INFLUENCE OF SPINODAL DECOMPOSITION ON THE MECHANICAL PROPERTIES OF DUPLEX STAINLESS STEEL

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Duplex austenitic-ferritic stainless steel is an alternative to austenitic stainless steel in some applications, *e.g.* where resistance to chloride induced corrosion is important. A characteristic feature of duplex stainless steels is the hardening of the ferritic phase that occurs in the temperature interval of 250 to 500°C. The subsequent loss of toughness has traditionally limited the use of duplex stainless steel to temperatures below 250-280°C. The present paper focuses on the relevancy of this limit and discusses the strain rate sensitivity of the mechanical properties. It is shown that the mechanical properties of hardened duplex stainless steels is very strain rate dependent.

INTRODUCTION

Duplex austenitic/ferritic stainless steels (DSS) are an interesting alternative to austenitic stainless steels in a wide variety of applications. The advantages of DSS are high mechanical and fatigue strength combined with high corrosion resistance. A characteristic feature of duplex stainless steels is the susceptibility of the ferritic phase to the formation of various intermetallics and precipitates in the temperature range 250-1000°C. In the literature, a variety of precipitates, intermetallics and other phases has been reported by Charles (1). An important phase transformation in the ferritic phase is the α'-formation that takes place at temperatures between 250 and 500°C. This leads to a hardening of the ferrite and a subsequent increase in yield stress and loss of impact toughness (Nilsson and Liu (2)). Traditionally, this behaviour has been considered as a limitation for the use of duplex stainless steel at temperatures above 250-280°C. The purpose of this paper is to discuss the relevancy of this limit and to show the potential of the spinodal decomposition as a beneficial hardening mechanism.

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MATERIALS & EXPERIMENTAL

The material studied is a duplex, ferritic-austenitic steel emanating from laboratory melts with chemical compositions according to Table 1. In order to better understand the behaviour of the duplex steel, single-phase austenitic and ferritic steels are included. The steels belong to a series of experimental alloys used in a larger programme investigating the mechanical properties of DSS (Nyström (3)). The duplex steel has a microstructure that is slightly banded along the rolling direction while the single-phase steels exhibit essentially isotropic microstructures. The mean sizes of grains ($\overline{L^{\alpha\alpha}}, \overline{L^{\gamma\gamma}}$) and phase regions ($\overline{L^{\alpha}}, \overline{L^{\gamma}}$) measured as mean intercept lengths in the transverse plane are given in Table 2. The steels were studied in two conditions: 1/ As received (designation AR) and 2/ As above, followed by heat treatment at 475°C for 100h to create hardening of the ferrite phase (designation HT). Tensile tests were performed along the rolling direction. Impact toughness tests were performed with standardised Charpy-V type specimens (LT-orientation, ASTM E399). Fracture toughness tests were carried out according to the single-specimen, three-point bending J_{IC} technique (ASTM E813).

TABLE 1. Chemical composition (w/o) of alloys studied.

Material	C	Cr	Ni	Mo	Mn	Si	N	Fe
Austenite	0.028	21.4	9.1	2.7	0.98	0.42	0.30	bal.
Ferrite	0.005	23.3	4.4	3.8	0.99	0.82	0.005	bal.
Duplex	0.018	22.1	5.8	3.0	0.88	0.51	0.17	bal.

TABLE 2. Microstructural data.

Material	V_V^{α}	V_V^{γ}	$\overline{L^{\alpha}}$ [μm]	$\overline{L^{\gamma}}$ [μm]	$\overline{L^{\alpha\alpha}}$ [μm]	$\overline{L^{\gamma\gamma}}$ [μm]
Austenite	0	1	-	-	-	46
Ferrite	1	0	-	-	94	-
Duplex	0.41	0.59	11.7	20.0	10.7	12.3

RESULTS

Monotonic deformation

The monotonic strain-stress behaviour of the ferritic and duplex materials are shown in Fig. 1. The spinodal decomposition raises the flow stresses rather uniformly in both the ferritic and duplex steels. Considering the lower yield stress and higher ductility (Table 3) of pure austenite, it is not surprising that the duplex material exhibits larger ductility than the ferritic specimens. The data show that the

