15th International Conference on *AEROSPACE SCIENCES & AVIATION TECHNOLOGY*, *ASAT - 15 –* May 28 - 30, 2013, Email: <u>asat@mtc.edu.eg</u>, Military Technical College, Kobry Elkobbah, Cairo, Egypt, Tel: +(202) 24025292 –24036138, Fax: +(202) 22621908



Effect of Hot Forging and Boron Content on the Mechanical Properties of Dual Phase Steel

A. Farahat^{*}, S. Ayyad[†], A. El-Desouky[†], W. M. Farouk[‡], A. Kassab[†]

Abstract: Carbon steel is widely used in different applications such as automotive industry. Boron is used as micro-alloying element to enhance the mechanical properties of carbon steel. The objective of the present work is to study the effect of boron on mechanical properties of dual phase steels. Dual phase (DP) steel is used in the underbody suspension for automotives. The material used in the present study was a carbon alloy steel (0.29 Cwt %) with different boron contents 0.0003 and 0.007wt %. The steels were cast using an open air induction furnace. The molten steel had the shape of Y-blocks. The parts of Y-blocks of alloys 0.0003B and 0.007B steels were heated up to 1200°C and then hot forged producing bars. After hot forging, the bars were subjected to air cooling. In the hardening process, the different alloys (0.0003B, 0.007B) were heated up to the intercritical annealing temperatures (between Ac1 and Ac3) for 15 minutes and then water quenched. The resultant microstructures after quenching process were observed as ferrite plus islands of martensite. After that, tempering was done at 300°C, 400°C and 500°C for different interval times. The experimental results revealed the mechanical properties of the selective alloys were significantly changed by boron content and tempering treatment. By increasing the boron content, hardness gradually increased with small effect on ductility of alloys. By increasing the tempering time and temperature, hardness was gradually decreased while ductility was improved. Compression testing was carried out to determine the compression strength and work-hardening coefficient. The studied steel presented typical manifestations related to dynamic strain aging: serrated flow (the Portevin-Le Chatelier effect).

Keywords: Inter-critical annealing, dynamic strain aging, dual phase (DP)

1. Introduction

Dual phase (DP) steel is one of the high-strength low-alloy steels, characterized by a microstructure consisting of a dispersion of hard martensite particles in a soft ferrite matrix. Due to its combination of high strength, good ductility and continuous yielding, dual phase steel has been considered to be ideal automobile component materials which require good formability to reduce the weight of vehicle for fuel economy [1]. Dual phase steel has unique properties, such as continuous yielding behaviour (no yield point), low 0.2% offset yield strength, high tensile strength, high work hardening rate, and unusually high uniform and total elongation [2-4].

^{*} Central Metallurgical R&D Institute, CMRDI, P.O. Box 87 Helwan, Egypt.

[†] Production Engineering and Mechanical Design Department, Faculty of Engineering, Menoufia University, Shebin El-Kom, Egypt

[‡] Mechanical Engineering Department, Faculty of Engineering, University, Banha, Egypt.

Dual phase microstructure can be developed in all low-carbon steels by intercritical annealing treatment (ICT) in austenite-ferrite region and cooling it rapidly to room temperature to transform the austenite to martensite [5]. It is easy and economical to produce DP steel by using the continuous annealing line equipped with a water quenching device which can produce high strength steels with much lower alloying elements [1]. Tempering has been used successfully to improve the strength/elongation ratio of dual phase steels after intercritical annealing [6-7].

The performance of DP steels mainly depends on their chemical composition such as alloy content of each phase and microstructural parameters such as phase volume fraction and distribution. The reasonable alloy composition design for DP steels can obtain the required mechanical properties at low cost. A few researchers have studied the effect of chemical composition, especially the micro-alloying elements on the mechanical properties of DP steels [8-11].

Boron is used as a micro-alloying element in a number of steels; during cooling from fully austenitized condition, boron increases hardenability [12,13]. This effect of boron is related to its ability to segregate to austenite grain boundaries and inhibit the grain boundary nucleation of ferrite. Its action, therefore, is to delay the formation of ferrite relative to the formation of lower temperature transformation products. In the production of dual phase steels, inhibition of ferrite formation would be expected to increase the yield of martensite [14].

The Portevin–Le Chatelier effect (PLC) describes a serrated stress-strain curve, which some materials exhibit as they undergo plastic deformation, specifically inhomogeneous deformation. This effect has been long associated with dynamic strain aging or the competition between diffusing solutes pinning dislocations and dislocation breaking free of this stoppage [15]. Because the PLC effect is related to a strengthening mechanism, the strength of steel may increase; however, the plasticity and ductility of a material afflicted by the PLC effect decrease drastically.

