INSTRUMENTED IMPACT TESTING AS A METHOD OF CLEAVAGE FRACTURE STRESS DETERMINATION (TEMPERED BAINITIC STEELS)

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Instrumented impact tester, low - blow technique and Charpy V - notch specimens have been used to measure the cleavage fracture stress of 2.25Cr -1 Mo low alloy pressure vessel steel and Cr - Mo - V creep resistant steel, respectively. The cleavage fracture stress, σ_{CF}, has been determined as a local maximum tensile stress at the onset of fracture at temperature at which the general yield force is coincident with fracture force. The relation $\sigma_{CF} = c_1 (F_{GY})_{tGY}$ was derived for calculation of σ_{CF} the constant c_1 being found to be 107 MPa/kN for tempered bainitic steels. Independence of cleavage fracture stress on temperature and stress rate was prooved experimentally. Values obtained using instrumented impact and static testing corresponds well to data generated by means of FEM calculations.

INTRODUCTION

Brittle fracture initiation in low carbon low alloy steels occurs when the maximum principal stress acting in the plastic zone ahead of the notch or the crack tip reaches locally the critical value (critical tensile stress criterion (1)). This local maximum principal tensile stress, regarded as a cleavage fracture stress, should represent the resistance of particular microstructure to the cleavage and should be characteristics independent of temperature and loading rate (deterministic concept of cleavage initiation (1-6)). According to Beremin's model (7) the cleavage initiation may be triggered in any small volume (cells) scaled in the plastic zone, having the characteristic microstructural dimensions and constituting the cleavage process zone (weakest-link theory). Two parametric Weibull functions are usually used as basic for cleavage fracture description in such case (probabilistic concept).

The latter concept is recently broadly explored and preferred as a fundamental micromechanistic model for the prediction of cleavage fracture and the scatter of the fracture mechanics characteristics, in tempered bainitic steels (7, 9) and welds (8). A draft is worked out for the measurement of required metallurgical parameters that enter in the model (10). Nevertheless, the deterministic approach

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of local fracture stress for brittle fracture initiation (transgranular cleavage or intergranular) appears to be useful for the solution of a number practical problems (e.g. for analysis of the influence of heat treatment on brittle fracture resistance (11), irradiation embrittlement (12) and the embrittlement induced by isothermal ageing (13) or long-term operation of power plants at elevated temperature (14)). Most recently, even in such advanced fracture mechanics methodology as represented by J-Q approach the cleavage fracture stress is used to determine J_C - Q fracture toughness loci (15) or to account for the fracture toughness scatter and the influence of specimen types (with various J-Q stress fields) on J_C -values (16).

Three types of specimens are effectively used for determination of local critical tensile stress at the onset of fracture: conventional Charpy specimens (6, 11, 12, 17), four point V-notched bend ones (3-5), and double-edge notched tensile specimens (18). The loading rate used are quasi-static, rapid or low blow impact. The tests are performed over the temperature range where fractures take place closely above and below general yield force F_{GY}, respectively. The prerequisite for the evaluation of the local maximum principal stress at the onset of a cleavage or intergranular rupture is the knowledge of stress distribution over plastic zone ahead of a notch-tip. The slip-line theory (19), the combined slip-line and Neuber's theory (20) and finite elements method (21, 22) have been used for this purposes.

In the present paper the utilisation of the instrumented impact tester, low-blow impact technique and Charpy V-notched specimens for the evaluation of cleavage fracture stress of various low alloy creep resistance steels with tempered bainitic microstructure is presented.

MATERIALS, TESTING METHODS

Instrumented impact tester with a force measurement by means of specially designated tup with electrical resistance strain gages and with hammer displacement measured by means of an inductive transducer was used to obtain force - displacement traces. Low-blow impact was employed to determine the true values of fracture force (23). The tests were carried out over appropriate temperature range for a particular microstructure. The general yield force F_{GY} the determination procedure of which is described elsewhere (14) and the fracture force F_{FR} were taken from the force - displacement traces.

