Journal
of Achievements in Materials
and Manufacturing Engineering

VOLUME 22
ISSUE 1
May
2007

Crack initiation and propagation in FeAl matrix

D, Renowicz [a], S.J. Skrzypek [b],*

[a] Department of Mechanics of Materials, Faculty of Materials Engineering and
Metallurgy, Silesian University of Technology, ul. Krasińskiego 8, 40-019 Katowice, Poland
[b] Department of Physical and Powder Metallurgy, Faculty of Metals Engineering
and Industrial Computer Science, University of Science and Technology-AGH,
Al. Mickiewicza 30, 30-059, Kraków, Poland
* Corresponding author: E-mail address: skrzypek@uci.agh.edu.pl

Properties

ABSTRACT

Purpose: of this paper is evaluation of macroscopic and microscopic residual stresses and their influence on nucleation and development of cracking in Fe-Al-C cast alloy

Design/methodology/approach: In the case of particular chemical composition of Fe-Al-C alloy phenomena of its self-disintegration appears. Fracture mechanic methods with additional consideration of residual stresses were applied. The last one was measured by X-ray diffraction method.

Findings: Measurnaments and calculations proved that crack nucleation and development is controlled by diffusion of hydrogen and oxygen to chemical reaction with Al_4C_3 precipitations. This process is enhanced by existing residual stresses. When total stress approaches to critical stress level the cracks gradually develops.

Research limitations/implications: Microstructure of high-aluminium alloy (35.5 wt.% Al) consisted of brittle matrix with Al_4C_3 precipitations. Microstructure of this matrix appeared in a form of intermetallic compound as a superlattice FeAl.

Practical implications: These kind of intermetallics is practically applied in high temperature working machine components. In many cases they are under high level of residual stresses. Any progress in describing of cracking in this type of microstructure has real practical importance. Modeling of crack nucleation and farther its growth using finite elements method confirmed with real measurements make an interesting approach in characterization of cracking of the alloys..

Originality/value: Morfology of Al_4C_3 precipitation in FeAl superstructure alloy and its self-disintegration process can be ruled by chemical composition and solidification conditions. The elaborated physical model of cracking can be used to estimate durability of this Fe-Al-C alloy.

Keywords: Crack resistance; Fracture mechanic; X-ray phase analysis; Computational material science

1. Introduction

Durability of machine parts depends on many factors and one of them are interactions having distortion nature.. They appear in a form of crystal defects and lattice curvature connected with elastic strains/stresses which are created by mechanical, chemical, metallurgical and heat flow factors. Among them there are

welding or assembly stresses [1-6], phase transformations [7] and thermal residual stresses. [8-10] and hydrogen interaction as well [11]. There are also distortions caused by chemical forces like due to chemical reactions between Al_4C_3 and oxygen and water vapor in high aluminium Fe-Al-C cast alloy. This is known phenomena which finally produces cracking and self-disintegration [12, 13]. Calculation and measurnament of microstresses around grains and

carbide precipitation and in intermetallic matrix are presented in this work. The level of macroscopic residual stresses were caused by solidification process and during degradation Al_4C_3 carbides in a form of plate.

2. Experimental

Macro and microscopic residual stresses were measured with X-ray diffraction methods. The difractometer D8 Advance with cobalt tube radiation was used. The modified g-$sin^2\psi$ metod with grazing incidence angle X-ray diffraction geometry were applied [14-16]. This metodolgy anabled tomography like measurnaments in non-destructive way. This geometry of diffractin is characterized with small and constant incidence angle and with constant effective depth of penetration which is regulated with incidence angle of X-ray beam [16].

Using this non-destructive technique it was possible to repeat measurnaments of the same area on the sample versus time of chemical reaction and cracking development. A phase analysis, lattice parameter and lattice elastic strains can be measured with this diffraction [17].

Bragg equation and some crystallographic relations were used in measurement methodology of residual stresses:

$$a_{\varphi\psi} = d_{hkl}\sqrt{h^2 + k^2 + l^2} = \frac{\lambda}{2\sin\Theta} \tag{1}$$

where: $a_{\varphi\psi}$- lattice parameter measured in direction defined with φ and ψ angels , d_{hkl}- interplanar distance between crystallographic planes $\{hkl\}$, λ- wavelength, Θ- Bragg angle, ψ– angle between normal to the sample and normal to diffracting planes $\{hkl\}$, φ– angle between x axis of the sample and direction of measured stress component.

An elastic strain measured in particular direction can be expressed with equation

$$\varepsilon_{\varphi\psi} = \frac{d_{\varphi\psi} - d_0}{d_0} \tag{2}$$

where: d_0- interplanar distance between crystallographic planes $\{hkl\}$ in unstressed sample (powder).

