase's pseudo-potential also can lead to flux variables (isotropic strain hardening variable  $R_i$ , back stress  $X_i$ , release ratio of elastic energy  $-Y_i$ , damage variable  $D_i$ ).

$$R_i = c_i(T)(1-D_i)[1 - \exp(-\gamma_i p_i)] \quad (8)$$

$$\underline{X}_i = \frac{2}{3} g_i(T) b_i (1-D_i) \underline{\alpha}_i \quad (9)$$

The yield function of each phase can be written:

$$f_i = f_i(\underline{\sigma}_i, R_i, \underline{X}_i, D_i) = \frac{J_2(\underline{\sigma}_i - \underline{X}_i)}{\sqrt{1-D_i}} - \frac{R_i}{\sqrt{1-D_i}} - \sigma_{yi} \quad (10)$$

then

$$F_i = f_i + \frac{a_i}{2(1-D_i)} J_2^2(\underline{X}_i) + \frac{b_i}{2(1-D_i)} R_i^2 + \frac{S_i(T)}{[S_i(T)+1](1-D_i)} \left[-\frac{Y_i}{S_i(T)}\right]^{S_i(T)+1} \quad (11)$$

The viscoplastic flow:

$$\underline{\varepsilon}_i^p = \frac{\partial \varphi_i}{\partial \underline{\sigma}_i} = \frac{3}{2} \frac{\dot{p}_i}{\sqrt{1-D_i}} \frac{\underline{\sigma}_i^D - \underline{X}_i^D}{J_2(\underline{\sigma}_i - \underline{X}_i)} \quad (12)$$

The evolution of the internal variable associated with isotropic hardening:

$$\dot{R}_i = -\frac{\partial \varphi_i}{\partial R_i} = u_i \langle F_i \rangle^{n_i} \quad (13)$$

The evolution of the internal variable associated with kinematic hardening:

$$\dot{\underline{X}}_i = -\frac{\partial \varphi_i}{\partial \underline{X}_i} = \frac{3}{2} \frac{\dot{p}_i}{\sqrt{1-D_i}} \frac{\underline{\sigma}_i^D - \underline{X}_i^D}{J_2(\underline{\sigma}_i - \underline{X}_i)} \quad (14)$$

## 2.2 NONLINEAR DAMAGE MODEL

The theory of the continuum damage mechanics is based on the assumption of the difference of scale between the micro-damage (microcracks and microvoids) and the Representative Volume Element (RVE). The damage analysis gives criteria for the creation of mesocracks, and then fracture mechanics is used to describe the phenomena. It is important to use a unique formulation to describe the different damage processes. It is based on the assumption that damage is driven by plastic strains, elastic strain energy and by an instability process. The macroscale scalar variable is defined to describe damage:

$$D = \frac{S_D}{S} \quad (15)$$

where  $S$  is the original surface, and  $S_D$  is the damaged surface.

$D=0$  : Undamaged material

$D=1$  : Fully broken material in parts

$0 < D < 1$  : Failure occurs but crack does not happen

The damage analysis gives criteria for the creation of mesocracks, and then fracture mechanics is used to describe the phenomena. For phase-transformation material, such as martensite stainless steel, there exist both martensitic phase and austenitic phase simultaneously during the specific heating or cooling stages. Therefore, it is more reasonable to use damage variables in two different phases respectively. Thus means the damage in the inclusions (martensite,  $D_\alpha$ ) is regarded different from damage in the matrix (austenite,  $D_\gamma$ ). In microscale approach, the local damage variable  $D_\mu$  at one point is defined by

$$D_\mu = \frac{dS_D}{dS} \quad (16)$$

In mesoscopic model, the damage variables can be given and developed by microscale definition of damage.

$$D_i = \frac{S_D^i}{S} = \frac{1}{S} \int_{S^i} dS_D = \frac{1}{S} \int_{S^i} D_\mu dS \quad (17)$$

where,  $D_i$  is the damage variable of phase  $i$ .

