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CRACK GROWTH RESISTANCE OF CREEP DAMAGED MATERIAL

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Abstract. *In this paper crack growth resistance of creep damaged material in thermoelectrically power plant "Kostolac A" was investigated. This was done by testing and comparison of impact, static and fatigue crack growth properties of virgin and serviced material (low-alloy steel marked 12×1M∅ according to GOST 10500-63), imposed to creeping during 175000 service hours. In order to obtain complete range of crack growth properties for both materials, following temperatures were selected for impact and static testing: 20^{o}C, 400^{o}C, 520^{o}C, 540^{o}C (operating temperature) and 560^{o}C. The impact testing was done by the instrumented Charpy machine, enabling separate evaluation of crack initiation and crack growth energies. The static testing was performed by standard method of J integral measurement. The fatigue testing was done by evaluating the dependence of crack growth rate on the stress intensity factor amplitude. Furthermore, characterization of materials was done by fractographic examination. According to all these examinations crack growth resistance of creep damaged material was evaluated.*

Key words: *creep, instrumented Charpy testing, J integral, fatigue, fractography*

1. INTRODUCTION

Deformation of metal in time dependent manner is well known as creep, which is typical for thermoelectrical power plants and chemical installations at all temperatures above absolute zero. At temperatures below $0.3 \cdot T_m$ (T_m - melting temperature), the time independent elastic-plastic behaviour can be applied, but many technical application demand temperatures far above. Under such conditions microstructure and mechanical

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properties of metallic materials degrade, causing sometimes significant reduction of high-temperature components life.

In order to investigate creep degradation of such a material, the low-carbon low-alloy steel (marked 12×1M∅ according to GOST), exposed to creep for more than 175.000 hours, has been compared with the same, but virgin material. More detailed description of this investigation is given in [1], including metallographic investigation and mechanical testing, while here only the outline of crack growth properties investigation is given.

2. IMPACT CRACK GROWTH PROPERTIES

The low-alloyed steel (designated 12×1M∅ according to GOST 10500-63) was chosen for this investigation, because it is widely used for steamlines in power plants in Serbia, and also because it has been used for long service period (from 1967), so that creep damage can be expected.

The exposed material is taken from the steamline (∅219×18) elbow which operates at 540^{o}C and pressure 100 bar, in thermoelectrical power plant Kostolac A. The elbow was cut out in 1990 because excessive creep damage was found. The virgin material is also cut from the steamline (∅273×24) elbow.

The impact testing was performed in accordance with the proposed standard method for the instrumented Charpy V impact test on metallic materials, [2]. The standard Charpy V notched specimens were used on the Schenck-Trebel pendulum, Fig. 1.

