THE EFFECT OF LOWER BAINITE VOLUME FRACTION ON TENSILE AND IMPACT PROPERTIES OF D6AC MEDIUM CARBON LOW ALLOY ULTRAHIGH STRENGTH STEEL

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Abstract: *The effects of lower bainite volume fraction on tensile and impact properties of D6AC ultrahigh strength steel were studied in the current work. To obtain mixed microstructures containing martensite and different volume fractions of the lower bainite, specimens were austenitized at 910° C, then quenched in a salt bath of 330°C for different holding times, finally quenched in oil. In order to obtain fully martensitic and bainitic microstructures, direct oil quenching and isothermal transformation heat treatment for 24 hours were used respectively. All specimens were double tempered at 200°C for 2 hours per tempered. Microstructures were examined by optical and scanning electron microscopes. Fracture morphologies were studied by scanning electron microscopy (SEM). Results showed that both yield and ultimate tensile strength generally decreased with an increase in volume fraction of lower bainite. However, a few exceptions were observed in the mixed microstructures containing 12% lower bainite, showing a higher strength than the fully martensitic microstructure. This can be explained on the basis of two factors. The first is an increase in the strength of martensite due to the partitioning of the prior austenite grains by lower bainite resulting in the refinement of martensite substructures. The second is a plastic constraint effect leading to an enhanced strength of lower bainite by the surrounding relatively rigid martensite. Charpy V-notch impact energy and ductility is improved with increasing the volume fraction of lower bainite.*

Keyword: *D6AC, Microstructure, Mechanical properties, Lower bainite, Ultrahigh strength.*

1. INTRODUCTION

Ultrahigh strength medium carbon low alloy steels, such as D6AC have been needed for the high performance engineering components [1].This steel can be successfully employed at the yield strength in excess of 1400MPa [2]. But its commercial use is often limited in practice by its poor ductility at high strength level [3]. One of the potential ways to overcome this problem is to develop steels having mixed or multi - phase microstructures in which separate constituents are responsible for the different property requirements [4, 5]. Many researchers reported a good combination of strength, toughness and ductility for mixed microstructures [6,7]. However, it has been reported that the mechanical properties of mixed microstructures were inferior to those of conventional microstructures [8, 9]. Matlock and krauss [10] have found that tensile properties and fracture toughness of ferrite- bainite- martensite (FBM) microstructure of micro- alloyed steels are inferior to those of conventional steels.

Sankaran et al. [11-13] have reported that the yield and tensile strengths of the multi - phase microstructure in micro- alloy steels are increased by 17% and 20%, respectively, compared with the values corresponding to the conventional microstructure. Salami et al. [14, 15] have reported that the mechanical properties of tempered martensite are more favorable than those of ferrite - bainite - martensite microstructure in 42CrMo4 steel.

Tomita and Okabayashi [16-18] suggested that when high strength low alloy steels such as AISI 4340 and 4140 have a mixed microstructure of martensite and bainite, the shape and distribution of the second phase bainite have a significant effect on the mechanical properties. A lower bainite, which appears in acicular form and partitions the prior austenite grains of the parent martensite, dramatically improves mechanical properties in association with tempered martensite. In addition, Tomita and Okabayashi [19, 20] explained if an upper bainite appearing as masses filling the prior austenite grains of the parent martensite is associated with the tempered martensite, it significantly lowers the mechanical properties. Contrary to these results, Narasimha et al. [21] reported that the presence of the upper bainite in the mixed microstructure in a low alloy high strength AISI 4330V leads to a significant improvement in toughness without affecting the strength of the fully martensitic microstructure. However no beneficial effect of the lower bainite on mechanical properties is observed in the lower bainite- martensite microstructure. There are contradictory results on the influence of multiphase or mixed microstructure on mechanical properties of steels. It is, therefore, interesting to investigate the effects of the lower bainite volume fraction on tensile and impact properties of D6AC medium carbon low alloy ultrahigh strength steel.

2. EXPERIMENTAL PROCEDURE

The D6AC steel was received as forged bars 85mm in diameter. The chemical composition of the steel is given in Table 1.