Because experimental results indicated that the kinetic law of damage evolution should conclude the actual damage state, the effective accumulated plastic strain and the damage state at failure. Experimental observation shows that almost microcracks and microvoids happened in the phase  $\alpha$ , because phase  $\gamma$  is much more "soft" and not easy to damage from the material view. Thus we can simply the model, and only damage in phase  $\alpha$  is taken into account. Therefore, following part of the article only studies damage in phase  $\alpha$  and  $D=D_\alpha$ . Damage dissipation potential is given as following equation

$$\varphi^D = \left[ \frac{1}{2} \left( \frac{-Y}{S_0} \right)^2 \frac{S_0}{1-D} \right] \frac{(D_{cr} - D)^{(\alpha-1)/\alpha}}{p^{(2+n)/n}} \quad (18)$$

and it provides damage rate

$$\dot{D} = - \frac{\partial \varphi^D}{\partial Y} = \frac{Y}{S_0(1-D)} \frac{(D_{cr} - D)^{(\alpha-1)/\alpha}}{p^{(2+n)/n}} \quad (19)$$

Because the elastic energy is

$$Y = \frac{\partial e^{tot}}{\partial D} = - \frac{\sigma_{eq}}{2E(1-D)^2} f\left(\frac{\sigma_H}{\sigma_{eq}}\right) \quad (20)$$

and the triaxiality factor is

$$f\left(\frac{\sigma_H}{\sigma_{eq}}\right) = \frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_H}{\sigma_{eq}}\right), \quad (21)$$

The damage rate becomes

$$\dot{D} = - \frac{\partial \varphi^D}{\partial Y} = - \frac{\sigma_{eq}}{2E(1-D)^2} f\left(\frac{\sigma_H}{\sigma_{eq}}\right) \frac{1}{S_0(1-D)} \frac{(D_{cr} - D)^{(\alpha-1)/\alpha}}{p^{(2+n)/n}} \quad (22)$$

For a ductile material, the equivalent Von Mises stress can be given as a function of the accumulated plastic strain using a Ramberg-Osgood power law as:

$$\frac{\sigma_{eq}}{(1-D)^2} = K p^{1/n} \quad (23)$$

Simplified evolution of damage is

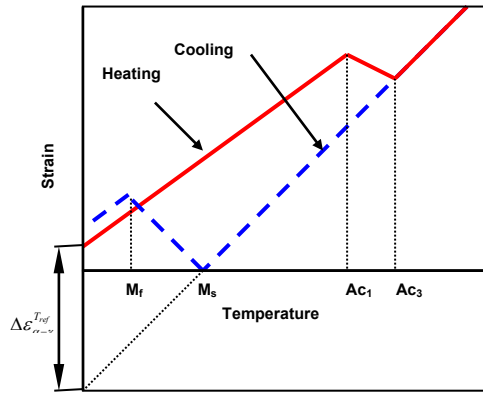
$$\dot{D} = - \frac{K^2}{2ES_0} f\left(\frac{\sigma_H}{\sigma_{eq}}\right) (D_{cr} - D)^{(\alpha-1)/\alpha} \frac{\dot{p}}{p} \quad (24)$$

### 3 MATERIAL PARAMETER IDENTIFICATION

This section deals with parameter identification of phase-transformation model and damage model for the material 15-5PH.

#### 3.1 PARAMETERS OF PHASE-TRANSFORMATION MODEL

The phase transformations often play a dominating role in the modeling of certain thermomechanical problems. Solid-state phase transformation causes the macroscopic geometric change because these different types of crystalline structures have different densities, which is so-called transformation-induced volumetric strain (Fig.2).



**Fig. 2** Schematic diagram of phase transformation under heating and cooling conditions

The empirical law of Koistinen and Marburger gives the voluminal fraction of martensite according to the temperature. The theoretical justification of this equation was given by Magee:

$$z_{\alpha} = 1 - e^{-\beta(M_s - T)} \quad (25)$$

where  $z_{\alpha}$  is voluminal proportion of martensite;  $M_s$  is martensite start temperature;  $\beta$  is coefficient depend on material;  $T$  represents temperature.

It also can be change to the form of increment by differential equation:

$$\Delta z_{\alpha} = -\beta \cdot e^{-\beta(M_s - T)} \cdot \Delta T \quad (26)$$

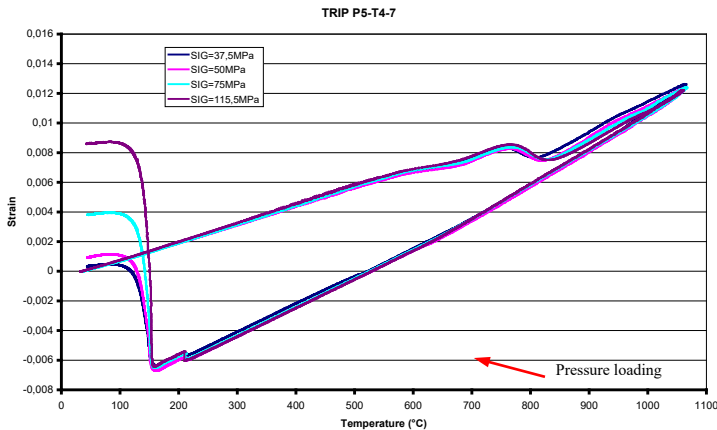
In our model, not only proportion of each phase but also volumetric change and transformation induced plasticity should take into account. Therefore, several parameters are required to apply. The project INZAT4 implements a series of relevant experiments in order to gain these parameters.

