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PREDICTION OF THERMAL DISTORTIONS BY A NEWLY DEVELOPED DIMENSIONLESS MODEL

Darko Landek[1], Dragutin Lisjak[1], Thomas Lübben[2]

[1]*University of Zagreb, Faculty for Mechanical Engineering and Naval Architecture, Ivana Lucica 1 10000 Zagreb, Croatia, {darko.landek, dragutin.lisjak}@fsb.hr*

[2]*Stiftung Institut für Werkstofftechnik, Badgasteinerstr. 3, 28359 Bremen, Germany, luebben@iwt-bremen.de*

ABSTRACT

Investigations of transformation free cooling processes of long cylindrical workpieces in a gas nozzle field conducted at project SFB 570, at research Centre for Distortion Engineering University of Bremen, Germany, indicated a specific behavior of the dimensional changes. It is find that the dimension changes are correlated to only a few dimensionless numbers which are created by the following parameters: shape and dimensions of component, its initial temperature, temperature of the quenching media, heat transfer coefficient, heat conductivity, heat capacity, density, thermal expansion coefficient, Young´s modulus, Poisson´s ratio, yield strength and strain hardening behavior. The mentioned material's properties were selected form from literature from a group of 29 austenitic stainless steels, and they are statistically analyzed. The mechanical response of steel on the transformation free cooling process is analyzed by the kinematic strain-hardening model by using the commercial FEM program SYSWELD. The relative changes of the component dimensions are analyzed in dependence of five autonomous dimensionless numbers with theirs interactions in aim to find the proper equations for prediction of unavoidable distortions in a transformation free cooling. For definition of these equations a standard method of regression analysis and a novel method known as genetic algorithm analysis are used. This new conception of predicting unavoidable distortions depended of specified material and process parameters by dimensionless numbers are proposed as the "FL3 model".

Keywords

unavoidable distortion, thermal strain, dimensionless numbers, austenitic steel

1. INTRODUCTION

Former investigations on prediction of distortion in austenitic steel without phase transformations includes compute simulations and experiments with cooling of austenitized cylinders in aim to find some relations between unavoidable thermal strains dependent from process parameters and material properties /1-4/. Cooling of austenitized parts has been always accomplished with inhomogeneous temperature distributions, which have thermal stresses and thermal strains as a consequence. If material cannot elastically accommodate these stresses, the thermal strains cause plastic deformation. These deformations occur before reaching first phase transformation, when steel microstructure is in the supercooled austenitic phase. So, investigating the problem of unavoidable distortions after transformation-free cooling gives knowledge about influential factors on the behaviour of workpieces and it supplies us with some ideas about practical measures in order to reduce these distortions /4/.

2. DIMENSIONLESS NUMBERS AND SIMULATION PLAN

Analysis of transformation-free cooling leads to a set of coupled differential equations, which describe development of thermal stresses with strain hardening caused by the processes of heat transfer and conduction /4,5,6/. Solution of these unsteady and nonlinear equations is a complex task even if the FEM software is used. The details for selection of material properties and setting up simulations for this problem are described in references /1,2,3/. For analyzing of simulation results, as also for setting up experiments the dimensionless analysis has been proposed /3/. The proposed dimensionless numbers for analyzing of relative change of length contained process parameters, material properties, and geometrical dimensions (table I) [2,3]. As the changes of length and diameter are functions of position, their mean values must be calculated, as it is shown in Fig. 1.

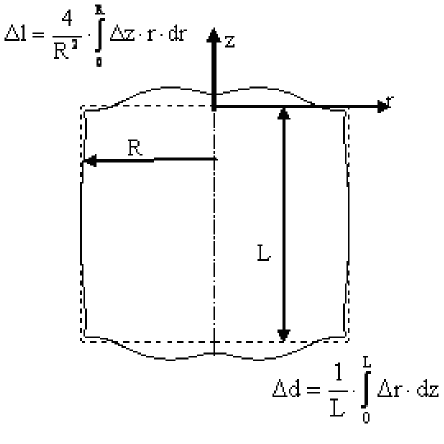

Figure 1. Method of determination of changes in length and in diameter /2/

The first of dimensionless numbers which indicates heat transfer at workpieces with very good heat conductivity is the Biot number.

$$F_I = Bi = \frac{(V/S)\cdot\alpha}{\lambda} \qquad (1)$$

The volume to surface ratio (V/S) at eq. (1) indicates characteristic linear dimension of a part, α means the average heat transfer coefficient and λ is the average heat conductivity in the considered temperature interval. The other dimensionless numbers are defined as shown in table I and ref. /3,4/.