To compare results from low-blow tests some experiments were performed at low load rate and at rapid loading. Conventional tensile testing machine and rapid hydraulic testing machine were used for these tests. For low temperature testing the cooling chamber with a fixture for three-point bending was available. Force versus cross-head or piston displacement was recorded.

The following creep resistance steel were employed for examination: -pressure vessel 2.25Cr-1Mo steel (ASTM equivalent A 387, Grade D) in as-received conditions, and after normalisation and various tempering. The microstructures produced were tempered bainite.

- Cr-Mo-V rotor steel in normalised and tempered condition. The microstructure produced was tempered bainite with about 5 % of proeutektoid ferrite.

For both steels used the tempering parameter M and room tensile properties are presented in Tab. 1.

TABLE 1 - Tempering Parameters used and Room Tensile Properties

steel	Temp. par. $M.10^{-3}$	R_{el}, $R_p0.2$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]	steel	Temp. par. $M.10^{-3}$	R_{el}, $R_p0.2$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]
Cr	as-rec	308	495	-	-	Cr	18.53	872	988	19	60.4
Mo	18.67	671	783	21	57.4	Mo	18.84	865	976	17	61.9
	19.08	622	727	21	55.4	V	19.34	771	886	18	63.5
	19.89	450	600	30	58.3		19.75	679	800	20	65.9
	20.63	419	579	31	51.8		20.85	471	612	25	68.1
	21.61	380	527	35	51.9		21.82	398	516	32	63.3

For all the microstructures examined the variation of the forces F_{GY} and F_{FR} as a function of test temperature was measured and temperature t_{GY} at which general yield force F_{GY} coincides with fracture force F_{FR} was determined. Local maximum principal stress at t_{GY}, which is regarded as a cleavage fracture stress σ_{CF}, was evaluated. As derived by Odette et al. (12) and verified by Holzmann et al. (14), the cleavage fracture stress σ_{CF} at t_{GY} for Charpy V-notched specimen can be calculated using the following relation

$$\sigma_{CF} = c_1 \, (F_{GY})_{tGY} \qquad (1)$$

for any loading rate. For tempered bainitic microstructures the constant c_1 is equal to 107 MPa/kN.

RESULTS AND DISCUSSION

The 2.25Cr-1Mo Pressure Vessel Steel

The plot of the general yield force, F_{GY}, and the fracture force, F_{FR}, for as-received condition and for a variety of loading rates is shown in Fig. 1. The temperature t_{GY} is marked in this figure. The calculated values of the cleavage fracture stress σ_{CF} are plotted against temperature in Fig. 2. The independence of σ_{CF} on loading rate and temperature is proved.

In the graph, Fig. 3, the temperature t_{GY} and FATT (fracture appearance transition temperature) are plotted as a function of M. The so-called upper nose temper phenomenon, i.e. the drop of t_{GY} and FATT at the initial stages of tempering followed by the increase these temperatures for the heavy tempered conditions, Fig. 4, may be observed (24).

Figure 4 shows the cleavage fracture stress as a function of tempering parameter M. Both results measured at low-blow impact and at quasi-static loading are presented. As seen the results of both methods are closely coincident and show almost linearly drop of σ_{CF} with the increase in M. The fall of σ_{CF} with increase M for SA 508 Class 2 pressure vessel steel was reported by Curry (5) as well.

The Cr-Mo-V Rotor Steel

The cleavage fracture stress σ_{CF} is plotted against M in Fig. 4. Similarly as for the Cr-Mo steel, the linear drop of σ_{CF} with increase M is observed. From comparison of plots for both steels investigated can be seen that the cleavage fracture stress σ_{CF} for rotor Cr-Mo-V steel is about 450 MPa lower than that for Cr-Mo steel.

