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Fractographic Analysis of Tensile Failure in Dual Phase Medium Carbon Low Alloy Steels

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ABSTRACT: *In this research work, the fracture mode of dual phase medium carbon low alloy steels which was subjected to uniaxial tensile testing, was studied. The dual phase microstructure was developed by adopting intercritical heat treatments at an isothermal temperature of 770°C for holding times of 15, 30 and 60 min. After characterising the tensile properties with the aid of a universal tensile testing machine, a scanning electron microscope (SEM-EDS) was further employed to analyse the microstructure of the developed DPS. From the results, it was observed that despite high strength being induced in the steel, the strain-to-fracture remains near 25%. The presence of dimple fractures and pull-outs, which led to the realisation of the existence of intermetallic compounds, was also obtained from the fractographs. In general, sample B-2 was soaked for 30 min and exhibits the best combination of mechanical properties.*

Keywords: Fractographic analysis, intercritical heat treatment, dimple fracture, tensile test, dual phase steel

1. INTRODUCTION

The versatility of ferrous materials has been attributed to their amenability to alloying and heat treatments, which makes it possible to modify their microstructure and to improve the properties that suit specific service requirements.[1,2] One often explored structural modification is the development of dual phase steels (DPS), which are used to a large extent in the production of automobile body parts.[3] DPS possess ferritic (soft and ductile) and martensitic (hard and brittle) microstructures, and the combination of both phases makes it possible to develop high-strength, ductile microstructures in low carbon micro alloy steel.[4,5]

Quantitative relationships between processing parameters (microstructure) and material properties are of considerable interest in the context of developing complex processing routes, which re-orient the microstructure and optimise the required material properties. This has thus led to experimental and theoretical studies examining microstructure-properties relationships.

Fracture-sensitive mechanical properties include ductility, ultimate tensile strength, fatigue life, and fracture toughness. These properties depend to a large extent on the processing parameters that are used when developing DPS.[6] Limited attention has been paid to the influence of microstructural distributions on such material properties, particularly when dealing with medium carbon low alloy steels. Accordingly, an important objective of this research is to perform a systematic investigation of this kind.

Clearly, there are differences and complexities in the structures of DPS that have been produced in modern times. Such variability in the fracture-sensitive properties of structural materials, such as advanced high-strength steels, is not desirable. In recent years, there have been several studies on the relationships between microstructure and the variability in ductility and other fracture sensitive properties of non-ferrous metals. It has been shown that the variability is related to the presence of processing defects and large pores, the spatial distributions of which within the cast component differ in a stochastic manner.[7,8]

Little has been reported in the literature on the complexities of the fracture-sensitive properties of structural steels, particularly of high-strength medium carbon steel. Consequently, there is a need to develop a thorough understanding of the microstructural origins of the observed complexities in the fracture-sensitive properties of advanced high-strength structural steels, such as dual phase medium carbon low alloy steels.

2. EXPERIMENTAL

2.1 Materials

Medium carbon low alloy steel was utilised in this work (the chemical composition is shown in Table 1). The following equipment was used during the course of the research: muffle furnaces, a Buhler grinding/polishing machine, a hacksaw with blade, a bench vice, an Instron universal testing machine, and a medium-size lathe.

Table 1: Chemical composition of the medium carbon low alloy steel.

Elements	C	Si	S	P	Mn	Ni	Cr
Composition	0.3300	0.1740	0.0499	0.0341	0.8225	0.1011	0.1585
Elements	Mo	V	Cu	W	As	Sn	Co
Composition	0.00180	0.0029	0.3031	0.0003	0.0060	0.0230	0.0094
Elements	Al	Pb	Ca	Zn	Fe		
Composition	0.0019	–0.0006	0.0002	0.0037	Bal.		

2.2 Method

Medium carbon low alloy steel was machined to a tensile specimen following the standard configuration that is given by ASTM E8/E8M-13a.[9] The specimens were intercritically treated by initially subjecting them to a normalising treatment, which erased the thermal and mechanical histories of the steel that were induced during the course of machining. The normalising treatment was carried out at an isothermal temperature of 870°C for 60 min in a muffle furnace. Intercritical treatment was then performed isothermally at a temperature of 770°C over holding times of 15, 30 and 60 min. At the end of every stage, the samples were quenched in warm water (37°C) to avoid quench cracking. After treatments, the samples were designated by symbols as B-1, B-2 and B-3 for the 15, 30 and 60 min holding times, respectively. Subsequently, room temperature uniaxial tension tests were performed on round tensile samples (5 mm diameter and 30 mm gauge length) that were machined from a steel sample. A universal tensile testing machine was built according to the standard test procedures established in ASTM E8/E8 M-13a.[9] The samples were tested at a nominal strain rate of 10^{-3} s^{-1} until failure. Multiple tests were performed for each set of conditions to ensure the reliability of the data. The tensile properties were extracted from stress-strain curves that were obtained from the tension tests and include the ultimate tensile strength (σ_u), the yield strength (σ_y), and the strain to fracture (ε_f). Finally, the fractographs were obtained in secondary electron (SE) and backscattered electron imaging mode (BSE) and analysed using an SEM fitted with a detector for energy dispersive x-ray spectroscopy (EDS). This test was conducted for an average of six iterations before analysis.