Table 1: Definition of dimensionless numbers /3,4/

	Dimensionless number					
	$Bi=F_1$	F_2	F_3	F_4	F_5	F_6
Term	$\frac{(V/S)\cdot\alpha}{\lambda}$	$\alpha_{th}\cdot(T_0-T_\infty)$	ν	$\frac{E}{\sigma_0}$	$\frac{\sigma_0}{K}$	$\frac{1}{n}$
Length L (m)						
Diameter D (m)						
Initial temp. of material T_0 (^oC)						
Temp. of quenching media T_∞ (^oC)						
Heat transfer coeff. α ($W/(m^2K)$)						
Heat conductivity λ (W/(mK))						
Coeff. of therm. expan. α_{th} (1/K)						
Poisson's ratio ν (1)						
Young's modulus E (MPa)						
Yield strength σ_0 (MPa)						
Plasticity modulus K (MPa)						
Strain hardening exponent n (1)						

The proposed six dimensionless numbers (table I) are not the only possible set of numbers. Nevertheless, their influence on thermal strains is confirmed by numerical simulations and by conducted experiments /1-4/. All products and quotients of these numbers are also dimensionless (e.g. $F_4F_5=E/K$), but the six terms are independent from each other. That means that it is not possible to create one of them with mathematical operation of two or more other terms. From the proposed set of dimensionless numbers at table I, their effect on thermal distortion has been systematically investigated for following four numbers (F_1, F_2, F_4 and F_5) (Table II). The levels of changes of material properties which correspond to these number values covered the group of twenty-eight representative austenitic stainless steels (table III) according to the database of Cambridge Engineering Selector programme. That means that derived model is valid for non transformation cooling of this group of austenitic steels. The research was directed to define an adequate expression (2) which enables to connect changes of dimensionless numbers showed at table I with the corresponding relative changes in length ΔL/L.

$$\frac{\Delta L}{L}=f(F_1,F_2,F_3,F_4,F_5,F_6) \quad (2)$$

Table II: The plan for selection of dimensionless numbers for numerical simulations of transformation-free cooling of cylinders made of austenitic steels /4/

Levels of Biot number $\mathbf{F}_1$ and corresponding heat transfer coefficients (α, W/m^{2}K)															
Bi	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
α	454	909	1363	1817	2272	2726	3180	3635	4089	4543	4998	5452	5906	6361	6815

Levels of other dimensionless numbers for every Biot number selected above						
$\mathbf{F_2}$			$\mathbf{F_4\ 10^3}$			$\mathbf{F_3}$
0.0130	0.0171	0.0213	0.3751	0.7522	1.1294	0.27
Initial temperature ($\mathbf{T_0}$, ^{o}C)			$\mathbf{F_5}$			$\mathbf{F_6}$
778	1020	1084	0.36455	0.18182	0.12091	1.9313

Table III. A representative group of analysed austenitic stainless steels /4/

Steel grades
27Cr-9Ni (as cast); 19Cr-10Ni-2,5Mo; 19Cr-9Ni-0,2C; 19Cr-10Ni ; 19Cr-11Ni-2,5Mo; 19Cr-9Ni; 19Cr-11Ni-3,5Mo; 24Cr-13Ni; 25Cr-20Ni ; X8CrNiS18.9 ; AISI 201; AISI 202; AISI 205;AISI 216; AISI 301; AISI 302; AISI 304; AISI 305; AISI 308; AISI 309; AISI 310; AISI 314; AISI 315; AISI 316; AISI 317; AISI 321; AISI 329; AISI 330

Numerical simulations of transformation-free cooling were performed by the computer program SYSWELD. During these simulations, the heat transfer problem has been solved simultaneously with the problem of mechanical stresses and strains. A cylinder of 20 mm diameter and 200 mm length was chosen as a geometrical domain for all simulations. The choice of this geometry can be explained as follows: the ratio of length and diameter is significantly larger than 3 and the most experimental results are sampled for that dimensions. All simulations have been carried out with 2D models using kinematic strain hardening model /1,2/.

3. RESULTS AND DISCUSSION

The first type of analysis of simulation results was using a nonlinear regression analysis to determine the correlation (2). For simplification of regression equation a parameter model is proposed and developed by sing the computer program Matlab with the Statistics Toolbox module. This regression model describes the correlation (2) as function of dimensionless numbers (F_i)/4/:

$$\frac{\Delta L}{L} = \begin{cases} \left(0.021773 + 0.118466 p_\varepsilon + 0.158284 p_\varepsilon^2\right) p_\varepsilon F_1^3 + \\ \left(-0.031725 - 0.096060 p_\varepsilon + 0.098018 p_\varepsilon^2\right) p_\varepsilon F_1^2 + \\ \left(-0.030447 - 0.186136 p_\varepsilon + 0.080925 p_\varepsilon^2\right) p_\varepsilon F_1 + \\ \left(0.000413 - 0.002881 p_\varepsilon + 0.001303 p_\varepsilon^2\right) F_1 + \\ \left(0.002591 - 0.017961 p_\varepsilon + 0.062401 p_\varepsilon^2\right) p_\varepsilon + \\ 0.000033 \end{cases} \tag{3}$$

$$p_\varepsilon = \left(\frac{F_2}{1-F_3} + \left(\frac{F_2 F_4 F_5}{1-F_3} \right)^{F_6} - 0.0610457 \right) \frac{1}{F_4} \tag{4}$$