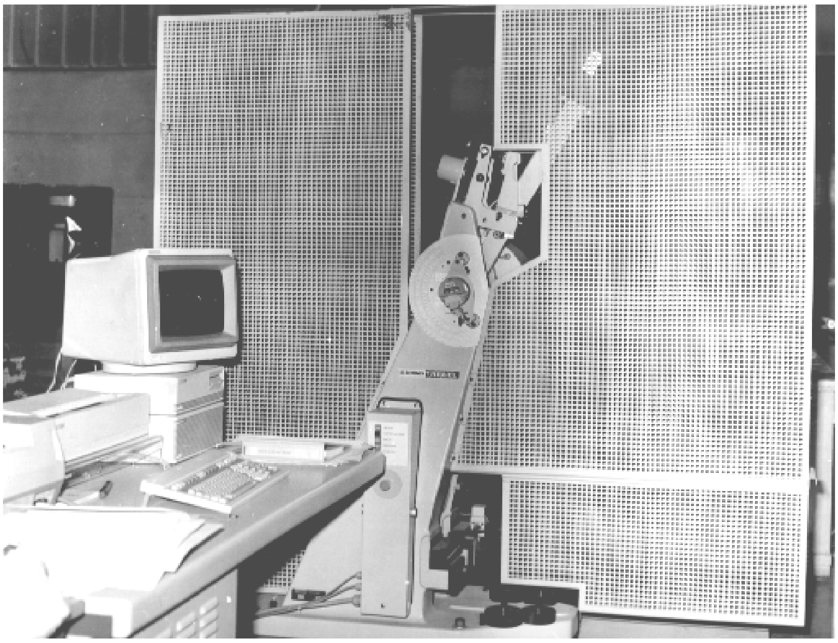


Fig. 1. The SCHENCK TREBEL instrumented pendulum

Separation of the total impact energy into the crack initiation and crack growth energies is done according to the principles shown in Fig. 2, where the area under the curve and left from F_m corresponds to the crack initiation energy, while the area under the curve and right to F_m corresponds to the crack growth energy displacement.

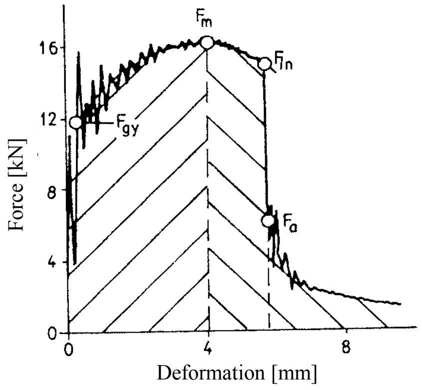


Fig. 2. Typical force-displacement curve obtained in impact test

Results of impact energy obtained by instrumented Charpy pendulum are shown in Tab. 1 and Tab. 2, as the average values (of three specimens) for virgin and exposed material, respectively. Besides the total impact energy, its components - crack initiation and growth energy, are given, as well as force maximal value, F_m, dynamic yield force, F_{gy} and ductile fracture ratio (%). One should notice that all diagrams force-displacement are of F type, except two specimens at 20°C, as shown in Fig. 3 for virgin material and Fig. 4 for creep damaged material. More details about type of force-displacement diagram can be found in [1, 2].

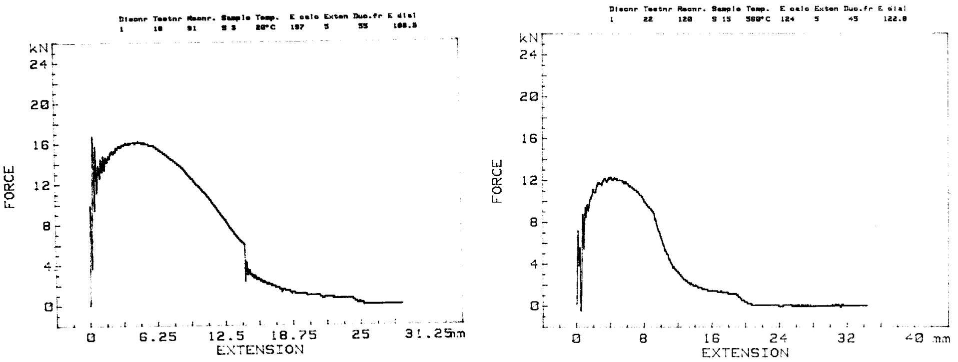
Table 1. Results of impact testing - average values for virgin material (A)

Testing temperature, °C	20	400	520	540	560
Total impact energy, J	192.5	205.9	126.5	122	118.9
Crack initiation energy, J	57.0	42.4	46.0	40.3	40.0
Crack growth energy, J	133.7	148.2	80.8	89.6	76.7
Ductile fracture ratio, %	55	56.7	45	43.3	43.3
Maximal force F_m , kN	16.6	12.3	12.0	12.5	12.4
Dynamic yield force F_{gy}, kN	11.3	8.1	7.1	6.8	6.7

Table 2. Results of impact testing - average values for damaged material (B)

