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## Dynamic Fracture Toughness of Non-Alloyed Bainitic Ductile Irons

### Introduction

The effects of austempering and test temperatures on dynamic fracture toughness of non-alloyed bainitic ductile iron have been investigated by means of the critical values of stress intensity factor  $K_{Ic}$ .

It has been established that  $K_{Ic}$  of non-alloyed bainitic ductile iron shows maximum of 60-65 MPa.m<sup>1/2</sup> after austempering at 340 °C.

The effect of test temperature on  $K_{Ic}$  is manifested by the monotonous reduction of dynamic fracture toughness values. At -100 °C this  $K_{Ic}$  reduction does not exceed 15-20% as compared to the values of dynamic fracture toughness at +20 °C.

Due to their high mechanical and operational characteristics bainitic ductile irons, obtained after austempering, are capable of replacing any component, made of cast, wrought and heat-treated low alloy structural steels [1-3].

Many articles have investigated microstructural characteristics in relation with chemical composition and heat treatment. Using transmission electron microscopy Franetovic [4] has studied the effects of austempering temperature, austenitization time and silicon contents on the properties of iron under impact load. Krassovsky [5] has shown the effect of graphite inclusions on the fracture process of ductile irons with different pearlite contents. A number of investigators [6, 7] have studied the mechanical properties of austempered ductile irons under static and fatigue loads during impact toughness testing.

As regards fracture toughness of austempered irons, available information is still insufficient and is mainly directed towards investigations under static load.

Some articles [8, 9] study fracture toughness of ferritic and pearlitic irons, fatigue crack propagation and the effects of ferrite and pearlite contents. Rossi [10] has shown that fracture toughness of ductile irons with bainitic structure is higher than that of irons with pearlitic and ferritic structure. One of the most comprehensive investigations on the mechanical properties of austempered ductile irons have been carried out by Dorazil et al. [11] but fracture toughness data are incomplete.

The authors of the present article have also studied fracture toughness and mechanical properties of bainitic ductile irons. Ref. [12] shows some mechanical characteristics and the effect of iron microstructure on those characteristics under dynamic

load and Ref. [13] gives data on plane-strain fracture toughness of irons and the effect of silicon content on its values.

The purpose of the present article is to provide data on the behaviour of ductile bainitic irons under dynamic load in terms of fracture mechanics and to study the variation of dynamic fracture toughness when varying the heat treatment parameters.

## II. Materials and procedures

Iron with the following chemical composition (wt. %) has been used as a starting material:

carbon — 3.20-3.45	phosphorus — 0.05-0.07
silicon — 0.47-0.55	sulphur — 0.005-0.007
manganese — 0.02-0.07	chromium — 0.04-0.05

The iron has been melted in a furnace of 10 tonne capacity with industrial frequency and acid quartzitic padding. After overheating up to 1480-1500 °C and correction of the chemical composition with respect to silicon, iron has been modified in accordance with "Sandwich" method by means of spheroidizing CKM-7N modifier (1.5% consumption and size 1 to 10 mm) in the ladle. After this process completion there has followed secondary modification by means of ΦC-75 modifier (consumption 0.5% and size from 1 to 5 mm). Chemical compositions of studied irons are shown in Table 1. Heat treatment of investigated specimens has been carried out in salt baths. Heat treatment parameters are shown in Table 2. The range of temperature variations as compared to preset ones:

- for high temperature furnace — from  $\pm 2^\circ\text{C}$  to  $4^\circ\text{C}$
- for low temperature furnace — from  $\pm 1^\circ\text{C}$  to  $2^\circ\text{C}$ .

**Table 1**  
Chemical composition of studied irons

Item	Marking	C	Si	Mn	S	P	Cr	N	Mg	Cu	Ni
1	A3	3.18	2.90	0.27	0.007	0.07	0.043	0.0077	0.032	0.037	0.035
2	A4	3.02	3.18	0.14	0.006	0.08	0.040	0.0060	0.044	0.034	0.033

**Table 2**  
Heat treatment parameters of studied irons

Item	Marking	Austenitization temperature (°C)	Austenitization time (min)	Austempering temperature (°C)	Austempering time (min)
1	A3	900	60	390	60
2	A3	900	60	340	35
3	A3	860	60	290	40
1	A4	900	60	390	35
2	A4	900	60	340	60
3	A4	860	60	290	60