The aim of this work is the processing of dual phase steel from hot forged carbon steel containing boron (0.0003B and 0.007B) and($0.29 \ \%C$) then subjected to a heat-treatment cycle for use in the under body suspension of automotives where a good combination of strength and formability is necessary.

2. Experimental Procedure

2.1 Materials

Medium carbon steel was prepared by using an open air induction furnace. The 0.29%C steel with Fe-B (20%B) was melted together to produce steel in the form of Y-blocks with chemical composition as listed in Table 1. The Y-blocks were machined and prepared for hot forging by removing the sand layer. The materials were heated up to 1200^oC and hold for 30 minute and then were subjected to hot forging and the cross-sectional area was reduced down to 20 mm with 90% cross-section reduction. Manufacturing of test specimens with 13.75mm diameter and 20mm height was carried out after hot forging.

2.2 Thermomechanical Processing

DP microstructure was achieved by annealing at different intercritical temperatures (770°C, 790°C and 810°C) depending on the dilatation curves for 15 min and cooling in water. After Quenching the samples were tempered at different temperatures (300°C, 400°C and 500°C) for (0, 30, 45, 60 and 120 minutes) and subsequently cooled in air as shown in Fig.1.

Alloy	С	Si	Mn	Р	S	Cr	Fe	В
3B	0.2652	0.3625	1.197	0.0199	0.0067	0.1667	97.9977	0.0003
70B	0.2900	0.2996	1.314	0.0302	0.0195	0.0699	97.975	0.007

Table 1 Chemical composition, wt%



Fig.1 Thermomechanical treatment

2.3 Microstructure Investigations

Optical microscope and scanning electron microscope were used to investigate the microstructure for as-cast, as-forged and heat-treated materials after etching the specimens with 0.2% nital. The volume fraction of martensite for same specimens was determined by an image analyzer on metallographic sections.

2.4 Mechanical Testing

Microhardness measurements were conducted on polished surface of the same specimens using load 0.5kg. Compression tests were carried out at room temperature for hot forged and heat-treated materials (same specimens) according to ASTM E9.

3. Results and Discussion

3.1 Microstructure and Martensite Volume Fraction

The microstructures of the as-cast and hot forged samples for both steel (3B and 70B) are shown in Fig.2. It is clear that the microstructure after casting consists mainly of ferrite matrix (white phase) and pearlite (dark phase). Fig.3 shows the SEM micrograph of these steels. It is apparent that hot forging highly grain refined the matrix.

By intercritical annealing of 3B and 70B steels at 770°C, 790°C and 810°C and subsequent water quenching, the ferritic-martensitic microstructure was obtained. Fig.4. shows the optical micrograph of this microstructure. The volume fractions of martensite after annealing for both steels are listed in Table.2. It is obvious that the martensite volume fraction increases as the amount of boron and inter-critical annealing temperatures are increased as shown in Fig.5.

The quenched specimens were then tempered at different temperatures. The microstructures of specimens tempered at 500°C for 120 minute have been shown in Fig.6. The microstructure of tempered specimens clearly differs from the non-tempered samples. It is clear that the ferrite volume fraction and cementite increase due to dissociation of martensite to cementite and ferrite totally.



Fig.2. (a) As-cast microstructure of 3B steel (b) Optical micrograph of hot forged of 3B (c) As-cast microstructure of 70B steel (d) Optical micrograph of hot forged of 70B



Fig.3. SEM micrograph of: (a) 3B as-cast steel (b) 3B hot forged steel (c) 70B as-cast steel (d) 70B hot forged steel



(a) 770°C, 3B steel; (b) 790°C, 3B steel; (c) 810°C, 3B steel; (d) 770°C, 70B steel; (e) 790°C, 70B steel; (f) 810°C, 70B.

Fig.4. Optical microstructure of samples inter-critical annealed for 15 min



Fig.5. Effect of inter-critical annealing temperature on the martensite and ferrite volume fractions for both steels

3.2 Hardness Results

3.2.1 Hardness of 3B steel

The mean hardness value of the as-cast 3B steel is 147HV and reaches 172.5 HV after hot forging, air cooled. Hardness slightly increase due to homogenization of fine precipitate $Fe_{23}(C, B)_6$ [16] and grain refinement. Figure 7shows the hardness (HV) distribution of 3B steel inter-critically annealed at 770°C for 15 minuts followed by water quenching. It is obvious that the average hardness value is 360.6HV as stated in Table.3. It is found that the hardness value after inter-critical annealing at 770°C then water quenching reaches 361HV.

