Fast model of phase transformations for cooling of Pyroware 53 steel

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1. Introduction

Gear wheels are important parts of the airplane engines, in particular as helicopter transmission gears, and their properties are critical for the safety of passengers. Among materials, which meet the severe requirements, Pyrowear 53 steel seems to be the most popular. This is a carburizing steel possessing good temper resistance and high hot hardness while maintaining high core impact strength and fracture toughness. It is characterized by good wear resistance and fracture resistance in cycling loading [1]. The exceptional properties of this steel are obtained in thermo-chemical treatment composed of carbonizing followed by austenitizing annealing, quenching, freeze-branding and low temperature tempering. While low pressure vacuum carburizing is generally used [1,2], high pressure process is under investigation by many researchers [3]. There is the fundamental difference between the liquid and gas quenching. It has been proven that gas quenching with constant heat transfer coefficient cannot generate the similar cooling rates compared to liquid quenching [4]. Thus, design of this new process requires numerical models, which describe heat exchange between furnace atmosphere and the part as well as phase transformations during cooling. Advanced CFD (Computer Fluid Dynamics) software has to be used in the microscale. These programs are characterised by very high computing costs. On the other hand, both models (macro CFD and micro phase transformations) have to be coupled as shown in [5]. It means that reduction of the computing costs of the phase transformation model is crucial for the effectiveness of the simulations. Thus, development of the fast and reliable phase transformation model for the Pyrowear 53 steel was the main objective of our work.

2. Model and results

Two models were considered and compared regarding their reliability and effectiveness. The first was an upgrade of the well-known JMAK (Johnson-Mehl-Avrami-Kolmogorov) equation:

$$X = 1 - \exp(-kt^n) \tag{1}$$

where: t – time, X – volume fraction of a new phase, k, n – coefficients.

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The upgrade of this equation composed [6]: i) Coefficient k depends on the temperature and the grain size. Modified Gauss function proposed in [7] was used for the temperature and power function was used for the grain size; ii) Equilibrium carbon and molybdenum concentration in the austenite was calculated accounting for precipitation of carbides, mainly M6C. Equation describing kinetics of precipitation during cooling was introduced; iii) Effect of the current composition of the austenite on the bainite start (B_s) and martensite start (M_s) temperatures was accounted for.

The second model is based on the Leblond equation [8]. The main assumption of Leblond was that the rate of the transformation is proportional to the distance from the equilibrium:

$$\frac{dX}{dt} = k(X_{eq} - X) \tag{2}$$

In equation (2) X_{eq} is an equilibrium volume fraction of the considered phase, which for ferrite is a function of the temperature:

$$X_{eq}(T) = \frac{c_{\gamma\alpha}(T) - c_0}{c_{\gamma\alpha}(T) - c_\alpha(T)} \tag{3}$$

where: c_0 – carbon concentration in the steel, $c_{\gamma\alpha}$, $c_{\gamma\beta}$ – carbon concentration in the austenite at the γ/α and at the $\gamma/cementite$ interface, respectively. These equilibrium carbon concentrations were calculated using ThermoCalc software.

Equilibrium volume fractions for pearlite and bainite are equal 1. Similarly to the JMAK model, coefficient k in equation (2) depends on the temperature and the grain size. Since equation (2) is the 1st order differential equation, the incubation time has to be introduce to account for the delay of the material response due to nucleation. Identical equations are used for ferrite, pearlite and bainite transformations but the coefficients are different. The incubation time is calculated from the equation:

$$\tau(T) = a_1 D_\gamma^{a_2} \exp\left(\frac{a_3}{RT_K}\right) \frac{1}{(T_s - T)^{a_4}} \tag{4}$$

In both models X represents volume fraction of each phase with respect to the maximum volume fraction of this phase in given temperature ($X \subset [0,1]$ for each phase) and F represents volume fraction of each phase with respect to the whole volume of the material, what means that $\sum_{i=1}^{i} F_i = 1$ (i represents ferrite, pearlite, bainite and martensite).

