CHARACTERISTICS OF FRACTURE BEHAVIOUR OF DUPLEX STEELS IN TRANSITION REGION

I. Dlouhý*, A. Procházková*, V. Kozák*, M. Holzmann*

Fracture behaviour of duplex stainless steel was analyzed arising from temperature dependencies of strength properties, fracture toughness, impact energy and, in particular, from characteristics of load - deflection traces obtained using instrumented impact tester. At uniaxial tensile loading, the ferrite transition behaviour is significantly compensated by austenite plasticity. Fracture of Charpy V-notch specimens and precracked compact tension specimens, respectively, in transition and lower shelf regions is controlled by fracture behaviour of ferritic constituent of the microstructure. Critical (effective) fracture stress at the onset of unstable fracture for Charpy type specimen was estimated. The values determined are well comparable with results of FEM calculation.

INTRODUCTION

For subzero design and application temperatures of steels, it is common practice to minimise the risk of brittle failure by imposing impact test requirements. For ferritic steels, the Charpy impact energy values and/or other fracture characteristics required are well standardised. For duplex stainless steels however, for which the application temperatures below ambient have not been quite typical, the toughness requirements in terms of Charpy V (1,2) or fracture toughness test (J_i (J-Δa) and/or CTOD approach (3-7)) are still open to discussion.

An instrumented impact testing suppose one of the method potentially purposeful for more exact description of fracture transition behaviour of duplex steel (7). Characteristic forces obtained from load - deflection traces (using low blow impact technique) can be used as for modelling microstructure property relationships so for revealing microstructures embrittled during technological and/or operational degradation. Furthermore, the knowledge about fracture behaviour such an in situ natural composite as represented by duplex steel, can give new opinion and ideas for their use in future or for development of new classes of materials.

*Institute of Physics of Materials ASCR, Žižkova 22, 61662 Brno, Czech Republic

In our work, a duplex stainless steel has been studied to evaluate the role of both phases the austenitic and ferritic ones in transition behaviour. The critical fracture stress and brittleness transition temperature for Charpy type specimens have been measured by means of instrumented impact tester to assess the relationships between the microstructure and the macroscopic fracture characteristics.

MATERIAL AND EXPERIMENTAL METHODS

The steel used had chemical composition (wt %): 0.022 C; 1.07 Mn; 0.25 Si; 4.98 Ni; 21.5 Cr; 3.1 Mo; 0.118 N; 0.035 P; 0.012 S. The steel was commercially produced forged thick wall pipe (outer diameter of 700 mm, wall thickness of 80 mm) with microstructure after solution treatment. Comparable amount of ferrite and austenite, both phases without preferential orientation, was identified.

Tensile and the Charpy V-notch specimens were extracted in all three possible orientations of their longitudinal axis in relation to pipe axis. The yield strength was taken to be the 0.2 % proof stress. Standard compact tension specimens with thickness of 25 mm were tested in tangential - radial orientation to determine fracture toughness characteristics.

To evaluate the temperature dependencies of CVN impact energy the Charpy V-notch specimens were tested by means of instrumented impact tester with hammer drop rate of 5.6 ms^{-1} over a temperature range of -196 to 100 °C. Low blow technique was used to generate load - deflection (F - f) traces from which fracture force F_{iu}, maximum force F_m, and general yield force F_{gy}, respectively could be determined (in accordance with recommendation (11)). General yielding was defined as the attainment of plastic deflection, f_p, of 0.1 mm.

The critical fracture stress, σ_F, was determined, it was taken to be the local maximum tensile stress ahead of the V-notch at the onset of unstable fracture. At temperatures where fracture and general yield forces were coincident (i.e. at brittleness transition temperatures t_{gy}) fracture stress can be derived directly from general yield force. The relation of measured static and dynamic yield strength and general yield force was tested. Arising from the linear relation between these characteristics a simplified approach for calculation of σ_F from general yield force could be applied using relation $\sigma_F = 97.F_{gy}$.