This hardness value is higher than the as-cast (147HV) and hot forged (172.5HV) ones and is attributed to the existence of martensite.

By applying the tempering process, it is found that hardness decreases as tempering time and temperature are increased due to dissociation of martensite phase into ferrite and cementite as shown in Fig.8.

Table.2.	Effect	ofi	inter	:-cri	itical	anr	nealed	ten	pera	ature	and	then	water	que	nched
		on	the	mar	tens	ite v	olum	e fra	ictio	n for	both	steel	ls		

Inter-critical annealing Temperature, °C	Martensite Volume Fraction, %, 3B steel	Martensite Volume Fraction, %, 70B steel
770	57.414	69.88
790	61.435	75.44
810	71.551	80.9



(a) 770°C, 3B steel; (b) 790°C, 3B steel; (c) 810°C, 3B steel; (d) 770°C, 70B steel;
(e) 790°C, 70B steel; (f) 810°C, 70B.





Fig.7. Hardness distribution of 3B steel

Table.3. Hardness statistical analysis of 3B intercritically annealed steel

	Hv0.5Kg-3B Steel							
e, %	Mean	360.6						
nlativ	Standard Error	6.8						
Cun	Median	363.0						
-	Mode	372.0						
-	Standard Deviation	18.0						
-	Sample Variance	323.3						
	Confidence Level (95.0%)	16.6						



Fig.8. Effect of tempering temperature and time on hardness value of 3B steel

3.2.2 Hardness of 70B steel

The mean hardness value of the as-cast 70B steel is 172.2HV and reaches 190.9 HV after hot forging, air cooled. Hardness slightly increases due to homogenization of fine precipitate $Fe_{23}(C, B)_6$ and grain refinement. Fig.9 shows the hardness (HV) distribution of 70B steel

inter-critically annealed at 770°C for 15 minutes followed by water quenching. It is obvious that the average hardness value is 478HV as stated in Table.4.



Table.4. Hardness statistical analysis
of 70B intercritically annealed steel

Hv0.5Kg-70B steel	
Mean	478.2
Standard Error	2.3
Median	478.0
Mode	477.0
Standard Deviation	7.4
Sample Variance	54.8
Confidence Level (95.0%)	5.3

Fig.9. Hardness distribution of 70B steel

It is found that the hardness value reaches 478HV. This hardness value is higher than the ascast and hot forged ones and is attributed to the existence of martensite. By applying the tempering process, it is found that hardness decreases as tempering time and temperature are increased as shown in Fig.10.



3.2.3 The effect of inter-critical annealing temperature on the hardness value for both steels

Figure 11 demonstrates the effect of boron content and different inter-critical annealing temperatures on the hardness. The hardness value increases with increasing boron content and inter-critical annealing temperature (from 10% to 32%). This is attributed to formation of $Fe_{23}(B,C)_6$ precipitate and increasing the volume fraction of martensite. The combined effect of both boron content and inter-critical annealing temperature on hardness is 46.5%.

3.3 Compression Properties

3.3.1. General behavior of compression flow curves

Figure 12 shows the general behaviour of compression flow curves of 3B steels tested at room temperature and initial strain rate (4×10^{-4}) of inter-critically annealed steel followed by water quenching and then tempering. The compression curve after inter-critical annealing exhibit single stage plastic flow curve while after tempering it provides two stage ones. The first stage demonstrates the plastic behavior of the compression specimens without cracking. The second stage of the stress-strain compression curve gives plastic line of higher slope due to side cracks. Therefore, in our study the second stage of the plastic flow of the stress-strain compression stress-strain curve is used to judge material plastic behavior. It is apparent that the compression curves give servation due to dynamic strain aging. All the tested materials show the same behaviour.



Fig.11. Effect of boron content and different inter-critical annealing temperature on the hardness for both steels

3.3.2 Compression properties for both steels

Figures 13 and 16 show the effect of tempering temperature and time on the true compressive strength at different intercritical annealing temperatures $(770^{\circ}C, 790^{\circ}C \text{ and } 810^{\circ}C)$ which decrease with increasing the tempering temperature and time due to dissociation of martensite into cementite and ferrite. It is also apparent that they have maxima at different time due to dynamic strain aging.

Figures 14 and 17 show the effect of tempering temperature and time on the work hardening exponent at different intercritical annealing temperatures (770° C, 790° C and 810° C) which increase with increasing the tempering temperature. It is also apparent that they have maxima at different time due to dynamic strain aging.



Figures 15 and 18 show the effect of tempering temperature and time on the uniform strain at different intercritical annealing temperatures $(770^{\circ}C, 790^{\circ}C \text{ and } 810^{\circ}C)$. Uniform strain increases with increasing the tempering temperature and has minima at different times due to dynamic strain aging.

