On basic computing of the titanium phase transformation during rapid heating and air cooling

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Abstract. A certain pulse of electric current is a powerful tool for rapid heating of metals. In recent years, much research has indicated that the current improves mechanical properties of a wide scope of alloys. Particularly, it can induce a novel phase transformation in titanium. In this fashion, the present paper focused on numerical analysis of the pulse-induced phase transformation occurring in Ti-6Al-4V alloy. Specifically, the article suggested how to build a simple model based on the key experimental results and carefully prepare the input data in order to map out the β-phase volume fraction.

1. Introduction

Titanium alloys are widely used in many industries due to their attractive combination of properties such as low density, excellent strength-to-weight ratio, superior corrosion, and erosion resistance [1-3]. However, their low uniform elongation, huge deformation resistance, and high yield to tensile ratio prevent titanium components from broadening their applications. In the past few years, there has been considerable interest in the practice of Electric Current Pulse (ECP) technique improving these properties as an alternative to a hot forming treatment. The ECP can not only improve an overall formability but also influences recovery, recrystallization, phase transformation, grain refinement, and amorphous nanocrystallization in a wide range of alloys [4-12].

In contrast to conventional diffusion-controlled transformation, Zhang et al. [13-14] suggested the ECP-induced rapid heating for α-Ti to β-Ti diffusionless phase transformation in Ti–6Al–4V alloy. They trained some 1 mm-thick dogbone-shaped sheets with less than 10% β-Ti phase volume percentage via subjecting them to the 400 μs ECP treatment. The temperature rise of the shoulder parts was 850–1000 ^{o}C. After that, during the subsequent air cooling, the diffusion-controlled phase transformation occurred from the high-temperature β-Ti to low-temperature α-Ti. As a result, the novel lamellar β-Ti martensite (with greater β-phase volume fraction) showed higher hardness when compared with other structures of Ti–6Al–4V. Namely, the average hardness of the final samples was 408 HV, larger than that of the original samples (382 HV).

Despite the huge dataset, the important question of phase transformation kinetics was not touched yet. Hence, the objective of the present work was (a) to compute a basic kinetics of Ti-6Al-4V phase transformations during the ECP-induced rapid heating and subsequent air cooling by tracing the β-phase volume fraction, and (b) define the hardness after all treatments.

2. Model overview

The modeling approach taken in the present work consisted of FEM analysis using standard models of phase transformations in DEFORM-2D v.9.0. The calculation included two operations: the ECP-induced rapid heating and air cooling. In both cases, the plain strain approximation and Lagrangian incremental method were employed. Material Data for α- and β-phase of Ti–6Al–4V was extracted from [15-16].

2.1. Rapid heating

The author utilized Resistance Heating module to compute the ECP treatment. The top face of the vertically placed, 4mm width and 50mm height, rectangular sample was subjected to the current flux ~10^4 A for 400 μs, while the bottom face was grounded with zero voltage. During the whole operation Heat Exchange with Environment was applied to all specimen boundaries. The sample's irregular grid was comprised of triangular elements with optimum number of 2000.

A kinetics model for martensitic diffusionless transformation was taken in accordance to Magee's equation [17]. Assuming that the sample had nominally the same carbon level during the heating and since there was no stress dependency in the presented model, the author quantified the phase volume fraction by the following relation:

$$\xi_m = 1 - \exp(\psi_1 \cdot T + \psi_4) \tag{1}$$

in which T - temperature, ψ_1 and ψ_4 are constants defined later.

2.2. Air cooling

After completion of the ECP-induced rapid heating, the air cooling via heat exchange with environment at room temperature was performed. In this operation, a simplified Avrami equation [18] for a volume fraction of diffusion-based transformation was denoted as

$$\xi_J = 1 - \exp\left(A \cdot \left[\frac{T - T_S}{T_E - T_S} \right]^D \right) \tag{2}$$

in which T - average element temperature, T_S - starting temperature of the transformation, T_E - ending temperature of the transformation, A and D - constants derived in section 3.

3. Results and discussion

It is well-known that the phase volume fraction, composition, grain size, and morphology all affect service properties, and consequently the specific application of Ti-6Al-4V components. However, coupled analysis of all these factors during phase transformation is challenging because of a number of reasons. Hence, arguably, the best approach was to study their influence one at a time and then try to make some generalization. In this regard, presented work concerned with β-phase volume fraction kinetics only and left plenty of space for the future research.

3.1. Rapid heating

In order to compute the α-Ti to β-Ti diffusionless phase transformation, the two values of $\psi_1 = -0.00433$ and $\psi_4 = 0.0353$ were defined using equation (1) and a couple of temperature and β-phase volume fraction datasets. Namely, the author assumed $\beta = 5\%$ at 20°C and $\beta = 95\%$ at 700°C.

Figure 1 and figure 2 summarize the average temperature change and β-phase alteration during the ECP-induced rapid heating, respectively. As can be seen in the figures, the chosen values for ψ_1 and ψ_4 enabled to get $\beta = 98\%$ at near-transus temperature of 994°C and thus approved the aforementioned assumption.