3. RESULTS AND DISCUSSION

3.1 Tensile properties

The tensile properties of the dual phase structures are summarised in Table 2. The yield strength (Y.S) and ultimate tensile strength (U.T.S) increased with the volume percent of martensite that formed. An apparent linear relationship was established between the strength and the amount of martensite phase in the samples when they were plotted in the order B-3, B-1, and B-2 (Figure 1). In contrast, the percent elongation for all developed duplex phase structures remained approximately 25%. The increase in tensile and yield strengths—sample B-2 possessed the greatest strength value of 638 MPa—with the increase in the volume percent of martensite is in agreement with the observations of Kumar et al.[14].

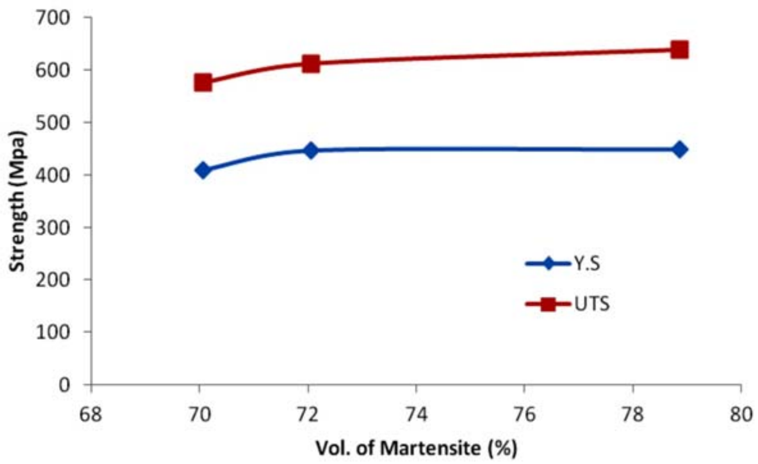

Figure 1: Variation of strength with volume in the martensites.

3.2 Fractography

Visual examinations indicate that the fractured samples exhibited ductile breaks. This is explicit from the cup and cone structures that are shown in all of the fractographs. This observation corroborated the findings by Gokhale et al.[6], Hirose et al.[10] and Alaneme et al.[11]

Figure 2 shows the fractographs for tensile sample B-1 that fractured as a result of uniaxial loading, and they revealed various morphologies in the microstructure. A dimple fracture was observed, and there are various causes that have been attributed to the pull-out of packets observed in the structure, including the ductility of the sample despite its high strength;[12] the low and consistent strain rate that was adopted in the tensile test; and the ferrite-martensite dual phase colonies that exist alongside some laths/platelets.[6]

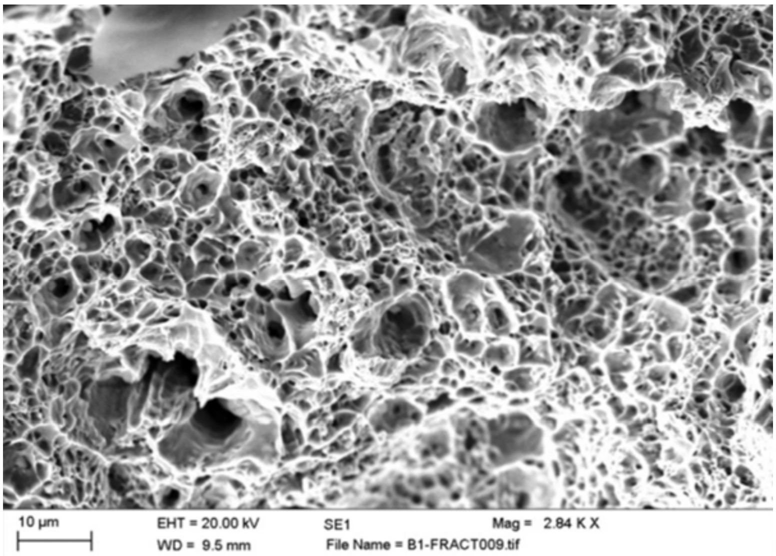

Figure 2: SEM structure of sample B-1 showing ferrite-martensite pull-out.

Figure 3 shows a scanning electron micrograph of sample B-2 in a region where a cluster of ferrite-martensite colonies—typical of DPS—in a ratio of approximately 21:79 was found. The arrangement of these colonies contributes to the high strength observed in the tensile properties of the developed DPS. SigmaScan Pro image analysis software was used to determine the phase proportions.