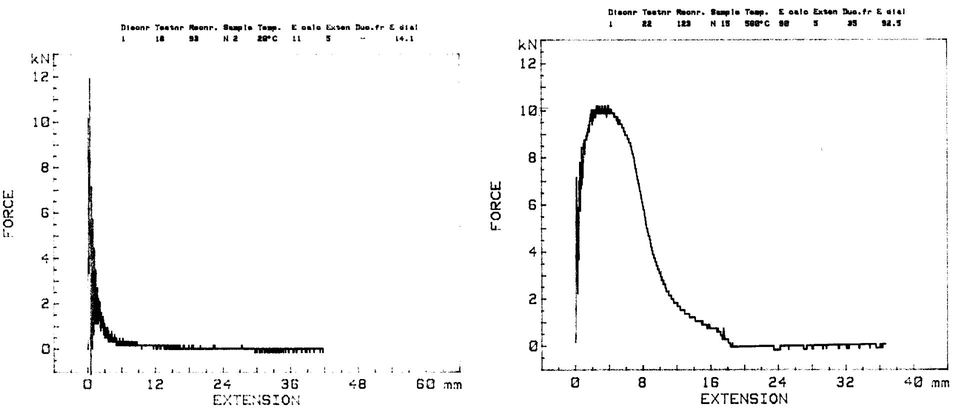
Testing temperature, °C	20	400	520	540	560
Total impact energy, J	10.5	215.8	165	92.3	91.2
Crack initiation energy, J	10.5	32.0	34.2	31.0	31.0
Crack growth energy, J	0	179.0	124	55.8	57.1
Ductile fracture ratio, %	0	58.3	56.7	20.0	35.0
Maximal force F_m , kN	-	10.0*	9.6	10.6	10.4
Dynamic yield force F_{gy}, kN	-	29.5*	24.0	17.5	17.0

* only one specimen valid



(a) (b)

Fig. 3. The force-displacement curves for virgin material (a) 20°C; (b) 560°C



(a) (b)

Fig. 4. The force-displacement curves for damaged material (a) 20°C; (b) 560°C

As one can see from results in Tab. 1, the total impact energy of virgin material increases slightly up to 400°C, and reduces significantly, but not drastically, above 400°C, so that its value is still more than sufficient at 560°C. Similar behavior is noticeable for crack initiation and growth energy, ductile fracture ratio, maximal force and dynamic yield force, with only differences at 400°C – while crack growth energy and ductile fracture ratio slightly rise, the other quantities lower their values to the level also recorded at other high temperatures.

The most important result for the exposed material testing is certainly extremely low value of total impact energy at 20°C. All three specimens fractured in the same, brittle manner, producing "A" type of force-displacement diagram [1, 2], which can not be used to separate crack initiation and growth energy (the latter one is practically zero). It is obvious that the transitional temperature has increased above room temperature, indicating significant change in the creep damaged material behavior at impact load.

Anyhow, at higher temperature the impact energy of exposed material is sufficient, both as total energy and as its parts for crack initiation and growth.

Comparison of total impact energies for virgin and exposed materials is given in Fig. 5. As already explained, significant change in material behavior occurs at 20°C, whereas differences at higher temperature are much smaller, but more expressed for higher temperatures than for the intermediate ones. In the latter case the total impact energy is actually higher for the exposed material.