Test plates of 60mm × 130mm with 6mm and 12mm thicknesses were cut from the steel bars. The length of plates was in the longitudinal direction of bar. Each plate was first stress relived at 650ºC and then fully annealed at 850 ºC for 2hrs. The austenitizing treatments carried out in an argon atmosphere furnace with a temperature accuracy of ±4ºC at 910ºC for 40min. Following the austenitizing treatments, specimens were either oil quenched to produce martensite, or isothermally transformed in a salt bath at 330 ºC above the M_S to obtain mixed microstructure of lower bainite - martensite with varying amounts of the lower bainite. A fully lower bainite microstructure was obtained by isothermal treatment in a salt bath at 330 ºC for 24 hrs. Finally, all specimens were double tempered at 200 ºC for 2hrs per tempered. The heat treatments procedures are shown in Fig.1.

After heat treatment the plates were machined and ground to the final thicknesses of 4mm and 10mm to eliminate any decarburized layer. Sub size

Table 1. Chemical composition of D6AC steel (Wt. %).

C	Si	Mn	P	S	Cr	Mo	Ni	V	Fe
0.47	0.26	0.76	0.009	0.004	0.99	0.93	0.54	0.11	Bal.

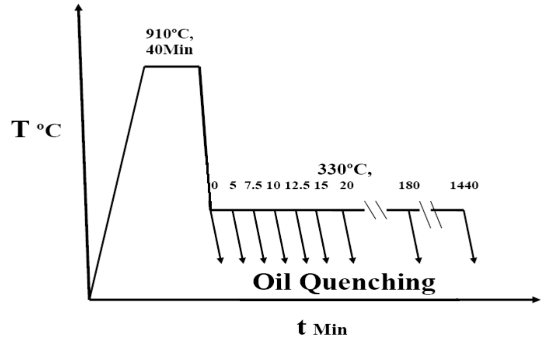


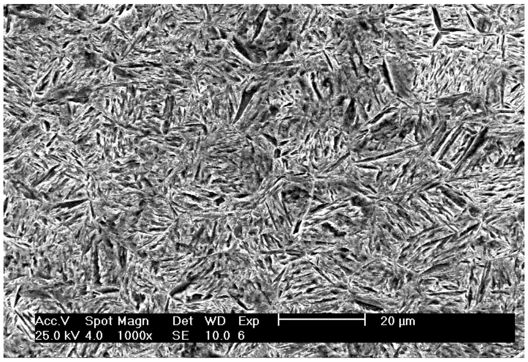
Fig.1. Schematic illustration of heat treatment cycles.

tensile specimens of the 4mm thickness and 25mm gauge length were wire cut from the 4mm thickness plate in accordance with ASTM E8M [22]. Charpy V - notch impact specimens were wire cut from 10mm thickness plate in accordance with ASTM E23 [23]. Tensile tests were carried out using an electromechanical universal CMT5205H machine at constant cross- head speed of 5mm min-1. The charpy V - notch impact properties were determined using a 300J metal pendulum impact ZBC2152 machine. A minimum of seven impact and three tensile specimens were tested in each case. The microstructures were examined by optical and scanning electron microscopes. Polished specimens were etched with a 2% nital to reveal the martensitic microstructure. To reveal the lower bainite in a matrix of martensite, specimens were etched with a solution of 4 wt% picral plus 2 wt% nital[24]. Volume fractions of lower bainite were determined by clemex vision image analysis software based on the difference color between lower bainite(dark) and martensite(white). At least 5 representative areas in each sample were studied through metallographic evaluations. To detect retained austenite, X-Ray diffraction technique was employed by using CuKá radiation[25]. Fracture morphologies of the impact specimens were characterized using a scanning electron microscopy (SEM).