For  $M_s$ ,  $Ac_1$ ,  $Ac_3$  and  $\Delta\varepsilon_{\alpha-\gamma}$  (Fig.2), these parameters can be directly measured through the measurement of free-expansion experiment of uniaxial round specimen under heating and cooling conditions, and the parameter  $\beta$  also can be gained through fitting experimental results (Tab.2).

**Table 2** Parameters of phase transformation measured by experiments

Parameters	$M_s$	$Ac_1$	$Ac_3$	$\alpha_{\alpha}$ (mean)	$\alpha_{\gamma}$ (mean)	$\Delta\varepsilon_{\gamma-\alpha}^{th}$	$\beta$
value	160 °C	760°C	820°C	1.25E-05	2.09E-05	9.58E-03	0.011

The transformation plasticity strain is guided by Leblond’s transformation plasticity model (Equ.6). Specific experiments are designed to measure to identify the phase transformation induced plasticity through loading pressure at cooling stage. Loading pressures with value of 37.5MPa, 50MPa, 75MPa and 115.5MPa, are applied at 200°C during the cooling stage (before  $M_s$  point), and last to the completion of martensite transformation. The corresponding figure describing the expansion strain is shown in Fig.3. In order to measure and gain TRIP, it is necessary to remove the elastic strain induced by the load stress, and then TRIP in various pressure loadings are given in Tab.3.



**Fig. 3** Expansion curves under stress loading of heating and cooling experiment

**Table 3** Phase-transformation induced plasticity under stress loads (experimental results)

$\sigma_{eq}$ (MPa)	37.5	50	75	115.5
$\varepsilon_{eq}^{pt}$ (%)	0.22	0.27	0.54	1.01

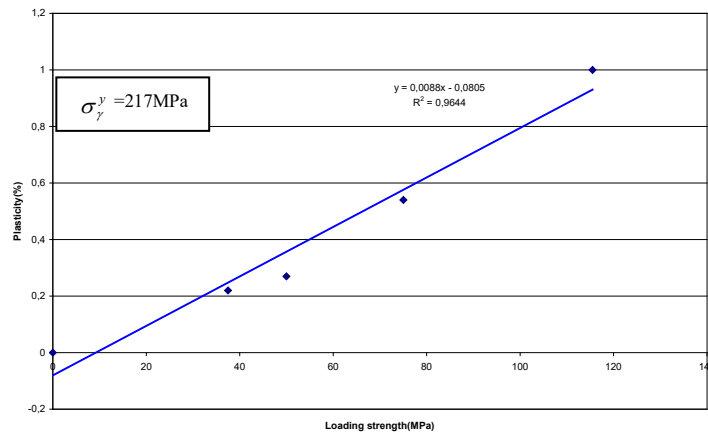
The equation (6) provides increment of transformation induced plasticity. In order to identify the parameter  $\sigma_{\gamma}^y$ , the integral form is given:

$$\varepsilon^{pt} = -\frac{2\Delta\varepsilon_{\gamma-\alpha}^{th}}{\sigma_{\gamma}^y} \cdot \sigma_{eq} \int_0^1 \ln z \cdot dz \quad (27)$$

$$\varepsilon^{pt}(z) - \varepsilon^{pt}(0) = -\frac{2\Delta\varepsilon_{\gamma-\alpha}^{th}}{\sigma_{\gamma}^y} \cdot \sigma_{eq} [z(\ln(z) - 1)]_0^z \quad (28)$$

$$\varepsilon^{pt}(1) - \varepsilon^{pt}(0) = \frac{2\Delta\varepsilon_{\gamma-\alpha}^{th}}{\sigma_{\gamma}^y} \cdot \sigma_{eq} \quad (29)$$

Through fitting the data in the Tab.2, the parameter  $\sigma_{\gamma}^y$  was identified in consequence (Fig.4).



