

CRACK INITIATION CAUSED BY DISTORSIONS

DONAT RENOWICZ

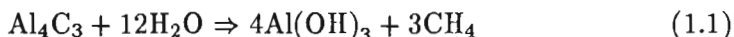
FRANCISZEK BINCZYK

*Chair of Mechanics and Plastic Working Technology
Silesian Technical University*

An attempt has been made to describe analytically the crack initiation process caused by the thermal and chemical distortions in Fe-Al-C alloys with high aluminium content. In order to describe the phenomenon, the linear-elastic parameters of fracture mechanics have been used. On the basis of kinetic analysis of the distortions growth, the crack initiation conditions affecting self-decomposition of the FeAl matrix have been determined.

1. Introduction

Data taken from literature (cf Eminger, 1955; Sakwa, 1974; Gierek, 1987) shows that the Fe-Al-C alloys with high aluminium content are characterized by strong tendency to fracture and autodestruction at the presence of humidity. As the result of chemical reaction between aluminium carbide and water on the surface of the casting, there is an intensive increase in the volume of the $\text{Al}(\text{OH})_3$ reaction product



The aluminium hydroxide has a destructive influence on the metal matrix and causes an increase in the crystal lattice deformation of the matrix and residual stress formation in the surface layer. The structure of 1.1.3. alloy on the FeAl superstructure base with the primary and eutectic precipitations of the Al_4C_3 carbide is presented in Fig.1. The phenomenon affects the distortion field formation (cf Eimer, 1976; Holnicki-Szulc, 1990)

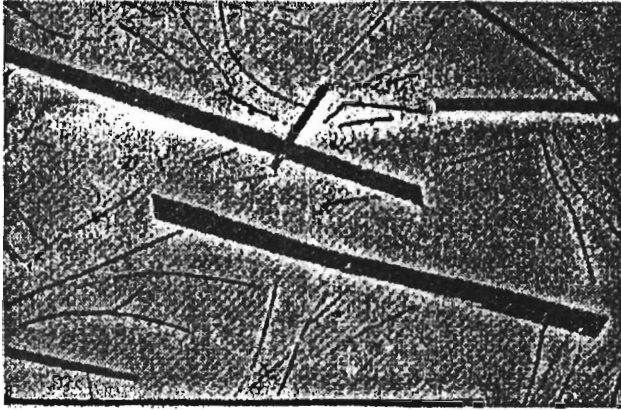


Fig. 1. Structure of the 1.1.3. alloy, FeAl + Al₄C₃, magnification 500×

In elastic solid, the deformation field caused by the external loading and distortions can be described by the formula (Nowacki, 1970)

$$\varepsilon_{ij} = \varepsilon_{ij}^0 + 2\mu'\sigma_{ij} + \lambda'\delta_{ij}\sigma_{kk} \quad (1.2)$$

where

- ε_{ij}^0 – deformations caused by distortions
- σ_{ij} – stress state tensor
- μ', λ' – material constants.

In the case of self-decomposition phenomenon, which occurs in the above-mentioned alloys, the deformation field caused by distortions is the function of place and time. There is a limit of time beyond which in some areas of the tested body the distortion field will exceed the critical stress in matrix causing the crack initiation. The progressive chemical reaction between carbide and water propagates with time into the whole surface layer time.

2. Physical model

In the case of the Fe-Al-C alloys in question the fracture process occurs as a result of interaction between the thermal and chemical distortion sources without an influence of the external loading. The physical model of the phenomenon is shown in Fig.2.

In the first period of time the process takes place on the surface of element (body) and is accompanied by the linear increment of the mass and

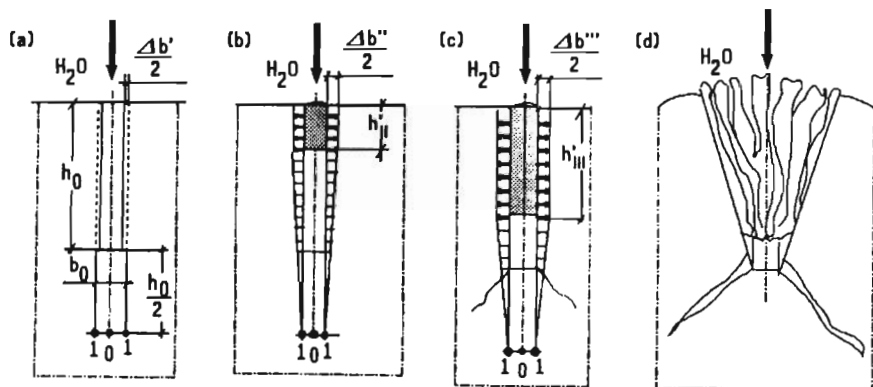


Fig. 2. The physical model of distortion fracture of the FeAl matrix: (a) distribution of thermal distortions, (b) distribution of chemical distortion after 24 h, (c) distribution of chemical distortion after 48 h, (d) intensive fracture of the surface layer