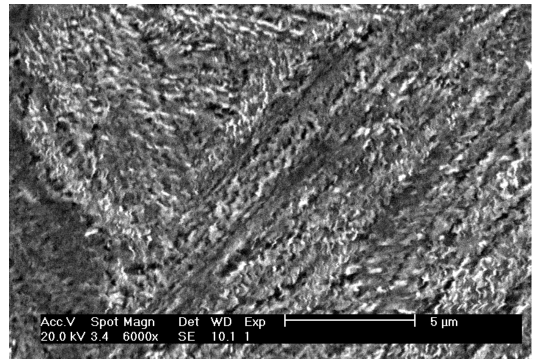
3. RESULTS AND DISCUSSION

3.1. Metallographic Observations

Figure 2 shows typical scanning electron and optical micrographs of various microstructures obtained from different heat treatment cycles. Lathes of martensite were distinctly presented



(a)



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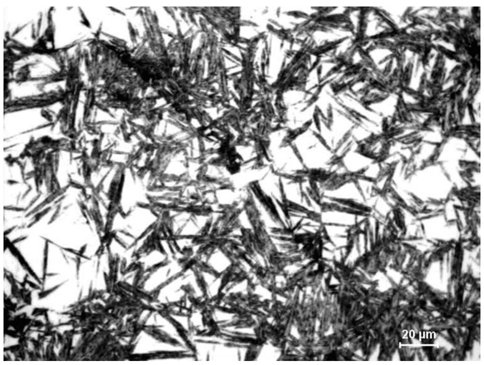

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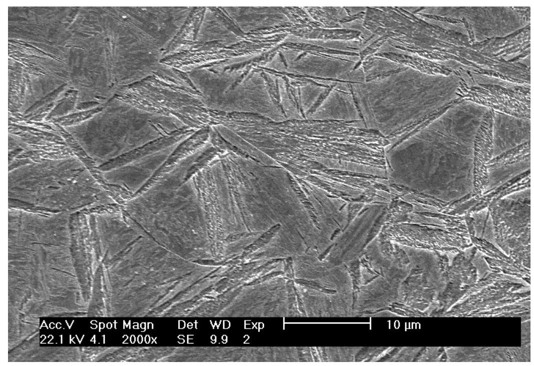

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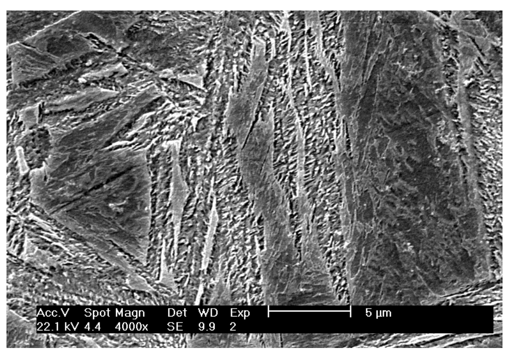


(e)

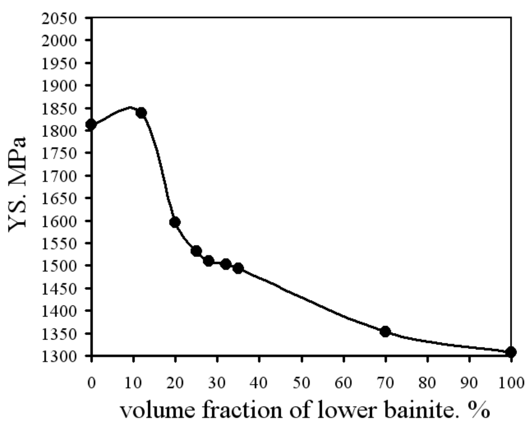
Fig.2. Scanning electron and optical micrographs of various microstructures obtained from different heat treatment cycles, (a) Scanning electron micrograph of martensitic microstructure, (b) Scanning electron micrograph of lower bainitic microstructure, (c)optical micrograph of mixed microstructure of lower bainite – martensit and (d and e) Scanning electron micrographs of mixed microstructures of lower bainite – martensite.

within the prior austenite grain (Fig.2a). Figure 2b shows the sheaves of the lower bainite in which internal carbide precipitates were oriented in one direction. Typical optical micrograph of mixed lower bainite – martensite microstructure is shown in Fig.2c, in which the dark etched regions correspond to lower bainite sheaves and the white regions corresponding to martensite.. This type of microstructure is similar to the one reported by Tomita[17]. and Wang et al. [29]. It can be also seen from corresponding scanning electron micrographs of this mixed microstructure of lower bainite – martensite (Fig.2d and 2e) that the lower bainite appears in acicular form and partitioned the prior austenite grain of the martensite.

