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Review

# Effect of 475 °C embrittlement on the mechanical properties of duplex stainless steel

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ABSTRACT

The binary iron–chromium alloy embrittles in the temperature range of 280–500 °C limiting its applications to temperatures below 280 °C. The embrittlement is caused by the decomposition of the alloy to chromium-rich phase, α′ and iron-rich phase, α. This phenomenon is termed 475 °C embrittlement as the rate of embrittlement is highest at 475 °C. Primarily the investigations on 475 °C embrittlement were confined to binary iron–chromium alloys and ferritic stainless steels. Duplex stainless steel grades contain varying proportions of ferrite and austenite in the microstructure and the ferritic phase is highly alloyed. Moreover, this grade of steel has several variants depending on the alloy composition and processing route. This modifies the precipitation behaviour and the resulting change in mechanical properties in duplex stainless steels when embrittled at 475 °C as compared to binary iron chromium systems. The precipitation behaviour of duplex stainless steel at 475 °C and the effect on tensile, fracture and fatigue behaviour are reviewed in this article.



**Contents**



## 1. Introduction

Duplex stainless steel (DSS) is finding increased applications as structural material in critical components of nuclear power plants [1–4], chemical industries [5,6], oil and gas sectors [7,8], paper and pulp industries [9,10], transportation [11] and other general engineering applications because of higher strength, superior

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resistance to stress corrosion cracking and better weldability [12]. The excellent combination of mechanical properties and corrosion resistance of duplex stainless steel is obtained from balanced amount of ferrite and austenite in the microstructure. However, this grade of steel embrittles when exposed in the temperature range of 280–500 °C limiting its application to temperatures below 280 °C. This phenomenon is termed 475 °C embrittlement as the rate of embrittlement is highest at 475 °C [13–15]. The embrittlement changes the tensile [16–22], fracture [23–32] and fatigue [33–47,23,48,49] behaviour of this steel.

The problem of the high temperature application of ferritic stainless steel as a result of 475 °C embrittlement was well known [13–15,50–52]. The decomposition of the ferritic phase to chromium-rich phase, $\alpha'$ and iron-rich phase, $\alpha$ in the temperature range of 280–500 °C due to the presence of miscibility gap in iron–chromium binary alloy system embrittles the microstructure. Since this problem was inherent to ferritic microstructure research emphasis on the embrittlement problem in this temperature range was mostly confined to solely binary iron–chromium alloys and in some cases commercial grades of ferritic stainless steels [13–15,52].

DSS on the other hand contains both ferrite and austenite in varying proportions in the microstructure and is undergoing continuous evolution to newer grades primarily based on adjusting the chemical composition and processing route. Recent development of DSS occurs mainly in the area of alloying molybdenum, copper, nitrogen, etc. for further improving mechanical and corrosion properties. As a result, this grade has a wide range of compositional variation. Cast DSS grades such as CF3, CF8, CF8M, predominantly used in nuclear power industries have ferrite volume fraction in the range of 9–15%, where as the ferrite volume fraction of wrought DSS such as SAF 2205, used in chemical tankers, line pipes is as high as 50%. The chemical compositions of some cast and wrought grades of DSS are listed in Table 1 (these compositions are approximate only and is intended for a comparison of cast and wrought DSS). The 475 °C embrittlement limits the volume fraction of ferrite in the cast grades of DSS (CF3, CF8, CF8M) to below 15% in the microstructure [53]. The volume fraction of ferrite in the wrought grades however varies from as low as 25% to as high as 75%.

As only the ferritic phase is embrittled during aging treatment at 475 °C the degradation in mechanical properties directly depends on the state of the ferritic phase. The volume fraction, distribution in the matrix, grain size and grain shape of the ferritic phase are observed to affect the nature of precipitation and the degree of embrittlement [54]. The bcc–fcc structural difference gives rise to factors such as load sharing between the two phases due to a difference in elastic and plastic response [55,56], difference in the ability to resist crack propagation. The majority of work, on the effect of 475 °C embrittlement on mechanical properties is reported from nuclear power industries. Now-a-days even wrought DSS with a high ferrite content are subjected to this range of temperature and a limited number of studies on 475 °C embrittlement on wrought DSS are reported.