volume caused by the reaction products (1.1) formation. At the first stage of crack initiation the matrix deforms under an influence of the thermal distortions during the casting solidification $\varepsilon^0 \Delta b' / b_0$ (Fig.2a) what causes casting stresses. On the basis of investigation results (cf Binczyk, 1981; Binczyk and Renowicz, in press) it was assumed that there was a uniform distribution of thermal distortions along the depth of the carbide h_0 . At the moment of chemical reaction (1.1) initiation, a new forming product $\text{Al}(\text{OH})_3$ causes the activation of chemical distortion growing in time and perpendicularly to the phase limit and to the depth of the matrix (Fig.2b,c) from the value of $h' = 0$ to $h' = h_0$. The strain growth is connected with the difference between the specific volumes of carbide and aluminium hydroxide, respectively.

Such a course of the distortion growth causes stress concentration in the area of carbide tip on the surface layer. Process of crack initiation starts after exceeding the critical stress of matrix. Fig.3 illustrates the initial stage of the structure decomposition.

3. Methodology and investigation results

The aim of investigations was to define the influence of the aluminium contents and fracture toughness of the alloys on kinetics of the fracture process. Regarding the high hardness and brittleness of the tested specimens, the K_{Ic}

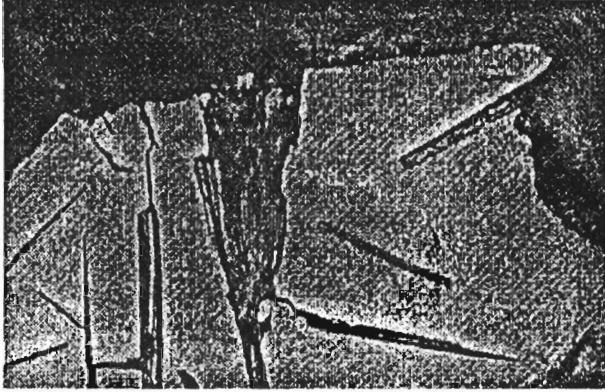


Fig. 3. The structure of specimen subsurface layer on microsection perpendicular to the external surface, magnification 400x

estimation was performed by the analysis of crack length caused by Vickers penetrator (cf Binczyk, 1981; Evans and Charles, 1976; Nihara et al., 1982). The results of investigations are presented in Table 1.

Table 1. Average value of K_{Ic} for the Fe-Al-C alloys

Kind of matrix	K_{Ic} [MN/m ^{3/2}]
phase: Fe ₃ Al (13.2% wt. Al)	14.90
phase: FeAl (32.85% wt. Al)	4.46
phase: FeAl ₂ (48.51% wt. Al)	1.67

Changing the temperature of the casting and cooling conditions of alloys, the specimens with different morphology features (number of precipitations, surface of precipitations S , length of carbide l , shape factor F) of the Al₄C₃ carbide precipitations were obtained. Values characterizing the morphology features were determined on the basis of structural investigations on TV analyzer Quantimet 720. On the basis of the determined features, the average value of the carbide edges length which has cuboid shape has been calculated. Three kinds of heats with similar chemical composition having different size were tested. The results are shown in Table 2.

Table 2. Chemical composition of the tested alloys and the parameters of their structure morphology features

Number of the heat	Content %			Average surface of AL_4C_3 [μm^2]	Number of carbides per mm^2	The size of AL_4C_3 [μm]	
	Al	C	Fe			h_0	b_0
1.1.1.	35.8	1.25	the rest	179	101	48.1	3.5
1.1.3.	36.2	1.20	the rest	525	50	84.6	6.2
1.1.4.	36.1	0.97	the rest	1970	25	164.0	12.0

where

- 1.1.1. - metal mould
- 1.1.3. - sand mould
- 1.1.4. - microsphere mould

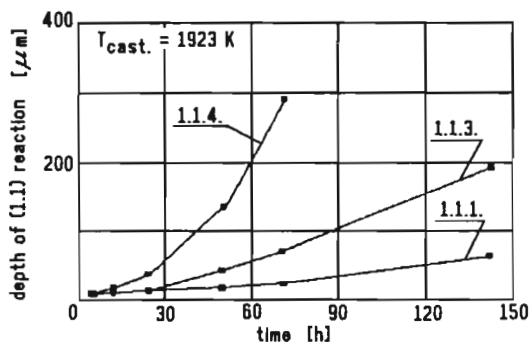


Fig. 4. Influence of (1.1) reaction time on the change of reaction depth $AL_4C_3 \rightarrow Al(OH)_3$

In order to describe the characteristics of distortion changes as a function of time, the measurement of mass change of the reaction products (1.1) during the initiation and crack growth has been carried out. It allowed to determine the depth change of reaction course in time (Fig.4). Characteristics of changes in the crystal lattice deformation as a function of time were described by the X-ray investigation method. On the basis of the tests it was possible to determine the thermal distortion value and changes in the chemical distortion characteristics (Table 3).