The fracture appearance and fracture micromorphology of broken CVN and CT specimen and microstructures in section perpendicular to fracture surfaces were assessed using SEM. Thin foils were examined by TEM. The complete results and a detailed analysis is out of scope of the paper and will be given elsewhere.

RESULTS AND DISCUSSION

Tensile Properties

Selected results of tensile tests generated at room temperature and at -110 °C are shown in Table 1. Example of temperature dependence of yield strength for tangential oriented specimen is in upper part of Fig. 1. No significant differences in strength properties of all three specimen orientations were found. At tensile loading the ferrite transition behaviour is significantly compensated by austenite plasticity. From thin foils cut from stopped tensile test was evident that the plastic deformation of austenite can contribute much more to the local stress in ferrite than the applied macroscopic stress. Therefore, regarding to the tensile deformation (the strength properties being increased with test temperature decrease) no embrittlement effects (assessed by means of tensile ductility and reduction in area) up to liquid nitrogen temperature could be observed. In case of brittle behaviour of ferrite (at lower temperatures and/or in aged condition too), the tensile curves display behaviour similar to skeletal composite.

TABLE 1 Selected Tensile Properties and Brittle Fracture Characteristics

	R.T.			at -100 °C			brittle fracture characteristics			
spec. axis	$R_p0.2$ [MPa]	R_m [MPa]	A [%]	$R_p0.2$ [MPa]	R_m [MPa]	A [%]	t_{gy} [°C]	t_{gy} [°C]	σ_F [MPa]	σ_F [MPa]
long.	479	616	37	713	876	59	- 90 (C)	-100 (R)	1820 (C)	1890 (R)
tang.	457	614	39	725	894	39	-110 (R)	- 95 (L)	1890 (R)	1890 (L)
rad.	440	605	33	705	875	32	-105 (C)	- 95 (L)	1900 (C)	1880 (L)

Impact Properties

The steel investigated exhibit notch impact toughness of nearly 200 J at room temperature. The satisfactory level of notch impact toughness values is retained to temperatures as low as -80 °C. The lower part of Fig. 1 shows typical CVN impact test data for tangential orientation (C) of specimens and radial orientation (R) of fracture area. Fig. 2 includes temperature dependencies of general yield, F_{gy}, maximum, F_m , and fracture forces, F_{iu}, respectively.

Fracture of CVN specimens at impact loading in transition and lower shelf region is primarily controlled by fracture behaviour of ferritic part of the microstructure. Compared to low alloyed steel, duplex steel exhibit some typical peculiarities (quite different from those usually observed for materials with cleavage-fibrous transition behaviour):

(i) Even at a very low temperatures the load - deflection records display stable crack propagation behaviour, unstable fracture component is much smaller than for common steel.

(ii) Fracture surfaces in the transition region do not display discrete area of both the ductile precrack and the brittle - unstable failure, the mixture of ductile tearing and cleavage facets under notch root and over the whole fracture surfaces could be observed. Therefore, it is impossible to define common transition temperatures in CVN impact energy versus temperature curve identifying, as usually, changes in crack initiation and/or propagation mechanisms. Two approaches for assessing fracture appearance transition temperature on sheet duplex steel were suggested elsewhere (8).

(iii) While steels with ferritic matrix display a quite sharp transition from ductile to brittle behaviour with decreasing temperature the transition region is comparably broader for duplex steel.

For CVN specimen (and similarly for CT specimen) fracture in transition region takes place in several steps. First, cleavage cracks are initiated in ferrite. These cleavage cracks cross ferrite and stop at the interface with austenite. Nevertheless, only the grains having a favorable orientation will lead to cleavage cracks in ferrite. After this stage, cracks subsequently grow by plastic deformation of austenite.

Critical fracture stress

The critical fracture stress is supposed to be one of the main characteristics controlling and successfully used for assessment of brittle fracture behaviour in low alloy ferritic steels. For first approximation, this similar approach was suggested for duplex steels.