This model has a possibility to give a unique analytical expression for prediction of relative change in length after transformation-free cooling of cylinders made of any austenitic steel mentioned in table IV. The obtained R-square value of the approximation expressed by equations (3) and (4) is equal to 0.9474 with 95% confidence bounds. The model has been called due to three levels of selection of materials properties used for their derivation, and due to the first characters in names of its authors (as the **F**rerichs -**L**andek - **L**isjak - **L**übben model).

The second type of analysis of simulation results was using a genetic methods. Only a brief description of genetic methods (genetic algorithms - **GA** and genetic programming - **GP**) will be given in this paper. The basic concepts of genetic algorithms were set forth by /5/, which showed how the evolutionary process could be applied to artificial systems /6/. The genetic algorithm is a mathematical algorithm which transforms a set (population) of mathematical objects into a new set using operations similar to reproduction and survival of the fittest, as Charles Darwin described in natural populations. The operations are called reproduction, crossover, and mutation. Each new population is called a generation. The fitness of each member of the current generation is evaluated according to some specified function. The members with the best fitness are more likely to be selected to be carried over to the next generation (reproduction) or used to create offspring (crossover) which will be included in the next generation. Members with poor fitness are more likely to be eliminated from the population. Members can also be selected at random and altered (mutation).

The expression for predicting dL/L obtained by genetic programming (GP) is in the form(5):

$$dL/L=(F_4 \cdot F_5^{F1} \cdot ((F_4 - F_5) \cdot F_5/(F_4 - F_3))^{F6} \cdot F_5 \cdot F_5^{F1} \cdot F_1+(F_2 \cdot F_3 \cdot F_5/(F_4 - F_3))^{F6}) \cdot F_1 \qquad (5)$$

Comparisons between experimental values vs. and genetic values are shown at the Fig. 2. The obtained R-square value of the GP model is equal to 0.743 with 95% confidence bounds. As showed the genetic programming model predicted relative changes of length dL/L not as good as regression analysis model but it needs more development and testing. On the other side GP model takes into account the every non dimensional number as specific members of equation.

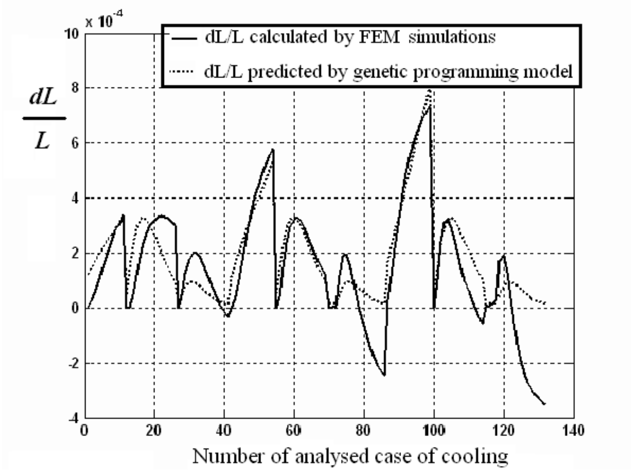

Figure 2. Correspondence between FEM calculated relative changes in length after transformation-free cooling of cylinders made of austenitic steels and predicted by genetic programming model

4. CONCLUSION

In this paper it was shown, that due to dimension analysis, the problem of the relative length change prediction of cylinders can be reduced firstly from 14 parameters down to 6 dimensionless numbers, and then with introducing of deformation parameter p_ε it can be further reduced to two dimensionless numbers only:

$$\frac{\Delta L}{L} = f\left(\frac{V\alpha}{S\lambda}, \alpha_{th}(T_0 - T_\infty), \nu, \frac{E}{\sigma_0}, \frac{\sigma_0}{K}, \frac{1}{n}\right) = f(F_1, F_2, F_3, F_4, F_5, F_6) = f(F_1, p_\varepsilon) \quad (6)$$

The approximation equations (3) to (5) for this task has been derived by nonlinear regression analysis and genetic programming method. The proposed mathematical model named as FL3-model can be used for the optimization of transformation-free cooling parameters, optimization of dimensions and also for the selection of optimum steel grades which get a minimum relative changes in length. But in some cases the differences between the regression model and the simulation by FE method are not negligible. Consequently the authors will study in future work other combinations of the dimensionless numbers to receive an improved description of the dimensional changes.

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