Table 3. Kinetic parameters of distortions growth

Time of reaction (1.1) τ [h]	Depth of reaction (1.1) h' [μm] and strain ε	Number of the heat		
		1.1.1.	1.1.3.	1.1.4.
0 therm.distor.	h'	0	0	0
	ε	$1.41 \cdot 10^{-3}$	$1.28 \cdot 10^{-3}$	$1.07 \cdot 10^{-3}$
24	h'	8.92	10.96	31.97
	ε	$2.35 \cdot 10^{-3}$	$2.95 \cdot 10^{-3}$	$3.52 \cdot 10^{-3}$
48	h'	19.11	38.10	134.08*
	ε	$5.14 \cdot 10^{-3}$	$3.84 \cdot 10^{-3}$	$3.31 \cdot 10^{-3}$
72	h'	34.6	76.47	295.1*
	ε	$5.49 \cdot 10^{-3}$	$4.12 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$
144	h'	75.9*	193.9*	-
	ε	$2.83 \cdot 10^{-3}$	$2.22 \cdot 10^{-3}$	-

where

h' - depth of reaction $AL_4C_3 \rightarrow Al(OH)_3$

ε - deformation of crystal lattice in a surface layer,
 $\varepsilon = (a_i - a_0)/a_0$

(*) - depth of carbide exceeded

4. Mathematical model

For a quantitative description of the distortion fracture process of the FeAl matrix, the linear-elastic material model with a crack loaded on its edge (Fig.2) was assumed. In calculations case of the crack initiation into the depth of material was considered. It leads to the problem of equilibrium of the crack in plane strain. In calculations the finite element method (FEM) was used. It has been assumed that loading of the matrix is caused by the carbide pressure on the surface of the phase limit which comes from the thermal distortion (the initial stage after casting) and next from the chemical distortion. On the basis of the X-ray investigations of the surface layer deformation at respective stages of fracture (Table 3), the nodes displacement of the FEM structure was described. It has been done for separate volume of material according to the physical model (Fig.2). The results of calculations made the description of the matrix strain and stress field as a function of time possible. In this way the extreme values of principal stress at the tip of carbide were obtained. On the

basis of the results, the maximum value of stress intensity factor at each stage of crack initiation was computed. K_I value was calculated from equation

$$K_I = \lim_{r \rightarrow 0} \sigma_y \sqrt{2\pi r} \tag{4.1}$$

Assuming the crack initiation criteria in the formula

$$K_I > K_{Ic} \tag{4.2}$$

the time of the first microcrack formation on the surface layer of the casting was determined.

5. Results

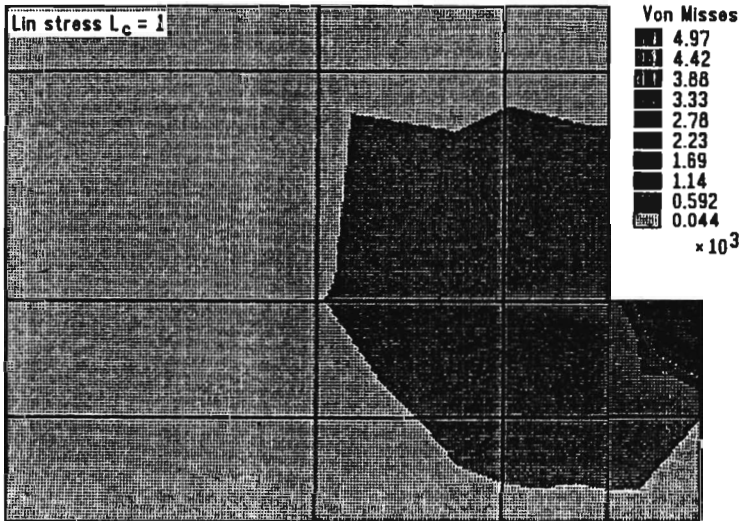


Fig. 5. The map of reduced stress for 1.1.4. alloy in [MPa]

Results of the numerical calculations are presented in Fig.5. It presents a map of stress reduced according to the Huber-Von Mises hypothesis determined for the 1.1.4. alloy in the state after casting. As it can be seen the concentration of stresses appears in the crack tip area of the carbide where the process of the matrix cracking is initiated. This process takes place when

critical stresses of the matrix, determined by the experimental tests, are exceeded. In the case of alloys on the FeAl superstructure base the moment of crack initiation can be determined on the basis of the diagram presented in Fig.6. As it can be seen in the case of alloy 1.1.4. the critical stresses are exceeded in state directly after casting. For the alloys 1.1.1. and 1.1.3., respectively, intensive cracking process of the surface layer is initiated by the chemical distortion growth after about 144 hours.