An elastic strain $\varepsilon_{\varphi\psi}$ can be transformed into sample coordinates with relation:

$$\varepsilon_{\varphi\psi} = \varepsilon_1 a_1^2 + \varepsilon_2 a_2^2 + \varepsilon_3 a_3^2 \tag{3}$$

$\varepsilon_1, \varepsilon_2, \varepsilon_3$– main strains, a_1, a_2, a_3– direction cosine of the angles between strain measurement direction and principal direction 1, 2, 3.

Using above equation and Hook's law for plane stress field, principle equation of $sin^2\psi$ diffraction method can be derived: [16,17]:

$$\varepsilon_{\varphi\psi} = \frac{1+\nu}{E}\sigma_\varphi \sin^2\psi - \frac{\nu}{E}(\sigma_1 + \sigma_2) \tag{4}$$

where: $\sigma_\varphi = \sigma_1\cos^2\varphi + \sigma_2\sin^2\varphi$, σ_1 i σ_2 – principle plane stresses, E, ν - elastic mechanical constances.

A microstresses were measured by X-ray diffraction method consisted in diffraction peak analysis. A physical widening of diffraction lines β were estimated with assumption of Gauss function fitting procedure [18].

$$\beta = \sqrt{B^2 - b^2} \tag{5}$$

here: B– half-width of measured diffraction line, b– half-width of reference sample.

Experimentally evaluated physical widening is used to calculate microstrains and microstresses [14,18]:

$$\bar{\varepsilon} = \frac{\beta}{4 \cdot tg\Theta} \tag{6}$$

Substituting microstrains to Hook's law microstresses (the second order of residual stresses) can be evaluated. Their range is of order of FeAl grains around Al_4C_3 precipitation.

For this purpose the diffraction line profile of $\{211\}$ were analysied. A dyfractograms were recorded in normal envioremental conditions i.e. room tempereture, moisture 70%÷80%. Using grazing angle X-ray diffraction geometry it was possible to measure surface layers with thickness of $g_1 = 3,75$ μm, $g_2 = 7,5$ μm, $g_3 = 10,5$ μm, $g_4 = 14,0$ μm during 0÷484 h in non-drstructive mode. X-ray diffraction patterns were recorded evry 24 hours. An example of microstresses distribution is presented on Figure 1.
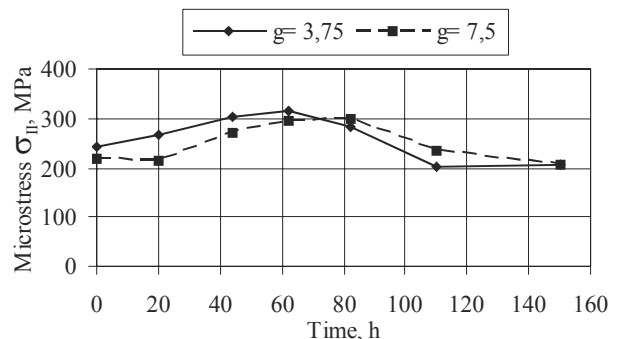

Fig. 1. Microstresses σ_{II} distribution in surface layer versus time of self-disintegration

Proces of microcracking was developing in surface layer (thickness about 14 μm), further calculations were curied out for the state of plane stress.

A local maximum of normal stresses was asumed as a characteristic criterion of the material as the stresses causing

cracking in surface layer. Following values were taken into account:

$$\sigma_\varphi = \sigma_I, \text{and } \sigma_3 = 0; \qquad (7)$$

where: σ_I – macroscopic residual stress in surface plane, σ_3-principal stress.

The macroscopic residual stress σ_φ was measured by $\sin^2\psi$ method (eq.5), and procedure needs strain measurnament $\varepsilon_{\varphi\psi}$ for choosen crystallographic planes {100},{110},{200} and {211} under different ψ angles [19]. An example of results for thickness of surface layer of g=3,75 μm is presented on Figure 2.

Residual stresses distribution σ_φ in surface layer of the sample versus time of self-disintegration for different thickness is presented on Figure 3.