3.2. Mechanical Properties

In order to study the effect of the lower bainite volume fraction on tensile and impact properties, tensile and impact tests were made on specimens having 0 (a fully martensitic microstructure), 12, 20, 25, 28, 32, 35, 70 and 100 volume pct lower bainite (a fully bainitic microstructure). The variations of yield and ultimate tensile strengths are shown in Figure 3a and 3b respectively, in which the average error for yield and ultimate tensile strengths are ±10 MPa and ±15 MPa respectively. According to the Figure 3a, the mixed microstructure containing about 12 vol. % lower bainite shows higher yield strength than the fully martensitic microstructure.

It is well established in fracture mechanics that the yield strength is increased by plastic constraint, upon which a soft thin layer can be constrained by the hard matrix surrounding it. For example a weak brazing alloy can be used effectively to bond much stronger specimens provided that the brazing material is thin enough to be constrained by the surrounding stronger matrix. Indeed the strength of the joint increases as the thickness of the brazing layer decreases. The same phenomenon occurs when the lower bainite plates form in the austenite which subsequently transforms to much stronger martensite. In other words the bainite plate plays the role of soft layer. Therefore the deformation of the bainitic ferrite can be expected to be constrained by the martensite. Figure 4 shows the silver, which does not alloy significantly with iron and whose ultimate tensile strength as measured in a standard tensile test is 150 MPa, will sustain a stress of up to 680 MPa when in the form of a filler in a joint to high strength steel. As the width of the joint is increased beyond the optimum value, the effect described diminishes and the strength declines towards that of the bulk filler [26].



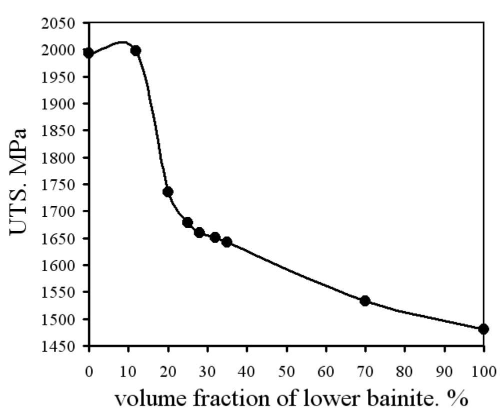


Fig.3. Effect of volume fraction of lower bainite on yield and ultimate tensile strength.

However, the presence of the maximum point in the graph shown in Fig.3 is also attributed to the other phenomena resulting in the refined martensite packets as schematically shown in Fig.5. As seen, the formation of lower bainite partitions the prior austenite grain and therefore, the remaining austenite subsequently transformed into the smaller martensite packet sizes.

As volume fraction of the lower bainite increases, the packet size of martensite decreases and according to the Hall – petch relationship, strength of the martensite increases. In other words, the formation of lower bainite in the austenite grains, increases the boundaries inside the grains which in turn increase the yield strength of the mixed microstructure of lower bainite – martensite.

Figures 6 and 7 show elongation, reduction of area and charpy impact energy of lower bainite, martensite and mixed microstructures of lower bainite – martensite. As shown, ductility and impact toughness of lower bainite exceeds those of all specemens, because of the lower yield strength of lower bainite. To identify retained austenite it is necessary to detect difraction

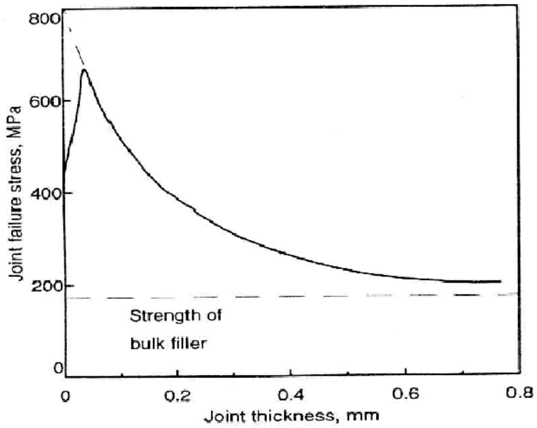


Fig.4. Effect of joint thickness on fracture stress of butt joint in medium carbon steel made with silver – base brazes [26].