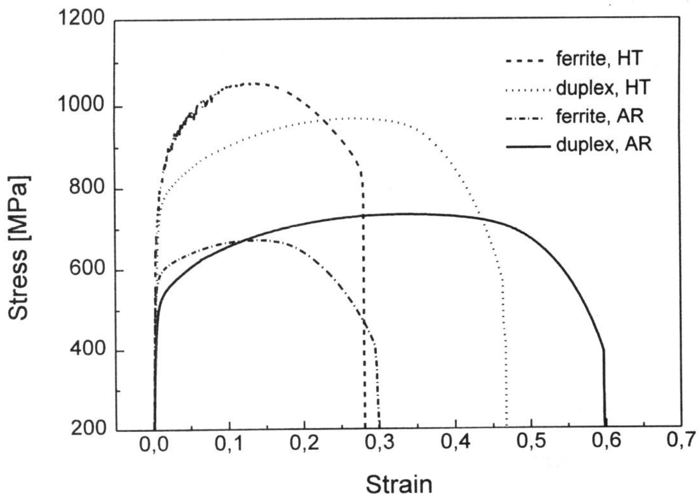

Figure1. Monotonic deformation characteristics of the ferritic and duplex steel.

ferritic and duplex steels essentially preserve their ductility after the hardening causing an increase in yield and tensile stresses by some 25-30%. It has earlier been shown that the austenite is unaffected by the annealing at 475°C (3).

Toughness

Impact toughness at ambient temperature was measured as a function of annealing time at 475°C, Fig. 2. Apart from the duplex steel, single-phase ferrite was tested. As is readily observed from Fig. 2 the duplex steel is superior to the ferritic for all ageing times up to 100 hours at 475°C. After 100 h the ferritic steel is completely brittle while the duplex steel has an impact toughness of approximately 60 J. Due

TABLE 3. Static mechanical data.

Material	σ_y [MPa]	σ_{UTS} [MPa]	A_g [%]	ε_f [%]
Austenite	400	782	53	79
Ferrite, AR	555	754	14	28
Ferrite, HT	701	1052	12.5	27
Duplex, AR	421	732	35	62
Duplex, HT	549	971	28	49

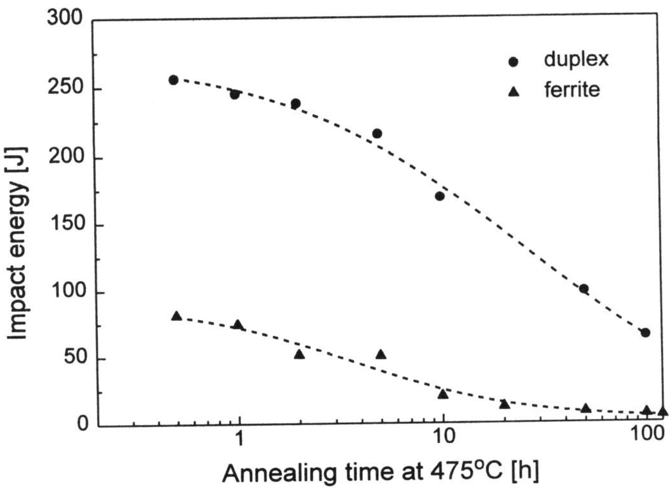

Figure 2. Impact toughness as a function of annealing time at 475°C.

to specimen thickness restrictions the J_{Ic}-tests produced valid measurements only in the case of hardened material. However, the toughness (J_{Ic}) of the HT condition was 100 kJm^{-1}, which corresponds to a K_{IC} of 143 $MPa\sqrt{m}$ ($K = \sqrt{JE}$).

5. DISCUSSION

The aim of the present study is to evaluate whether the versatility of duplex stainless steel at high service temperatures can be enhanced if the merit of duplex stainless steel is described with adequate material properties. Further, the potential of using the spinodal decomposition as a hardening mechanism is indicated. The discussion below is devoted to microstructural effects as well as strain rate effects for virgin and spinodally decomposed materials. The results indicate that the strength properties of the duplex steel in the annealed, "embrittled" condition is strongly strain rate dependent. Thus, it is important to describe the merit of duplex stainless steel with material properties relevant for the intended application.