These values suggest that the mechanism responsible for dynamic strain aging in dual phase steel is the locking of dislocations by carbon atoms in ferrite and that the formation of clusters and/or transition carbides and carbide precipitation in martensite do not interfere with the dynamic strain process[17].











Fig.18.Effect of tempering process on the uniform strain, % of 70B steel

The phenomenological aspects of dynamic strain aging presented in this work, i.e., the presence of the PLC effect in the stress-strain curves; the maximum in the variation of flow stress, tensile stress and work hardening exponent with temperature; the minimum in the variation of uniform strain with temperature; as well as the shift of these maxima and minima to higher temperatures, indicate that the dual phase steels behave mostly in the same manner as steels of low carbon steels, alloyed or not, and perlitic steels, regarding dynamic strain aging[18].

4. Conclusions

The microstructure of as-cast and hot forged is ferrite-perlite and the grain size of hot forged steel is finer than that of as-cast steel. For both steels, increasing the inter-critical annealing temperature and boron content increase the martensite volume fraction and decreases the ferrite volume fraction subsequently the hardness value increases. For both steels increasing the tempering temperature and time cause the dissociation of martensite and decreases hardness value.

Increasing the inter-critical annealing temperature increases the true compressive strength due to increasing the martensite volume fraction while increasing the tempering temperature and time decreases the true compressive strength due to dissociation of martensite. Increasing the

tempering temperature increases the compressive strain while increasing the tempering time sometimes increases and sometimes decreases it due to dynamic strain aging.

The dual phase steel studied in this work presented all the manifestations commonly related to dynamic strain aging: the PLC effect, the maximum in the variation of tensile stress with temperature, and the minimum in the variation of uniform strain with temperature.

References

- [1] Xuan Liang, Jun Li and YingHong Peng, Materials Letters 62 (2008) 327-329.
- [2] R. Nadlene, H.Esah, S.Norliana and M.A. Mohd Irwan, World Academy of Science, Engineering and Technology 74-2011.
- [3] P.E. Repas, "Dual Phase and Cold-Forming Vanadium Steels in the Automobile Industry", Vanitec, Berlin, 1978.
- [4] R.G. Davies, C.L. Magee, in: T. Davenport (Ed.), Structure and Properties of Dual Phase Steels, A.I.M.E., New York, 1979.
- [5] A. Anazadeh Sayed and Sh. Kheirandish, Material Science and Engineering A 532 (2012) 21-25.
- [6] A.K. Panda, D.S.Sama, R.I. Ganguly and S.Misra, Steel Res. Int.64 (51) (1993) 3-516.
- [7] G.T.Eldis, The Influence microstructure and testing procedure on the measured mechanical properties of heat treated dual-Phase Steel, TMS-AIME, 1982, pp.310-316.
- [8] Qingge Meng, Jun Li, Jian Wang, Zuogui Zhang and Lixiang Zhang, Materials and Design 30(2009) 2379-2385
- [9] Sun S, Pugh M. Properties of thermomechanically processed dual-phase steels containing fibrous martensite. Mater Sci Eng A 2002; 335:298–308.
- [10] Demir B, Erdog`an M. The hardenability of austenite with different alloy content and dispersion in dual-phase steels. J Mater Process Technol 2008;208:75-84
- [11] Geib MD, Matlock DK, Krauss G. The effect of intercritical temperature on the structure of niobium microalloying dual-phase steel. Metall Trans A 1980;11:1683-9
- [12] M.K.Koul and C.L. McVicker: Met. Prog., 1976, vol.11, p.2.
- [13] N. Shikana, M. Kurihard, and H. Tagaw: Thermec-88, I. Tamura, ed., Iron and Steel Institute of Japan, Tokyo, 1988, pp.98-105.
- [14] X.p. Shen and R. Priestner, Metallurigical Transactions, vol 21A, September 1990-2547.
- [15] <u>http://en.wikipedia.org/wiki/Main_Page</u>
- [16] Mohammad Djahazi (Influence of boron distribution on precipitation and recrystallization in hot worked austenite), M.SC Thesis, Department of Mining and Metallurgical Engineering, McGill University, Montreal, Canada, p.5, Augest 1989.
- [17] R.R.U. Queiroz, F.G.G. Cunha and B.M. Gonzalez "Study of dynamic strain aging in dual-phase steel", Materials Science and Engineering A 543(2012) 84-87
- [18] W.R. Calado, C.S.B. Castro, O.J. Santos, R. Barbosa, B.M. Gonzalez, J. Mater. Sci. 43 (2008) 6005–6011.