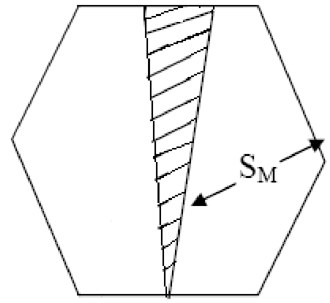
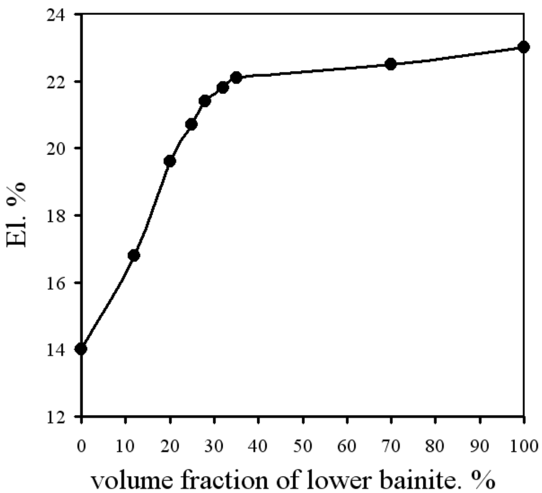
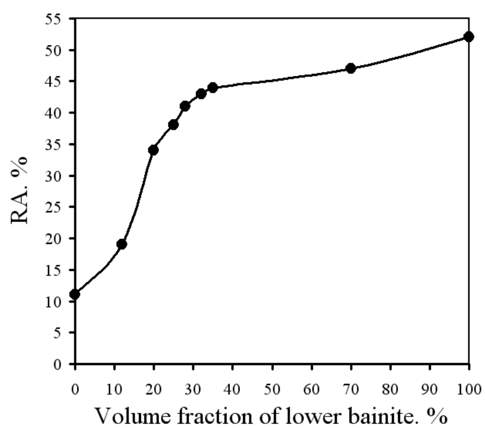


Fig. 5. Schematic diagram of the partitioning the prior austenite grain by lower bainite

peacks of (200)γ, (220)γ, (113)γ, (222)γ, (004)γ . As these peaks were not found in XRD patterns of the specimens transformed at 330 ºC, it is believed that the amount of retained austenite was too low to be detected(less than 3 volume pct). This amount of retained austenite has no significant effect on the mechanical properties. The ductility and impact toughness increased with increasing the lower bainite volume fraction. On the other hand, a crack propegted within the martensite, when reches the more flexible lower bainite plates will be blunt and therefore, the impact energy increases. This is because the bainites bring into full play the arresting effect of the crack and stress – relief, which the ductile phase essentially possesses, as



(a)



(b)

Fig.6. Effect of volume fraction of lower bainite on elongation and reduction area.

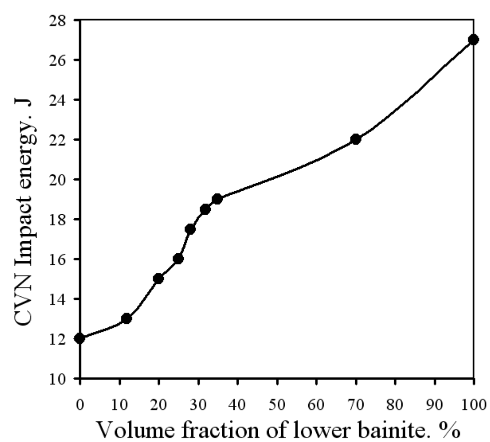
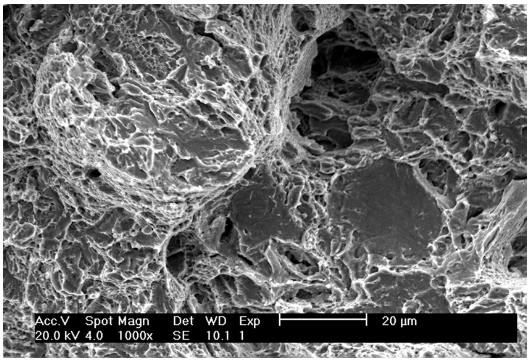