**Fig. 4** Fitting of parameter of Leblond's model

### 3.2 PARAMETERS OF DAMAGE MODEL

The damage model requires several parameters to be identified. These constants and their explanation are as follows:

$D_0$  : The initial damage value. It is accepted that the initial damage is difficult to determine because it is strictly related to the inclusions distribution in the virgin material microstructure. A scanning electron microscope investigation can provide an idea of the initial particle distribution and sizes and amount of damage in the strained material structure. However, as usual, this parameter is assumed to be zero for a virgin material or at the beginning stage of the damage calculation.

$\varepsilon_{th}$  : The plastic strain caused to threshold damage. Plasticity damage starts to occur only after a specific strain level. Below this strain level the material microstructure behaves as a continuum. Microvoids can nucleate either by debonding of the included particles from the ductile matrix or by particle breaking. If the bond between the matrix and the particle is weak, the threshold strain can be of the same order of magnitude as the matrix elastic strain proportional limit and its exact determination can be difficult. While when large plastic flow occurs prior to damage, the threshold strain can be accurately identified.

$\varepsilon_{cr}$ ,  $D_{cr}$  : Strain at failure and critical damage. When this critical strain is reached, failure occurs.  $\varepsilon_{cr}$  is directly related to the critical amount of damage that critically reduces the load carrying capability of the effective resisting section. In theory, when failure occurs the critical damage variable  $D_{cr}$  should be equal to 1. In fact, Experimental observations of almost metals show that failure occurs before  $D = 1$ . It is possible to suppose that the final deformation phase prior to failure is dominated by the void coalescence process that rapidly pushes the net resisting area to instability. As usual, we can roughly identify the values through the tensile experiment with loading and unloading, while a scanning electron microscope investigation can provide more accurate value of  $D_{cr}$ .

$\alpha$  : The damage exponent. This constant carries information regarding the type of the kinetic law of damage evolution and can be determined from tensile tests. The value of gives the degree of nonlinearity of

the damage evolution law and takes into account the global effect of the three void growth stages on the damage evolution as a function of the accumulated plastic strain. For a given  $\varepsilon_{cr}$ ,  $\varepsilon_{th}$ ,  $D_0$ , and  $D_{cr}$ , a discriminating  $\alpha$  value exists which determines the convexity of the damage evolution as a function of plastic strain.

In order to identify above parameters of damage, integrating the damage evolution from  $D_0$  and  $D_{cr}$ , we get

$$(D_{cr} - D_0)^{1/\alpha} = \frac{1}{\alpha} L \ln\left(\frac{p_{cr}}{p_{th}}\right) \quad (30)$$

as we mentioned above  $D_0 = 0$ , then

$$D_{cr} = \left[ \frac{1}{\alpha} L \ln\left(\frac{p_{cr}}{p_{th}}\right) \right]^\alpha \quad (31)$$

Integrating the damage evolution from  $D$  to  $D_{cr}$ , we get

$$(D_{cr} - D)^{1/\alpha} = \frac{1}{\alpha} L \ln\left(\frac{p_{cr}}{p}\right) \quad (32)$$

$$D = D_{cr} \left\{ 1 - \left[ \frac{\ln(p_{cr}/p)}{\ln(p_{cr}/p_{th})} \right]^\alpha \right\} \quad (33)$$

In the experiment of uniaxial loading, the effective accumulated plastic strain  $p$  is equal to the uniaxial plastic strain.  $p_{th}$  is equal to the uniaxial plastic strain threshold  $\varepsilon_{th}$  and  $p_{cr}$  is equal to the uniaxial strain at failure  $\varepsilon_{cr}$ . Here, elastic strain can be neglected and plastic strain can be replaced by the total uniaxial strain.

$$D = D_{cr} \left\{ 1 - \left[ \frac{\ln(\varepsilon_{cr}/\varepsilon)}{\ln(\varepsilon_{cr}/\varepsilon_{th})} \right]^\alpha \right\} \quad (34)$$

The model involves three constant  $\varepsilon_{cr}$ ,  $\varepsilon_{th}$  and  $D_{cr}$ , and also can be expressed as a function of the uniaxial fracture strain  $\varepsilon_{cr}$  corresponding to a triaxiality ratio:

$$p_{cr} = \varepsilon_{cr} \left[ f\left(\frac{\sigma_H}{\sigma_{eq}}\right) \right]^{-\alpha} \quad (35)$$

The exponent  $\alpha$  is determined as the slope of the best fitting line of the experimental damage measurements given by

$$\ln\left(1 - \frac{D}{D_{cr}}\right) = \alpha \ln\left[\ln\left(\frac{\varepsilon_{cr}}{\varepsilon}\right)\right] - C \quad (36)$$

$$C = \alpha \ln\left[\ln\left(\frac{\varepsilon_{cr}}{\varepsilon_{th}}\right)\right] \quad (37)$$

and where the constant C is the intersection of the fitting line with the ordinate axis. Usually the failure strain can be measured pretty well, but the threshold strain is not always so easy to determine as a result of the experimental scatter.