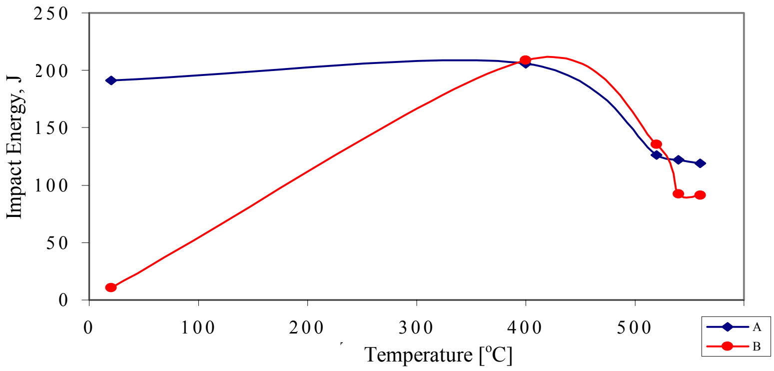
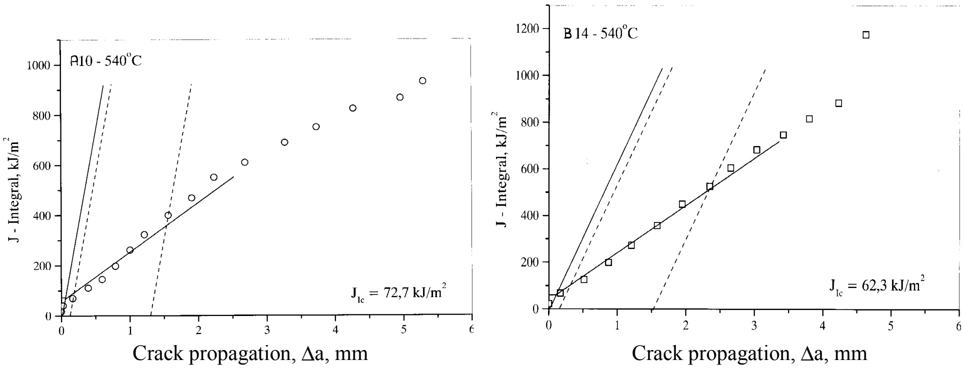


Fig. 5. Comparison of total impact energies for virgin (A) and exposed (B) materials

3. STATIC CRACK GROWTH TESTING - J INTEGRAL EVALUATION

Static crack growth testing was done on standard pre-cracked CT specimens of Charpy size. Using force-displacement records and standard procedure to get J-R curve [3], relevant data for critical J integral values (J_{Ic}) has been obtained at all testing temperatures, as shown as an example for virgin and damaged material, Fig. 6a and 6b, respectively. The results for both materials are given in Fig. 7 as J_{Ic} vs. temperature dependence.



(a) (b)

Fig. 6. Evaluation of J_{Ic} values from J-R curves at 540°C
(a) virgin material (A); (b) damaged material (B)

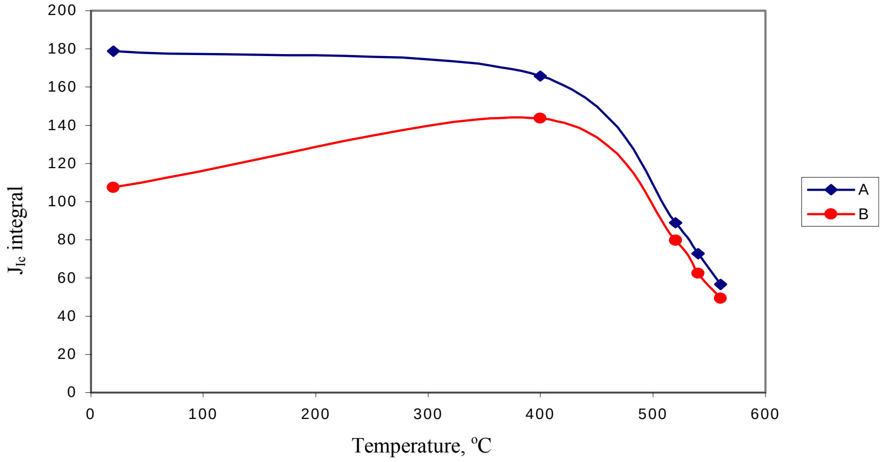
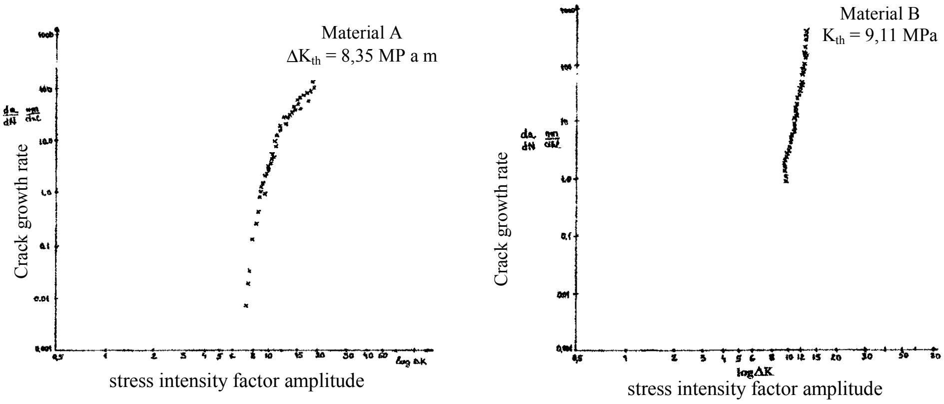