As the critical fracture stress, σ_F, the local maximum tensile stress ahead of the notch at the onset of unstable fracture was taken. Although some effect of plastic strain preceding the fracture in transition region has to be supposed (9) the fracture should be very close to stress controlled at brittleness transition temperature (i.e. temperature defined as coincidence of general yield and fracture force). It is necessary to note that the higher strain rates commonly with stress intensification caused by notch, both shift the brittleness transition temperature to higher, i.e. for duplex steel acceptable values. Selected data of t_{gy} and σ_F are given in Table 1.

True stress vs. true strain curves recorded for tangential tensile specimen at -110 °C were approximated by bilinear function and used for calculation of principal stress below the V - notch using FEM (ANSYS 5.1). Part of results is introduced in Fig. 3. For selected levels of load up to general yield (i.e. fracture) force the peak stress increase up to value of 1790 MPa. For C-R orientation σ_F was determined on level of 1890 MPa. Taking into account the stress-strain approximation used and duplex composite microstructure approximated by isotropic continuum quite good agreement of both values was found.

Fracture Toughness

Dependence of fracture toughness on temperature in transition and lower shelf region is introduced in Fig. 4. Three types of fracture toughness values could be identified: Fracture toughness values K_{IC} were determined according to linear elastic fracture mechanics. Values of K_{JC} were determined using equivalent energy approach. Characteristics designated as K_{Ju} (generated also by equivalent energy approach) are only values for which the ductile tearing was identified in fracture surface.

CONCLUSIONS

Fracture behaviour was analyzed arising from temperature dependencies of strength properties, fracture toughness, CVN impact energy and, in particular, from load - deflection curves obtained by means of instrumented impact tester.

1. For uniaxial tensile loading, no embrrittlement phenomena up to liquid nitrogen temperature could be observed. The ferrite transition behaviour was significantly compensated by austenite plasticity.
2. Fracture of CVN specimens at impact loading in transition and lower shelf regions is controlled by fracture behaviour of ferritic part of the microstructure. Similar behaviour was identified for precracked CT specimen.
3. Brittleness transition temperatures could be determined (from temperature dependencies of general yield and fracture forces) using low blow impact testing.
4. The critical fracture stress determined experimentally is on level comparable with FEM calculation. The values obtained seems to be sensitive on material behaviour in transition and lower shelf region.

The phenomena were specified to prove experimentally that the fracture behaviour of duplex stainless steel similar to skeletal composite rather than standard steel behaviour.

ACKNOWLEDGMENTS

The research was financially supported by grant Nr 101/94/0304 of the Grant Agency of the Czech Republic.

REFERENCES

(1) Charles, J., Proc. of I.C. on Duplex Stainless Steels, Glasgow (1994), TWI, Vol. 1, Keynot paper I.

(2) Toru, G., Takeshi, N., Takasi Y., Proc. of. I. C. Materials ageing and component life extension, Milan, pp. 629 - 645.

(3) Mockler, C. J., Spence, M.A., Humpreys, A., Proc. of I.C. on Duplex Stainless Steels, Glasgow (1994), TWI, Vol. 1, p.52.

(4) Neubert V, Dolling, R., Proc. of I.C. in Duplex Stainless Steels, Glasgow (1994), Vol 1, p. 114.

(5) Iturgoyen, L., Alcala, J., Anglada, M., Proc. of E.C.F. 9, Varna (1992), Vol. p. 331-336.

(6) Irisari A.M., Eurazkin, A.M., et al., Proc. of E.C.F. 8, Torino (1990), p. 373-376.

(7) Pineau, A., Joly, P., In: Defect assessment in Components..., ESIS/EGF 9, 1991, p. 381-414.

(8) Dlouhý, I., Kozák, V., Holzmann, M. Proc. of 4th E. Conf. on Advanced Mat. and Processes, Euromat'95, Szmp. D,E, p. 605-608.