Once the slope is found, it is possible to have a good estimation of  $\varepsilon_{th}$  from the previous expression as

$$\varepsilon_{th} = \varepsilon_{cr} \exp(-B) \quad (38)$$

where  $B = \exp(C/\alpha)$ .

Through fitting the experimental results, it is not difficult to identify the parameters of damage model (Fig.5). Since the parameters are calibrated (Tab.4), the evolutions of damage provided by constitutive equations are obtained. The Fig. 6 provides the comparing between the fitting curve and experimental results of damage evolution of martensite at 20°C.

**Table 4** Identified damage parameters of 15-5PH (martensitic phase)

Temperature	$\varepsilon_{th}$	$\varepsilon_{cr}$	$D_{cr}$	$B$	$\alpha$
20°C	0.01	0.21	0.18	5.4	0.16
200°C	0.01	0.20	0.07	4.0	0.08
600°C	0.02	0.19	0.06	3.3	0.08
700°C	0.02	0.19	0.20	3.4	0.29



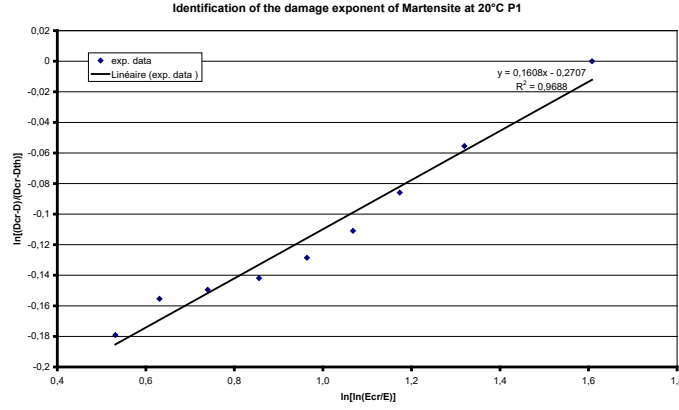


Fig. 5 Identification of the damage exponent of martensite at 20°C

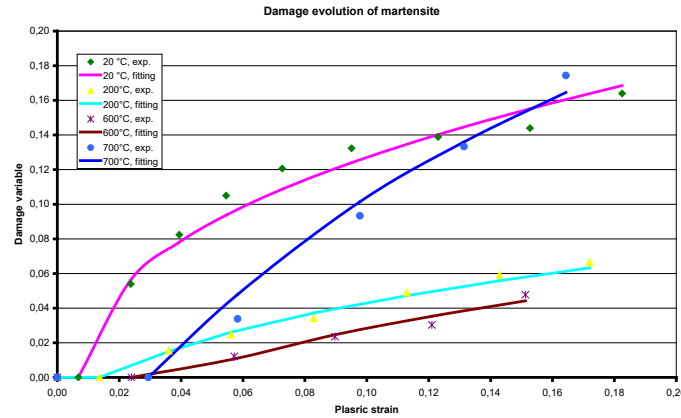


Fig. 6 Fitting of damage evolution of martensite at 20-700°C

#### 4 NUMERICAL IMPLANTATION

In order to apply to the numerical predication of welding, the constitutive equations should be implant into program. CASTEM 2000 is a proper program, which integrates not only the computing processes themselves but also the functions of construction of the model (preprocessor) and the functions of processing of the results (postprocessing). The algorithm in small displacements is given in the following part.