Thus, for each phase we have $F = X_{eq}X$. Both models contain several material coefficients, which had to be determined for the steel Pyrowear 53. Inverse algorithm developed by the Authors in [6] was used for an identification of the coefficients on the basis of results of dilatometric tests performed at various cooling rates. The tests were carried out for the samples with the nominal chemical composition of the Pyrowear 53 (0.065% C, 0.38% Mn, 1% Cr, 2% Ni and 0.86% Si) and for the samples with the 1% of carbon. The former supplied the data for identification of the phase transformation models for the core of the gear and the latter for the carburised material of the teeth. Various preheating cycles before the tests were applied and, as a consequence, various grain size prior to transformations was obtained. In consequence grain size could be introduced as a variable in the model.

Numerical tests have shown that the predictions of the models are close to each other, therefore, the results for the JMAK only are presented below. Selected results of the validation of the models are shown in Figure 1. Validation confirmed very good accuracy of both models.

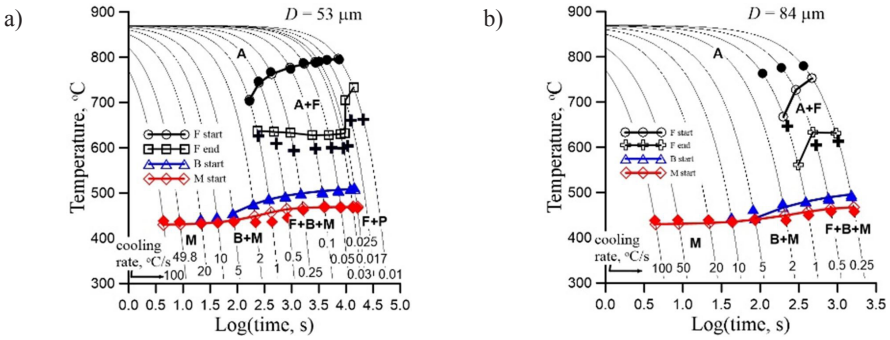

Figure 1. Measured (full symbols) and calculated (open symbols) start and end temperatures of phase transformations in the CCT tests for the grain size 53 μm (a) and 84 μm (b).

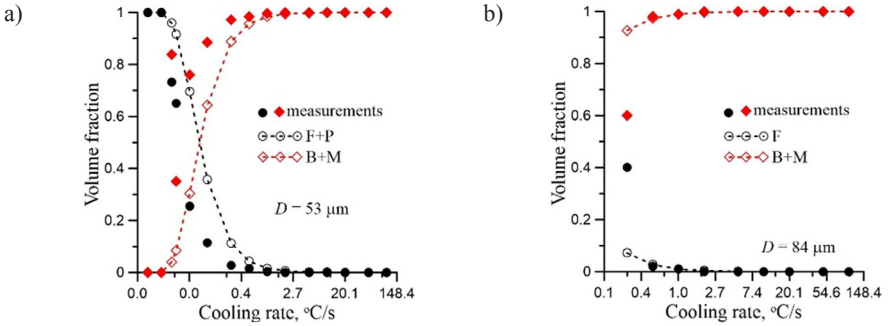

Figure 2. Measured (full symbols) and calculated (open symbols) volume fractions of phases for the grain size 53 μm (a) and 84 μm (b).

The following conclusions were drawn on the basis of experimental results and numerical modelling: i) Precipitation of carbides, in particular M6C, has influence on the phase transformation in the Pyrowear 53. Therefore, changes of the carbon and molybdenum concentration were accounted for in the model; ii) Kinetics of the phase transformations was simulated using upgrades of the JMAK and Leblond models. Both models gave good results comparable with the experiments. The Leblond model, which does not need application of the additivity rule, was selected as better for coupling with the FE software; iii) The critical cooling rate for the core samples with nominal chemical composition was about 1°C/s, which is attainable in the gas quenching. For lower cooling rates ferrite with ultra-fine precipitates appeared. Purely ferritic microstructure was obtained for very low cooling rates below 0.02°C/s.The critical cooling rate for the carburized samples was about 0.1°C/s. For very low cooling rates pearlite appeared in the microstructure but martensite was observed in the whole investigated range of the cooling rates.

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