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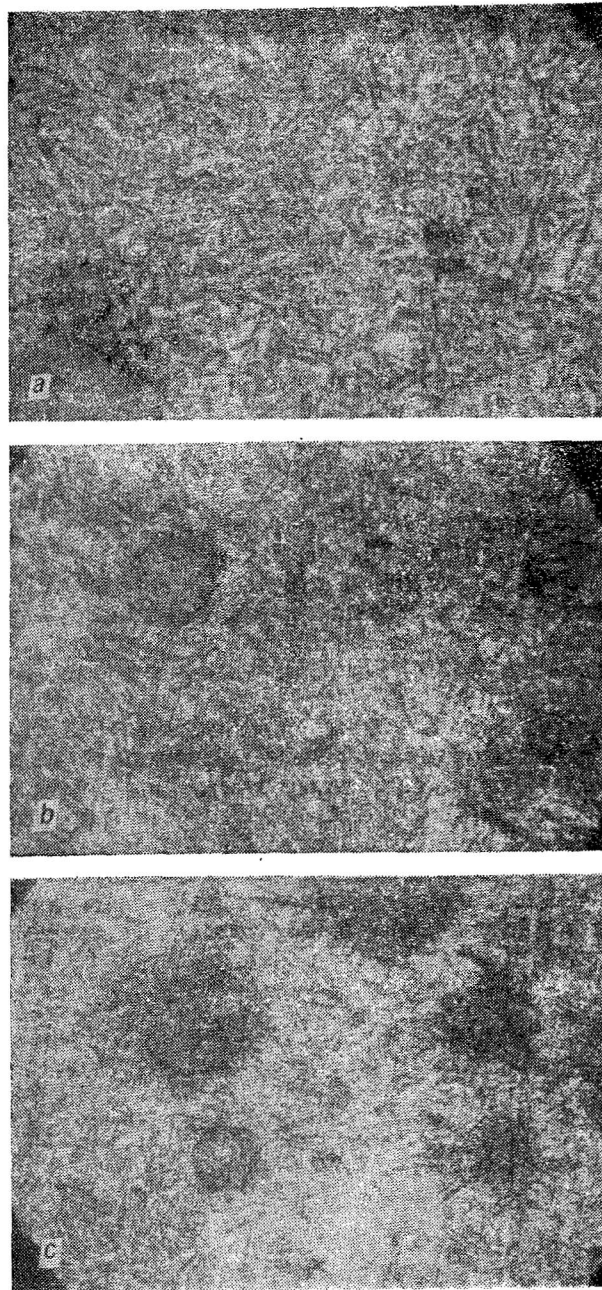


Fig. 1. Structure of heat-treated ductile iron ;  
*a* — upper bainite ; *b* — intermediate bainite ;  
*c* — lower bainite

Specimens have been oil-cooled.

As a result of the heat treatment specimens with the following matrix structure have been obtained:

- upper bainite at austempering temperature  $T_{\text{aus}} \approx 390^\circ\text{C}$  (Fig. 1a),
- intermediate bainite at  $T_{\text{aus}} \approx 340^\circ\text{C}$  (Fig. 1b),
- lower bainite at  $T_{\text{aus}} \approx 290^\circ\text{C}$  (Fig. 1c).

Brittle fracture resistance under dynamic load is determined in accordance with the requirements of Bulgarian State Standard BDS 16833-88 and ASTM E 24.03.03.

After heat treatment the test specimens have been fatigue-cracked at the notch tip. The number of cycles for creating a fatigue crack varies from 120000 to 140000.

The specimens have been tested by a 300 J hammer of Charpy. Load-time and load-offset diagrams have been made.

A chamber containing liquid nitrogen and ethanol has been used for the negative temperature tests. Specimen temperature has been controlled by platinum-platinum, rhodium thermocouple and digital millivoltmeter. Tests have been carried out in the temperature range from  $-100^\circ\text{C}$  to  $+20^\circ\text{C}$ .

### III. Experimental results

The tests carried out earlier [13] regarding the effect of silicon in the range of 2.0 to 4.5% on plane-strain fracture toughness of austempered ductile iron (Fig. 2) have shown that maximum  $K_{Ic}$  values can be obtained in case silicon content varies within the range of 2.9 to 3.2%. In such case stress intensity factor values  $K_{Ic}$  of non-alloyed austempered ductile iron vary from  $40 \text{ MPa}\cdot\text{m}^{1/2}$  to  $65 \text{ MPa}\cdot\text{m}^{1/2}$  depending on the austempering temperature.

Due to the above reason for the purpose of testing the dynamic fracture toughness of non-alloyed bainitic ductile irons there have been chosen chemical compositions with silicon contents of 2.9% and 3.2%, respectively. Manganese content is  $\leq 0.3\%$ . Figs 3 and 4 show data regarding effects of silicon, austempering and test temperatures on  $K_{Ic}$  of non-alloyed bainitic ductile iron. It has been found out that  $K_{Ic}$  changes from  $55 \text{ MPa}\cdot\text{m}^{1/2}$  to  $65 \text{ MPa}\cdot\text{m}^{1/2}$  depending on austempering and test temperatures,  $20^\circ\text{C}$ . Maximum brittle fracture resistance under dynamic load has been obtained after austempering in the intermediate bainite zone, i. e. at a temperature of  $340^\circ\text{C}$ . In comparing the results of plane-strain to dynamic fracture toughness it is evident