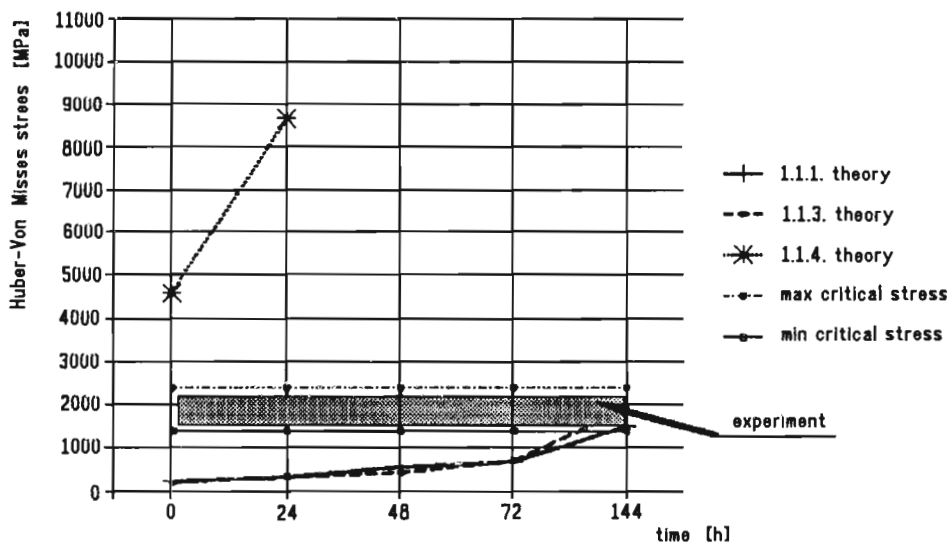


Fig. 6. Reduced stress versus time of the distortion growth

References

1. BINCZYK F., 1981, *Czynniki kształtujące strukturę wysokoalumiowych stopów układu Fe-Al-C i analiza zjawisk destrukcyjnych prowadzących do ich samorzutnego rozpadu*, Hutnictwo, 40, Gliwice
2. BINCZYK F., RENOWICZ D., in press, *Fracture of the High Aluminium Alloy Castings*, Archiwum Nauki o Materiałach
3. EIMER C., 1976, *Naprężenia własne w ośrodkach wielofazowych*, Teoria Ośrodków wielofazowych cz.II, Ossolineum
4. EMINGER Z., 1955, *K otazce vyrobu odlitku z Pyroferalu*, Slevarenstvi, 10

5. EVANS A.G., CHARLES E.A., 1976, *Fracture Toughness Determination by Indentation*, J. of the American Ceramic Society – Discussions and Notes, 59, 7/8
6. GIEREK A., 1987, *Analiza przyczyn samorozpadu niektórych wysokoaluminio-
wych stopów żelaza z aluminium*, Inżynieria Materialowa, 4
7. HOLNICKI-SZULC J., 1990, *Dystorsje w układach konstrukcyjnych, analiza,
sterowanie, modelowanie*, PWN Warszawa-Poznań
8. NIAHARA K., MORENA R., HASSELMAN D.P., 1982, *Evaluation of K_{Ic} of
Brittle Solids by the Indentation Method with Low Crack-to-Indent Ratios*, J.
of Material Science Letters, 1, 13
9. NOWACKI W., 1970, *Teoria sprężystości*, PWN, Warszawa
10. SAKWA W., 1974, *Żeliwo*, Wyd. Śląsk, Katowice

Inicjacja pęknięć wywołanych dystorsjami

Streszczenie

W pracy przedstawiono próbę analitycznego opisu procesu inicjacji pęknięć wywołanego dystorsjami o charakterze termicznym i chemicznym w wysokoaluminio-
wym stopie Fe-Al-C. Do opisu zjawiska wykorzystano parametry liniowo-sprężystej
mechaniki pęknięcia. Na podstawie analizy kinetyki wzrostu dystorsji określono wa-
runki inicjacji pęknięć prowadzące do samorzutnego rozpadu osnowy FeAl.

Manuscript received October 1, 1993; accepted for print October 14, 1993