In Fig. 3 the temperatures t_{GY} and FATT of Cr-Mo-V steel are plotted as well. As seen, these temperatures for Cr-Mo-V steel are shifted towards much higher temperatures compared to those of Cr-Mo steel. The main cause of this shift is lower values of σ_{CF} and the higher values of yield stress/proof strength for any level of tempering parameter M, Tab. 1. Moreover, both mentioned material characteristics resulted in the shift in fracture toughness - temperature curve for Cr-Mo-V steel to higher temperature, e.g. the temperature at which K_{JC} = 100 MPam$^{1/2}$ for Cr-Mo-V steel was shifted as high as 100°C compared to the temperature at which K_{JC} exhibited the same level in Cr-Mo steel.

CONCLUSIONS

The instrumented impact tester, Charpy-V notched specimen and low-blow impact technique have been proved to be successful tool for determining the cleavage fracture stress of tempered bainitic Cr-Mo and Cr-Mo-V steels. Determining the temperature t_{GY}, at which general yield force coincides with fracture force, the cleavage fracture stress may be evaluated by simple multiplication of this general yield force by a constant c_1, that, for tempered bainitic steels, is equal to 107 MPa/kN. It has been shown, that the position of ductile to brittle transition region as characterised e.g. by FATT, is located for Cr-Mo-V at much higher temperatures compared to that of Cr-Mo steel. This result may by accounted for in terms of the lower cleavage fracture stress and the higher level of yield stress/proof strength of Cr-Mo-V steel for any level of tempering parameter M.

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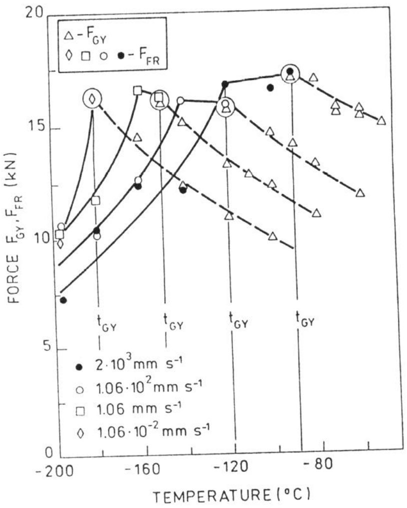

Figure 1 General yield force and fracture force as function of temperature

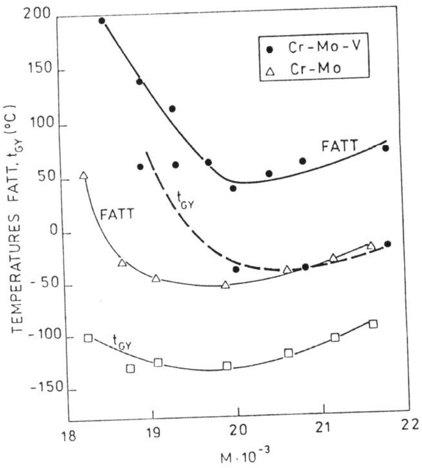

Figure 3 Transition temperatures as a function of tempering parameter M

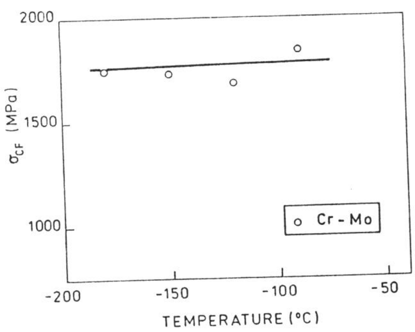

Figure 2 Cleavage fracture stress versus temperature

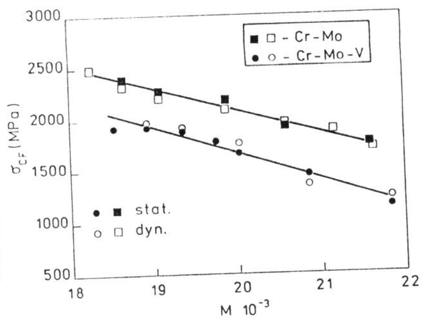

Figure 4 Cleavage fracture stress as a function of tempering parameter