The partition of the deformations at the microscopic level is preserved. On the other hand, the macroscopic deformation of phase  $\gamma$  is:

$$E^I = \varepsilon_\gamma + \Delta \varepsilon_{\alpha-\gamma}^{T_{ref}} \quad (39)$$

The incremental problem then becomes:

$$\begin{aligned} \Delta_{12} \underline{F} = B^T & \left[ \sum_{i=\gamma, \alpha} z_{i(2)} H_{(2)} \right] (\Delta_{12} E - \Delta_{12} E^{pl}) - B^T \left[ \sum_{i=\gamma, \alpha} z_{i(2)} H_{(2)} \Delta_{12} \varepsilon_i^{th} \right] \\ & - B^T \left[ \sum_{i=\gamma, \alpha} z_{i(2)} H_{(2)} \Delta_{12} \varepsilon_i^p \right] + B^T \left[ \sum_{i=\gamma, \alpha} (z_{i(2)} H_{(2)} - z_{i(1)} H_{(1)}) H_{(1)}^{-1} \sigma_{i(1)} \right] \end{aligned} \quad (40)$$

Then, we can get:

$$K_{(2)} \Delta_{12} \underline{U} = \Delta_{12} \underline{F} + \Delta_{12} F^{th} - \Delta_{12} F^e + \Delta_{12} F^p + \Delta_{12} F^{pl} \quad (41)$$

with

$$\Delta_{12} F^{th} = B^T \left[ \sum_{i=\gamma, \alpha} z_{i(2)} H_{(2)} \Delta_{12} \varepsilon_i^{th} \right]$$

$$\begin{aligned}\Delta_{12}F^e &= B^T \left[ \sum_{i=\gamma,\alpha} (z_{i(2)}H_{(2)} - z_{i(1)}H_{(1)})H_{(1)}^{-1}\sigma_{i(1)} \right] \\ &= B^T \left[ \sum_{i=\gamma,\alpha} H_{(2)}(z_{i(2)}H_{(1)}^{-1}\sigma_{i(1)} - z_{i(1)}H_{(2)}^{-1}\sigma_{i(1)}) \right] \\ \Delta_{12}F^p &= B^T \left[ \sum_{i=\gamma,\alpha} z_{i(2)}H_{(2)}\Delta_{12}\varepsilon_i^p \right] \\ \Delta_{12}F^{pt} &= B^T \left[ \sum_{i=\gamma,\alpha} z_{i(2)}H_{(2)} \right] \Delta_{12}E^{pt}\end{aligned}$$

The resolution of residual balance is:

Initialization:

$$\begin{aligned}\Delta_{12}U^{(0)} &= K_{(2)}^{-1} \left[ \Delta_{12}F + \Delta_{12}F^{th} - \Delta_{12}F^e \right] \\ \Delta_{12}E^{pt(0)} &= 0\end{aligned}$$

Iteration for the balance:

calculation of total deformation

$$\Delta_{12}E^{(j)} = B\Delta_{12}U^{(j)}$$

iteration for the phases

$$\Sigma_{(2)}^{(j)} = \sum_{i=\gamma,\alpha} z_{i(2)}\sigma_{i(2)}^{(j)}$$

$$\underline{F}_{\text{int}}^{(j)} = B^T \Sigma_{(2)}^{(j)}$$

$$\underline{R}^{(j)} = \underline{F}_2^{(j)} - \underline{F}_{\text{int}}^{(j)}$$

test

$$\|\underline{R}^{(j)}\| \leq \xi$$

if not

$$\Delta\Delta_{12}U^{(j)} = K_{(2)}^{-1}R^{(j)}$$

$$\Delta_{12}U^{(j+1)} = \Delta_{12}U^{(j)} + \Delta\Delta_{12}U^{(j)}$$

$$\Delta_{12}E^{pt(j+1)} = E_{(2)}^{pt} \Sigma_{(2)}^{(j)} - E_{(1)}^{pt} \Sigma_{(1)}^{(j)}$$

if yes

finish of iteration

Finish

## 5 CONCLUSIONS

The objective of this study is to develop the damage model, which implant in the numerical welding model. The model takes into account the thermal, metallurgical and mechanical phenomena. In the study, not only the theoretical derivation of model is given, but also the experimental of material 15-5PH provided the calibration of parameters of transformation model and damage model.

The model coupled thermal, metallurgical and mechanical behaviors can be used to predict not only the strain and stress fields but also the damage distribution in welded work piece. The mechanical calculation, which includes the difference in phase compactness and transformation plasticity, takes the actual behavior of each phase and damage effects. There is no coupling between elastoviscoplasticity, transformation plasticity and damage.

The material 15-5PH has the phenomenon of transformation between martensite and austenite phase with the temperature development. The identification of parameters of model, especially for damage model, is not

easy and more experience orientation to some extent. The study provides the parameters of damage model at different temperature level, and they make it possible to apply the model to numerical simulation.

The constitutive equations and numerical implantation lead to the numerical prediction, and provide an useful tool to analyze strain, stress and damage distribution of welded workpieces.

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