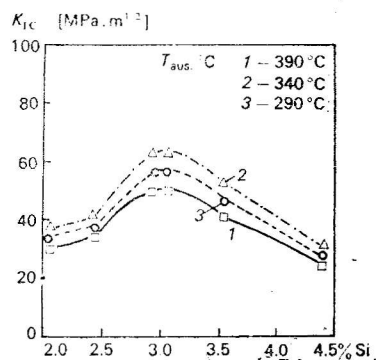


Fig. 2. Effects of silicon and austempering temperature on plane-strain fracture toughness of non-alloyed bainitic ductile irons [7]

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that the difference between them is minimal. While  $K_{Ic}$  and  $K_{Iid}$  values of bainitic ductile irons, austempered at 340°C, are practically equal, those values of irons, austempered at 390°C and 290°C increase for the benefit of  $K_{Iid}$  by 20% and 10%, respectively.

The reason for the high dynamic fracture toughness of bainitic ductile iron is due to the structure and size of the phases.

Dispersion-coarsened ferritic-austenitic structure of the metal base, formed after austempering at 390°C (retained austenite,  $A_{ret} = 50-55$  vol. % and bainitic ferrite  $\alpha_B = 50-45$  vol. %), shows lower crack resistance as compared to structures, obtained at 340°C and 290°C. In these cases phase relationships in the structures are as follows: materials, austempered at 340°C —  $A_{ret} = 35-40$  vol. % and  $\alpha_B = 65-50$  vol. %; those, austempered at 290°C —  $A_{ret} = 20-25$  vol. % and  $\alpha_B = 80-75$  vol. %. The occurrence of  $K_{Iid}$  maximum at 340°C is an indication of optimal combination of the parameters structure and size of its phases. It is known [14] that the reduction of grain size, which in this case is identical to the decrease of spacing between the lamellae of bainitic ferrite, results in simultaneous increase of yield strength and toughness. For bainitic irons, austempered at 390°C, this increase is not so clearly manifested due to large zones of retained austenite between the lamellae of bainitic ferrite. The decrease of grain size of structural components in iron, austempered at 290°C, is great but the amount of retained austenite is insufficient — 20-25 vol. %. Those are the reasons determining the occurrence of a maximum of dynamic fracture toughness at 340°C.

Figs 3 and 4 also show the effect of test temperature within the range of +20°C to -100°C on  $K_{Iid}$  variation in non-alloyed bainitic ductile irons. It has been established that the changing of dynamic fracture toughness is monotonous. This kind of  $K_{Iid}$  decrease is due to the occurrence of retained austenite in the structure of bainitic ductile iron.

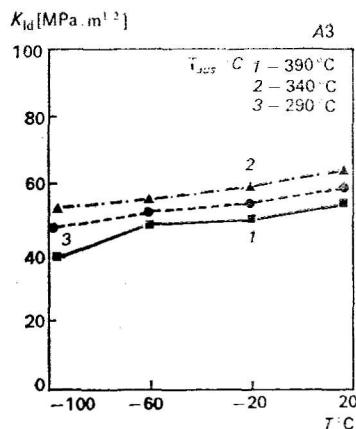


Fig. 3. Effects of austempering and test temperatures on dynamic fracture toughness of bainitic ductile iron, containing 2.9% silicon

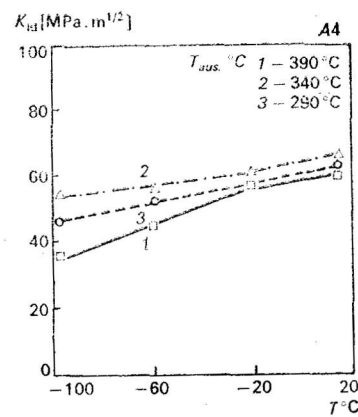


Fig. 4. Effects of austempering and test temperatures on dynamic fracture toughness of bainitic ductile iron, containing 3.2% silicon

Comparing the obtained results for  $K_{Ic}$  [13] and  $K_{Id}$  the proximity of their values can be easily seen, i. e. the effect of load rate on the variation of dynamic and plane-strain fracture toughnesses is negligible. The reason for such behaviour is due to the fact that the effect of temperature-rate conditions on brittle fracture materials with yield strength of 800-900 MPa is negligible, i. e. they are insensitive to changes of test rate and/or temperature.

#### IV. Conclusions

1. Non-alloyed bainitic ductile iron shows the highest resistance to brittle fracture under dynamic load after austempering in the zone of intermediate bainite, i. e. at 340 °C.

2. Decrease of test temperature within the range of +20 °C to -100 °C causes a decrease of stress intensity factor  $K_{Id}$  of bainitic iron. Differences between  $K_{Id}$  values at +20 °C and at -100 °C do not exceed 15-20 %.

3. It has been found that the values of plane-strain and dynamic fracture toughnesses ( $K_{Ic}$  and  $K_{Id}$ , respectively) are practically equal.

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