(9) Marrow, T. J., Harris, C. J., The fracture mechanism of 475°C embrittlements in DSS., J of Fatigue and Fracture, 1996, submitted to publication.

(10) Johanson, L., Ohlson, N.G., Proc. of I.C.M 6, Tokyo (1991), pp. 237-241.

(11) Proposed standard method for the instrumented Charpy-V impact test, ESIS TC5, 1994.

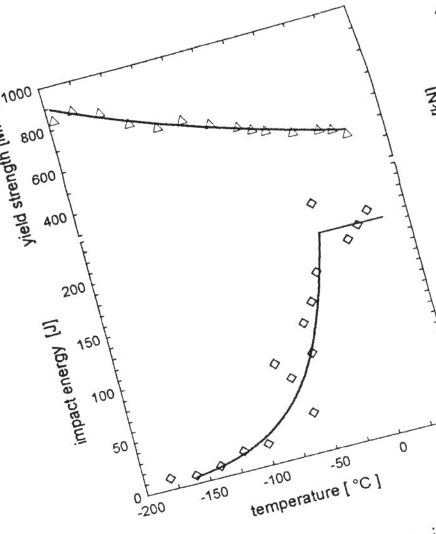

Figure 1 Temperature dependencies of yield strength and CVN impact energy

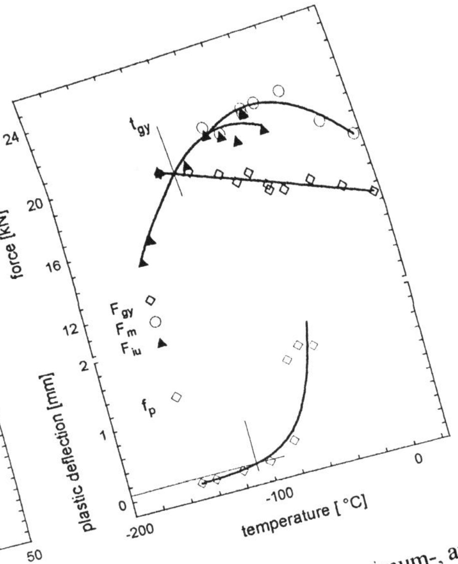

Figure 2 General yield-, maximum-, and fracture forces versus temperature

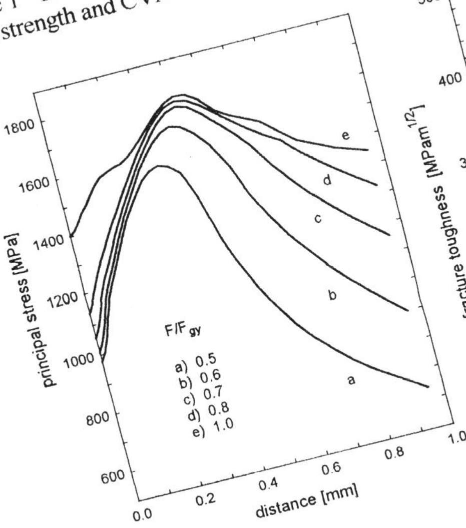

Figure 3 Dependencies of principal stresses below the notch on applied stress

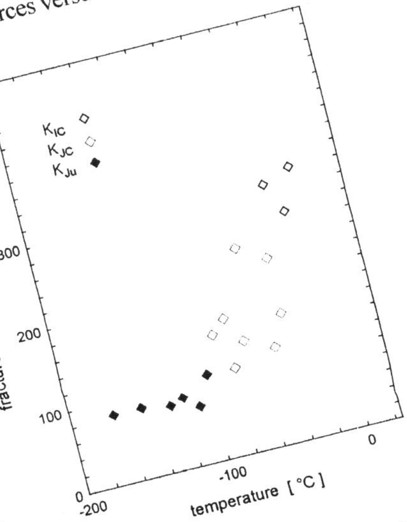

Figure 4 Fracture toughness as a function of temperature