Linear law of mixture modelling

The plastic deformation properties of duplex stainless steels naturally depend on the properties of the austenitic and ferritic constituents, but also on the interaction between these two phases. The simplest approach is to assume equal strain in the constituent phases ferrite and austenite and add the stresses in proportion to their volume fraction. By doing so and adjusting for differences in grain sizes, a simple model to estimate the stress-strain behaviour for the duplex steel is obtained. The stress levels in the ferritic and austenitic phases were adjusted for grain sizes (Table 2) by the Hall-Petch factors k_y(ferrite)= 20 $MPa\sqrt{mm}$, (Reisner and Werner (4)) and k_y(austenite)= 24,8 $MPa\sqrt{mm}$ (3). A test on this approach is shown in Fig. 3, where the predicted flow stresses overestimate the recorded ones by less than 10%. More realistic modelling with strain concentration in the softer austenitic phase would lower the predicted stress levels. Other factors like differences in crystallographic texture between phases in the duplex material and in pure form would also influence on the modelling as would internal stresses (3). Regarding these complicating factors the simple law of mixture works surprisingly well.

Influence of strain rate

For the present duplex stainless steel with hardened ferrite, there exists a clear strain rate effect regarding the mechanical properties. The most obvious example is a comparison between the tensile properties and the impact toughness. It is clear from the tensile tests that the hardened ferrite has a minor effect on the elongation

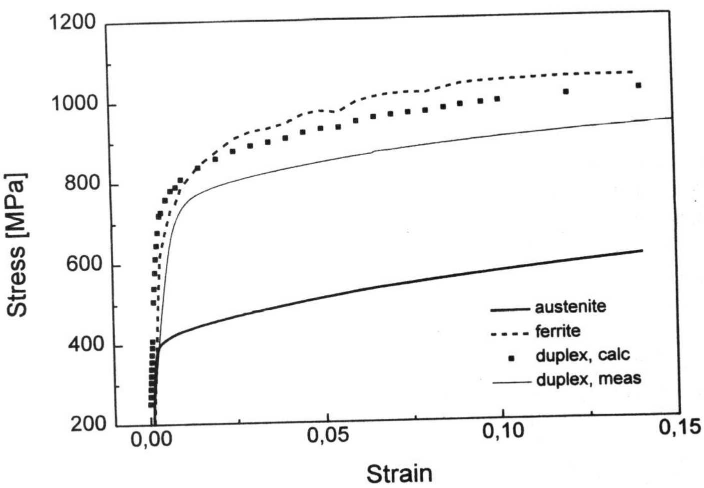

Figure 3. Modelling the monotonic behaviour of the duplex steel; linear law of mixture, parallel case

to fracture. On the other hand, the effect of the embrittled ferrite is much more evident in the Charpy impact toughness levels, where a large drop can be seen for the duplex steel due to the annealing at 475°C. It seems plausible to attribute this difference to the vastly different strain rates. During the tensile tests the strain rate is $3 \cdot 10^{-4}\ s^{-1}$, while equivalent strain rates for the intensively stretched zone in Charpy V impact testing is $>10^3\ s^{-1}$. The plastic deformation of the spinodally decomposed ferrite takes place by twinning during tensile straining (Fig. 1). Such twinning is known to be strain rate sensitive and associated with loss of toughness at high strain rates. From an engineering standpoint the influence of strain rate is of importance. Thus, the potential of spinodal decomposition as a hardening mechanism and the associated decrease in toughness should be judged from actual engineering strain or stress intensification rates. In the present case the hardened duplex steel can sustain hardening with reasonably low loss of toughness provided the loading rates are reasonably low. As the sensitivity to strain rate is limited to the ferritic phase the problem of embrittlement is less pronounced at lower volume fraction of ferrite where spinodal decomposition is still an effective means of hardening (3).

CONCLUSIONS

1. The ductility of duplex stainless steels, with a spinodally decomposed ferrite, is very sensitive to the strain rate. Thus it is important to describe the merit of duplex stainless steel, subjected to high service temperatures, with adequate test methods.
2. In the present study a duplex stainless steel with 40% ferrite exhibited Charpy-V impact toughness exceeding 60 J even after 100 hours annealing at 475°C. Such exposure resulted in considerable increase in yield and ultimate tensile stresses with only marginal loss of elongation to fracture.
3. Strength values for the duplex material could be approximately evaluated by simple mixture rules from corresponding data from the constituent phases, provided that grain size effects were accounted for.

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