In the present paper, effort has been made to discuss in detail and assimilate the work done by different research groups on the mechanisms, kinetics and thermodynamics of $\alpha'$ precipitation, changes in impact, tensile and fatigue behaviour of DSS as a result of 475 °C embrittlement. The work relating the precipitation characteristics to mechanical properties are discussed. The paper also suggests some of the gray areas where further investigations need to be carried out.

## 2. The 475 °C embrittlement

Reidrich and Loib [50] were the first to report embrittlement, caused by elevated temperature exposure of iron–chromium alloy system. They conducted bend test and observed that steels containing 19–23 at.% chromium showed poor ductility after 1000 h exposure at 500 °C. However, the ductility was not impaired when the samples were aged at 550 °C. This observation indicated that the embrittlement is sensitive to temperature in a very narrow range. Fisher et al. [57] were the first to suggest the decomposition of the ferritic phase in a binary iron–chromium alloy to chromium-rich phase ($\alpha'$) and an iron-rich phase ($\alpha$), in the temperature range of 280–500 °C. They observed fine spherical precipitates of diameter, 200 Å in steel samples containing 28.5 at.% chromium aged at 475 °C for 1–3 years. The precipitate observed by them had bcc structure containing about 80 at.% chromium and was nonmagnetic in nature. The lattice parameter of these precipitates was reported to be between that of iron and chromium. After the detection of precipitates caused by aging treatment and the resulting embrittlement, the focus of research shifted to identify the phases in iron–chromium binary alloy system in the temperature range of 280–500 °C that cause the embrittlement. William [58] was the first to propose explicitly, the existence of a miscibility gap in the iron–chromium phase diagram in the temperature range of 280–500 °C as the cause of precipitation of $\alpha'$ as shown in Fig. 1. According to this phase diagram 475 °C embrittlement may be expected at temperatures below 516 °C in the composition range of 12–92 at.% chromium in iron–chromium binary alloy system. So this study was a confirmation of the earlier study by Reidrich and Loib [50] on the redissolution of $\alpha'$ precipitate when aged at 550 °C. Blackburn and Nutting [51] completely redissolved the $\alpha'$ after 24 h of aging at 550 °C. The neutron diffraction studies conducted by Vintaikin and Loshmanov [59] confirmed the clustering and decomposition of ferritic phase in the temperature range of 280–500 °C.

Some of the critical reviews on the theory of decomposition in metastable ferritic alloys were done by Cahn [60] and Hilliard [61]. These reviews discussed the thermodynamical distinction within the miscibility gap for: (a) spinodal decomposition; (b) nucleation and growth of $\alpha'$. Spinodal decomposition refers to a reaction where two phases of the same crystal lattice type, but different compositions and properties, form due to the existence of a miscibility gap in the alloy system by means of uphill diffusion without nucleation. Thermodynamically this is possible at concentration between the points where the second derivative of free energy with composition equals zero. This phase separation process occurs at a very fine

**Table 1**
Chemical composition of cast and wrought grades of DSS, wt.%*.

| | Grades | C | Mn | P | S | Ni | Cr | Mo | N | Cu |
|---|---|---|---|---|---|---|---|---|---|---|
| Cast | CF3 | 0.030 | 0.60 | 0.003 | 0.002 | 8–12 | 17–21 | <0.5 | – | – |
| | CF8 | 0.057 | 0.62 | 0.003 | 0.002 | 8.23 | 19.94 | 0.21 | – | – |
| | CF8M | 0.074 | 1.21 | 0.032 | 1.140 | 9.59 | 18.67 | 2.73 | – | – |
| Wrought | 2205 | 0.030 | 2.00 | 0.030 | 0.020 | 4.5–6.5 | 22–23 | 3.0–3.5 | 0.15 | – |
| | 2507 | 0.030 | 1.20 | 0.035 | 0.020 | 6.0–8.0 | 24–26 | 3.0–5.0 | 0.24 | 0.5 |
| | 255 | 0.040 | 1.50 | 0.040 | 0.030 | 4.5–6.5 | 24–27 | 2.9–3.9 | 0.25 | 2.0 |

* These comparisons are approximate only and are intended for a comparison of cast and wrought DSS.