Fig. 7. The J_{Ic} vs. temperature for virgin (A) and exposed material (B)

From Fig. 7 it is evident that both materials behave similarly as in the case of Charpy testing, but with one exceptional difference: fracture toughness reduction at room temperature for exposed material is not nearly that drastic as it was the case with impact toughness.

4. FATIGUE CRACK GROWTH TESTING

The high cycle fatigue testing was performed on pre-cracked Charpy specimens using AMSLER FRACTOMAT machine. The crack growth rate was registered by strain gages RMF- A5. The results are shown in Fig. 8a and 8b for the virgin and damaged material, respectively, in form of crack growth rate (da/dN) dependence on the stress intensity factor amplitude (ΔK). These results indicate an order of magnitude higher crack growth rate for the damaged material, but almost the same threshold values for the stress intensity factor amplitude (ΔK_{th}).



(a) (b)

Fig. 8. Crack growth rate vs. stress intensity factor amplitude
(a) virgin material (A); (b) damaged material (B)

6. DISCUSSION AND CONCLUSIONS

On the basis of results obtained in this paper by impact, static and fatigue testing, one can conclude the following:

- Impact Charpy testing revealed significant influence of creep damage causing increase of transitional temperature for the damaged material and its brittle behavior at room temperature. Anyhow, such reduction of material resistance to impact load is not of great practical importance, except for unlikely combination of impact load during cold start. Otherwise, impact energies, both for crack initiation and growth, were sufficiently high, although their values were reduced at high temperature, especially for the damaged material.
- Static fracture mechanics testing indicated similar behavior as during impact testing, but the values obtained for fracture toughness (J_{Ic}) were satisfying for all temperatures and for both materials. Therefore, one can conclude that impact load is more critical than the presence of cracks under static loading.
- Fatigue testing resulted in significant increase of crack growth rate for the damaged material, indicating high susceptibility of this material to fatigue crack growth under creep conditions. Anyhow, since the threshold values for stress intensity factor amplitude are almost the same, one can conclude that crack initiation phase in fatigue process is not affected in the same way.

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OTPORNOST PREMA RASTU PRSLINE PUZANJEM OŠTEĆENOG MATERIJALA

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U radu je istraživana otpornost prema rastu prslina puzanjem oštećenog materijala u termoelektrani "Kostolac A". To je izvedeno ispitivanjem i poređenjem udarnih, statičkih i zamornih osobina rasta prsline novog materijala i materijala izloženog puzanju tokom 175000 radnih sati (niskolegirani čelik 12×1 M∅ prema GOST 10500-63). Da bi se dobio puni opseg osobina rasta prslina za oba materijala za udarno i statičko ispitivanje izabrane su temperature 20^{o}C, 400^{o}C, 520^{o}C, 540^{o}C (radna temperatura) and 560^{o}C. Udarno ispitivanje je izvedeno na instrumentiranom Charpy-jevom klatnu, koje omogućava razdvajanje energija stvaranja i rasta prsline. Statička ispitivanja su izvedena standardnim postupkom za merenje J integrala. Zamorna ispitivanja su izvedena ocenom zavisnosti brzine rasta prsline i amplitude faktora intenziteta napona. Prema ovim ispitivanjima otpornost prema rastu prsline puzanjem oštećenog materijala je ocenjena.