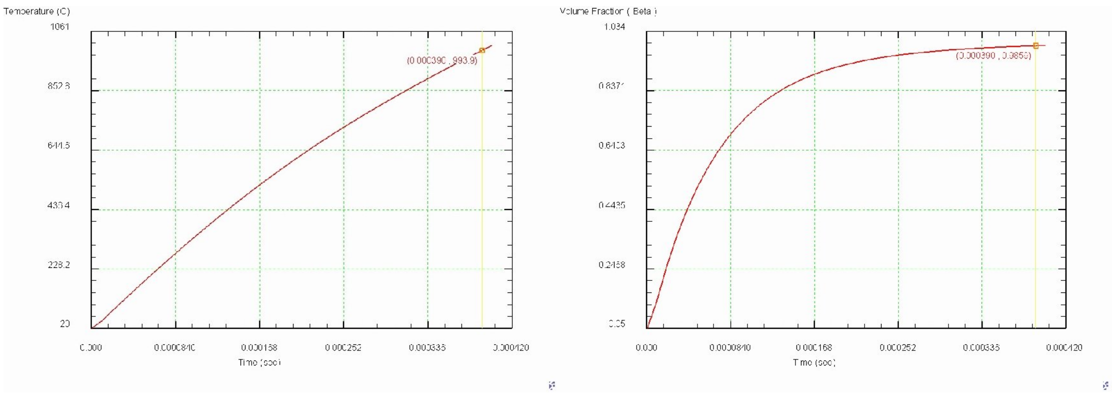

Figure 1. The ECP-induced alteration of temperature (on the left) and β-phase volume fraction during rapid heating (on the right).

3.2. Air cooling

Computation of the air cooling and succeeding β -Ti to α-Ti diffusion-controlled transformation required definition of A and D parameters in equation 2. These demands were met via applying the following strategy. First, based on collected results in the published literature, the author assumed the core transformation occurring in between 400-900°C, i.e. $T_S = 900^o C$ and $T_E = 400^o C$ in equation (2). Second, a set of temperature and β-phase volume fraction was taken out of a previous rapid heating calculation: $T_{0.98} = 884^o C$ with $\beta = 97.7\%$. Finally, a number of temperatures between 500 and 700 °C at intervals of 1 to 10 °C were numerically examined in order to determine $T_{0.5}$, i.e. the temperature with $\beta = 50\%$. Specifically, this temperature was meant to meet two criterions: (a) the β-phase volume percentage after the rapid heating and subsequent air cooling was to be higher than an initial one of 5%. This limitation resulted in a bunch of "valid" temperatures for $T_{0.5}$ all between 500 and 635 °C. However, it still had left 170 valid pairs for A and D parameters in equation 2. Hence, assuming that the hardness at room temperature was proportional to the β-phase volume percentage and considering the experimental data (the hardness experienced a 5-to-7% increase in its value after the rapid heating and air cooling), the following restriction was assigned: (b) the hardness after the heating and subsequent air cooling should have been 5 to 7% higher than an initial value.

The applied strategy zeroed in $T_{0.5} = 633^o C$, $A = -1.48284$ and $D = 1.21218$ with consecutive results shown in figure 2.

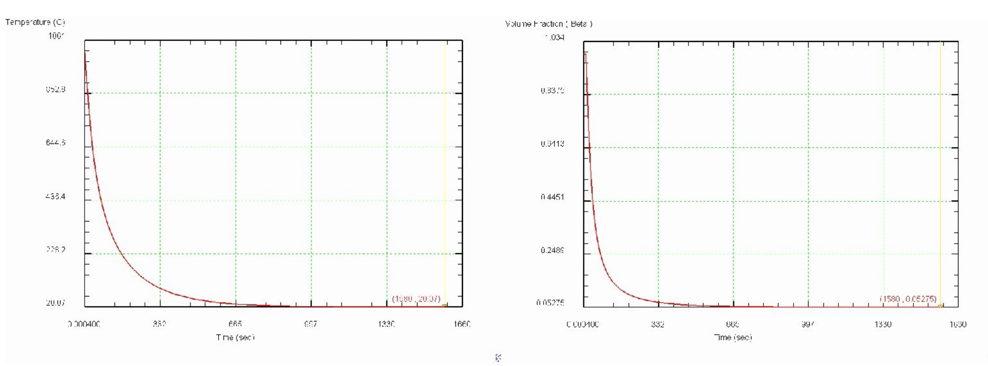

Figure 2. The alteration of temperature (on the left) and β-phase volume fraction during air cooling (on the right).

Thus, the overall computation revealed that: (a) the final β-phase volume percentage was higher than initial, namely 5.28% against 5% before the treatment; and, (b) the final hardness was 42.2 HRC against 40.0 HRC for the "as-received sample". Both, results agreed with experimentation done by Zhang et al.

Although an accuracy of the computation should be greatly improved with additional experimentation, the present study may be particularly useful for the design of thermomechanical processes for titanium alloys in which the phase transformations play a key role.

4. Conclusion

The numerical analysis conducted herein has tracked down the β-phase volume fraction during the Ti-6Al-4V phase transformations. The assessed hardness after the rapid-heating and subsequent air cooling was within the appropriate scope. The overall computation complied with major experimental results [13-14].

ACKNOWLEDGEMENTS. The author is grateful to Prof. Beklemishev N N for useful discussions and Kharlamov A A for providing DEFORM-2D license. This work was supported by Grant No.P653 "Research in the Effect of Electrical Current on Structure and Operational Characteristics of Crystalline Materials" within the Federal Target Program "Scientific and Scientific-and-Pedagogical Personnel of Innovative Russia" for 2009 – 2013.

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