Measurnaments were curied out from begining (state after casting) to the powder state what appeared after 484 hours. The irradiated area was defined by geometrical conditions and cross-section of the incidence X-ray beam and for Bragg-Brentano geometry. The surface was S=4,8-11,5 mm^2 and was changing continuously versus θ angle. In the case of grazing angle X-ray diffraction radiated area was twice larger but for particular incidence angle constant.
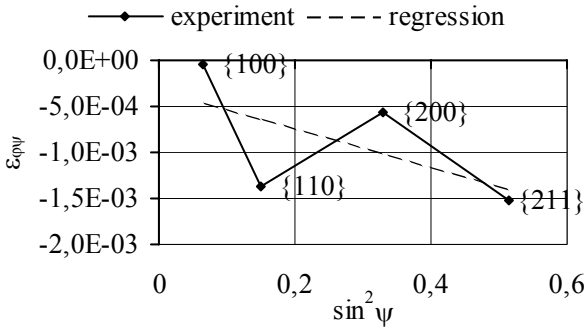

Fig. 2. Basic relation for measured macroscopic residual stress of FeAl lattice for g-$\sin^2\psi$ method for the thickness of surface layer 3,75 μm

Microscopic residual stresses σ_{II} in FeAl grains around Al_4C_3 precipitation was calculated from Hook's law with assumption of plain stress field:

$$\overline{\varepsilon} = \frac{1}{E}\left(\overline{\sigma}_1 - v \cdot \overline{\sigma}_2\right) \qquad (8)$$

where: $\overline{\sigma}_1$, $\overline{\sigma}_2$ - are averaged main micro-stresses. For uniform tensile it was assumed $\overline{\sigma}_1 = \overline{\sigma}_2 = \sigma_{II}$. Above assumption is taken from fact that there are two neighboring areas where tensile and compression appear to fulfill equilibrium conditions. Therefore absolute value of second order stresses can be expressed as:

$$\sigma_{II} = \frac{\overline{\varepsilon} \cdot E}{1 - v} \qquad (9)$$

The averaged crystal lattice microstrain can be treated as a measure of elastic cumulated energy in grains which can contribute in cracking process [20].

According to superposition rule total stress distributions in surface layers can be calculated. Superpose both i.e. solidification stresses and stress components due to chemical reaction of Al_4C_3 of self-disintegration the total stresses can be analyzed and presented on Figure 4.
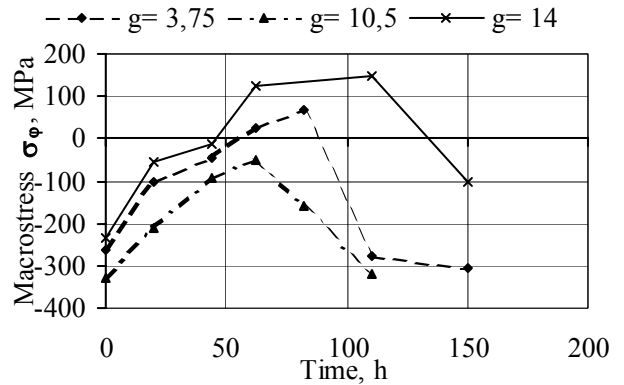

Fig. 3. Macroscopic residual stresses change versus time of self-disintegration of FeAl in surface layer for different thickness g, μm

3. Analysis of the results

The obtained results of calculations and measurements confirmed importance of residual macro and micro-stresses in grains of FeAl superlattice around Al_4C_3 precipitation. Micro-stresses like oscillation fields from averaged macroscopic stress level energetically contributes in chemical reaction with environment and in self-disintegration process. The micro-stresses decrease versus time after 60 hours. After 484 hours they approach to zero what was found before (Fig.1.).
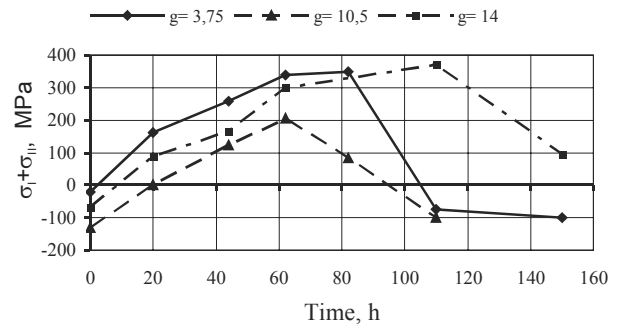

Fig. 4. Total stress distribution versus time of self-disintegration of FeAl in surface layer for different thickness g, μm

Macroscopic stresses at the very beginning were compressive. They changed in another way for the reason of self-disintegration

of Al_4C_3 carbide. When cracking has started macroscopic stresses decreased and in time of cracking i.e. after 60-90 hours they approached to tensile (Fig. 3). The maximum of the total stresses indicate also that most intensive cracking took place after about 60-110 hours. A relaxation processes i.e. decrease of stresses appeared in that time.