Fig.7. Effect of volume fraction of lower bainite on charpy V – notch impact energy.



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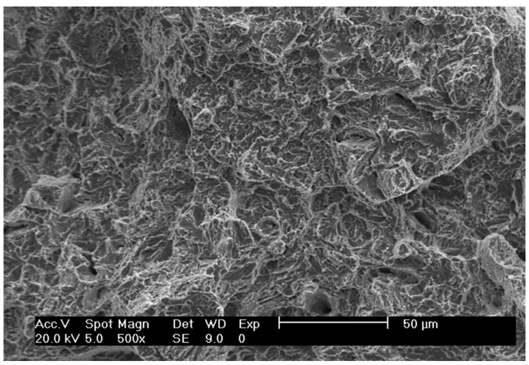

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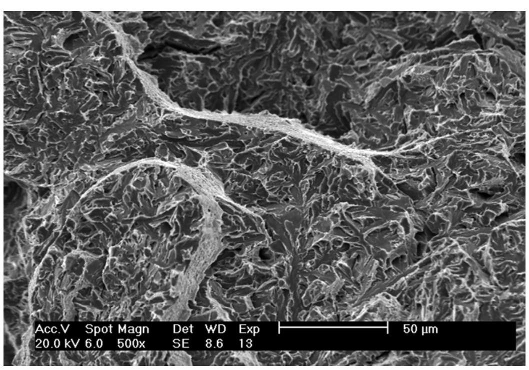

(c)

Fig. 8. Scanning electron microscopy of the fracture surface of different microstructures after impact testing, (a) tempered martensite, (b) lower bainite and (c) Mixed microstructure of lower bainite – martensite.

a result of their deforming in association with martensite being due to their plastic restraining by the martensit. The superior toughness and ductility of the lower bainite compared with martensite in Q&T condition samples was also found in the earlier works. However, it is note worthy that this is only observed when lower bainite is formed by isothermal transformation. The mixed microstructures of bainite - martensite formed by continious cooling and slack quenching have lower toughness than martensitic microstructures[27].

3.3. Fractography

Figure 8(a-c) shows the fracture morphologies from charpy impact specimens of lower bainite, martensite and the mixed microstructure of lower bainite – martensite. The dominant fracture morphology in all microstructures was a mixed mode of dimple rupture and quasi - cleavage. However, the martensitic microstructure exhibited some cleavage surfaces. Quasi – cleavage exhibites both cleavage and plastic deformation, but it is really just a form of cleavage [28].

4. CONCLUSIONS

1. In general, both yield and ultimate tensile strengths decrease with an increase in the volume fraction of lower bainite. However, a few exceptions were observed on the mixed microstructures containing about 12% lower bainite, which show a higher strength than the fully martensite microstructure.
2. It seems that the presence of the maximum point in the strength of mixed microstructures of lower bainite – martensite can be explained on the basis of two factors. The first is an increase in the strength of martensite due to the partitioning of the prior austenite grains by lower bainite resulting in the refinement of martensite substructures. The second is a plastic constraint effect leading to an enhanced strength of lower bainite by the surrounding relatively rigid martensite.
3. With an increase in volume fraction of lower bainite, the tensile elongation, tensile reduction area and charpy V – notch impact energy increased because of significantly

greater ductility and impact toughness of lower bainite compared with tempered martensite.

4. The fracture surface of all impact specimens exhibited mixed fracture morphology of quasi – cleavage and dimple rupture, however the martensitic microstructure also contains some cleavage surfaces.

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