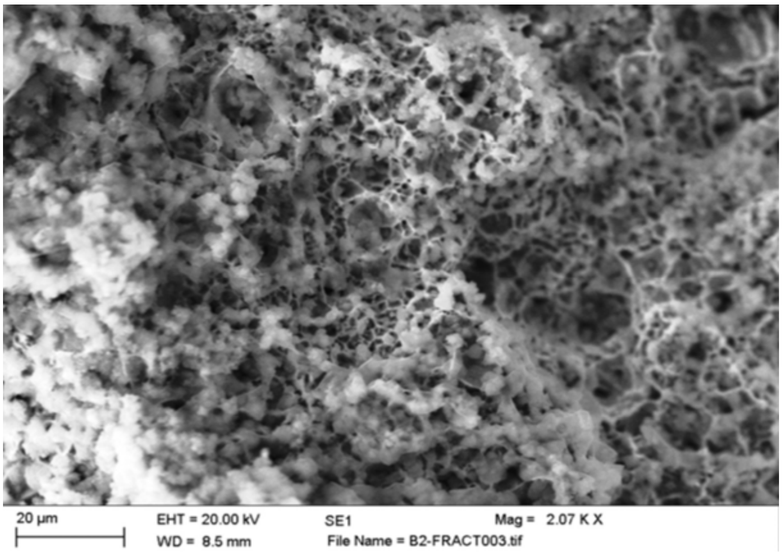

Figure 3: SEM structure of sample B-2 showing ferrite-martensite colonies.

The pull-outs in sample B-3 revealed the presence of cementite, which is a metastable intermetallic compound (Figure 4) that has been observed to gradually decompose into the dual phase base structure.[13] This is the type of fracture that ensued from the incoherence of individual ferrite-martensite interfaces. The large martensitic pull-out regions are generated because of a non-uniformity in the strain distribution at the ferrite-martensite interface, which leads to the whole martensitic region, along with ferritic regions, being extracted. Clearly, such pull-outs have deleterious effects on fracture sensitive properties, such as ductility. This sample is also observed to possess critical features that can be identified as intermetallic compounds. These features ensued from the precipitation of elements that were observed to be rich in silicon and carbon by up to 28 wt% and 18 wt%, respectively. The extreme holding time of 60 min that the sample was subjected to—prior to rapid cooling—could account for this special intermetallic compound formation.

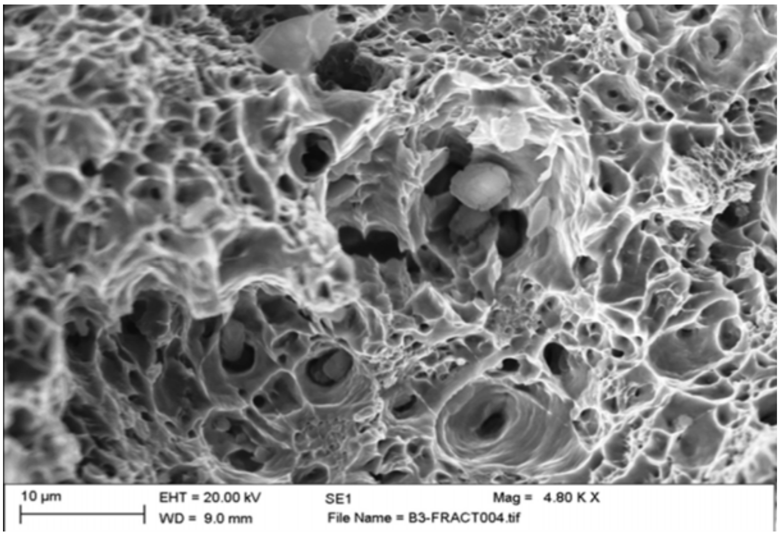

Figure 4: SEM structure of sample B-3 showing intermetallic compounds amidst ferrite-martensite pull-outs.

4. CONCLUSION

The effect of intercritical heat treatments on the fracture mode of medium carbon low alloy steel was studied. The DPS was developed by adopting intercritical heat treatments at an isothermal temperature of 770°C for different holding times. After characterising the DPS tensile properties with the aid of a universal tensile testing machine, a scanning electron microscope SEM-EDS was used to analyse the morphology of the microstructure. The results indicate that in spite of the observed high strength in the developed DPS, the strain-to-fracture remained approximately 25%, thus indicating good ductility. The presence of dimple fractures and pull-outs, which led to the revelation of intermetallic compounds, were also observed in the fractographs. This type of fracture is confirmed to originate from the incoherence of individual ferrite-martensites interfaces. In general, sample B-2, which soaked for 30 min, exhibits the best combination of mechanical properties.

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