4. Conclusions

The maximum of normal tensile stresses in FeAl grains of matrix was main cause of cracking. Nucleation of cracks and their development can be observed in microstructure. Some cracks in Al_4C_3 carbides appeared as the result of disintegration and their chemical reactions with moisture.

Direction of crack development and time relations of cracking and stresses change indicates on critical total stresses.

The results confirmed on algebraic add of micro and macroscopic residual stresses in particular directions can be treated as the fulfilling conditions for hypothesis of maximum normal stresses in self-disintegration process.

The measured compressive macroscopic residual stresses resulting from solidification superimposed with microscopic stresses and finally in carbide-matrix interface zone tensile total stresses caused cracking.

Acknowledgement

References

[1] N.T. Ninh, M.A. Wahab, The effect of residual stresses and weld geometry on the improvement of fatigue life, Journal of Materials Processing Technology 48 (1995) 581-588.

[2] A.G. Olabi, M.S.J. Hashmi, Stress relief procedures for low carbon steel (1020) welded components, Journal of Materials Processing Technology 56 (1996) 552-562.

[3] M. Kovač, A method for residual stress measurement in welded seams, Journal of Materials Processing Technology 52 (1995) 503-514.

[4] A.P. Wu, J.L. Ren, Z.S. Peng, H. Murakawa, Y. Ueda, Numerical simulation for the residual stresses of stellite hard-facing on carbon steel, Journal of Materials Processing Technology 101 (2000) 70-75.

[5] A.M. Paradowska, J.W.H. Price, R. Ibrahim, T.R. Finlayson, The effect of heat input on residual stress distribution of steel welds measured by neutron diffraction, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 385-388.

[6] M. Vural, H.F. Muzafferoglu, U.C. Tapici, The effect of welding fixtures on welding distortions, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 511-514.

[7] B. Chen, X.H. Peng, S.N. Nong, X.C. Liang, An incremental constitutive relationship incorporating phase transformation with the application to stress analysis for the quenching process, Journal of Materials Processing Technology 122 (2002) 208-212.

[8] M. Mahdi, L.C. Zhang, Residual stress in ground components caused by coupled thermal and mechanical plastic deformation, Journal of Materials Processing Technology, 95 (1999) 238-245.

[9] Y.C. Lin, S.C. Chen, Effect of residual stress on thermal fatigue in a type 420 martensitic stainless steel weldment, Journal of Materials Processing Technology 138 (2003) 22-27.

[10] N. Noda, Thermal stresses in functionaly graded materials, Proceedings of the 3rd International Congress on Thermal Stresses, THERMAL STRESSES '99, Cracow, 1999, 33-38.

[11] A. Askari, S. Das, Practical numerical analysis of a crack near a weld subjected to primary loading and hydrogen embrittlement, Journal of Materials Processing Technology 173 (2006) 1–13.

[12] F. Binczyk, Factors forming the microstructure of high-aluminum alloys of Fe-Al-C system and analysis of degradation phenomena leading to self-disintegration, Metallurgy, Science Review of Silesian University of Technology 40, 1991 (in Polish).

[13] F. Binczyk, D. Renowicz, Fracture of the high aluminum alloy castings, Archives of Materials Science 3 (1994).

[14] S.J. Skrzypek, J. Karp, Application of the diffraction line profile for investigation of the fatigue softening of martensite, Proceedings of XIII Conference on Applied Crystallography, Kozubnik, Poland, 1984, 429-435.

[15] K. Sigrist, DSC and X-ray measurements as methods to detect lattice distortions, Thermochimica Acta 311 (1998) 213-216.

[16] S.J. Skrzypek, New approach to measuring residual macro-stresses with the application of the grazing angle X-ray diffraction geometry, Dissertations Monographies, 108, Kraków, 2002 (in Polish)

[17] D. Renowicz, S.J. Skrzypek, Effect of residual stresses on casting fracture of Fe-Al-C alloy, III Symposium on Mechanics Destruction of Materials and Construction, Augustów, 2005, 327-330, (in Polish).

[18] Z. Bojarski, T. Bołd, X-ray method of determination of the lattice deformation and size of polycrystalline metal blocks, Works of Mettalurgy Institute 22 1970 115–127 (in Polish).

[19] J. Bystrzycki, Nonconventional methods of microstructure forming and the properties of the alloys with FeAl intermetallic phase, WAT, Warszawa 2004, (in Polish).

[20] D. Renowicz: Influence of Original State of Microstructure on Fracture of Metals, The 3rd International Conference On Quenching And Control Of Distortion, ASM Heat Treating Society, Prague, 1999, 277-287.