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# Optimization of Thermomechanical Parameters to Produce an Ultra-High Strength Compressor Disk

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**Abstract:** Structural steels with very high strength levels are often referred to as ultrahigh-strength steels (UHSS). The usage of UHSS has been extensively studied in aerospace industries and offshore platforms. In this study, medium carbon low alloy steel (AMS6305) was thermomechanicaly treated to obtain an ultra-high strength bainitic steel for aircraft engine compressor disk. A novel themomechanical treatment was introduced to optimize microstructure and mechanical properties. By replacing the common quench-temper microstructure of compressor disk with bainite microstructure, an ultra-high strength bainitic steel was achieved. Based on the results obtained, the final microstructures following pre-deformation and subsequent heat treatment showed a very good combination of strength and toughness. Furthermore, it has been shown that austempering time and temperature play a major role in achieving ultra-high strength bainitic steels. The optimized strength and toughness was achieved by up quenching treatment. This is due to partitioning of prior austenite grains by tempered martensite plates.

**Keywords:** Thermomechanical treatment**,** Bainite microstructure**,** Mechanical properties**,** Up quenching

## 1. Introduction

Structural steels with very high strength levels are often referred to as ultrahigh-strength steels (UHSS). During recent decades, the usage of UHSS has been extensively studied in aerospace industries and offshore platforms, such as ships and pressure vessel building. Mechanical properties and subsequently the utility of these steels in service condition significantly depend upon the microstructure [1]. The UHSS, ordinary are quenched and tempered to ensure that the required combination of strength and ductility has been achieved [2-3]. Thus, these steels basically have a dislocated martensitic microstructure with fine precipitates such as carbides and carbonitrides. Furthermore, there are numerous differences between these steels, including the size and shape of martensite, the amount of carbon in solid solution, the amount of retained austenite, and the nature of the particles precipitated during aging [4,5].

The strength of UHSS is increased by lowering the tempering temperature. However, it means as a loss in ductility and toughness well [3]. As a result, the steels suffer from low toughness values even in the quenched and tempered condition [1]. Up to now, many investigations on the effect of austempering treatment on mechanical properties of these steels have been published [6-8]. Bainitic steels are now at the forefront of some potentially exciting developments in the steel industry, especially when the steels are destined for high technology applications [9]. The quenched and tempered processing cost is less expensive than the austempering processing cost. On the other hand, austempering is less expensive when the total cost of heat treatment is combined with the cost of distortion and cracking [10].

The microstructure of bainite consists of fine plates of ferrite, growing in clusters known as sheaves. The plates in each sheaf are parallel with identical crystallographic orientation [11]. Tu et al. [12] compared the microstructures and mechanical properties of lower bainite and tempered martensite in JIS SK5 steel. The results showed that for some hardness, the lower bainite has higher impact toughness than

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*Corresponding author (maghaei@kntu.ac.ir) tempered martensite. Mirak and Nili-Ahmadabadi [13] have also studied the effect of austempering treatments on the microstructure and mechanical properties of AISI 4130 type steel. In this study, the isothermal and up-quenching heat treatments were used to improve the mechanical properties. The results revealed that the best combination of mechanical properties is obtained when an up-quenching heat treatment is used. Microstructural studies showed that partition of grains by lower bainite is probably the main reason for this improvement. Another study has been made by Liu and Kao [14] which is indicated that the presence of lower bainite in prior austenite grains causes refinement of the martensite pocket size. On the other hand, the refinement of prior austenite grain size causes beneficial effect on both tensile strength and ductility of steel with mixed lower bainite-martensite structure.

Due to the complexity of bainitic microstructure such as lath structure of the matrix and variation in distribution and morphology of carbide precipitates, the correlation between microstructure and mechanical properties is not clear in bainitic steels [15].

AMS6305 steel is usually used to produce aircraft engine compressor disk. The conventional heat treatment used is martempering that results in a high strength martensitic steel. To the best of the authors' knowledge, no any report concerning the mechanical properties of bainitic microstructures in AMS6305 steel has been published. In the present paper, different bainitic microstructures were prepared by thermomechanical treatment and the influence of microstructures on the mechanical properties of the ultra-high strength steel was investigated.

## 2. Material and Experimental Procedure

Aircraft engine compressor disk of AMS6305 steel was used as the starting material. The chemical composition of the steel is given in Table1.

Table 1. Chemical composition of AMS6305 steel (wt %).

| Element | C | Mn | Si | Cr | Mo | Ni | Cu | V | P | S | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| wt% | 0.45 | 0.55 | 0.25 | 0.95 | 0.55 | 0.15 | 0.3 | 0.3 | 0.015 | 0.015 | Balance |

4×30×120mm specimens were machined out of the compressor disk and subjected to different thermomechanical treatments. Five identical samples were predeformed (20% thickness reduction by rolling) at austenite temperature and heat treated (according to Table 2) to obtain different bainitic structures. The hot rolling was carried out at 930°C by a laboratory rolling mill with 160mm diameter rolls and rolling speed of 21m/min (43RPM). Since the chemical composition of AMS6305 is similar to AISI4140, the TTT (time temperature transformation) diagram of AISI4140 is used to determine the critical temperatures [16]. For instance, according to this diagram, it is evident that the martensite start temperature ($M_S$) is about 340°C. The thermomechanical schedules used in this investigation are given in Table 2.

Table 2. Heat treatment schedules.

| | Heat treatment |
|---|---|
| LB1 | Austenize at 930℃ (15 min), predeformed (20%) and Austemper at 370℃ (30 min), Air cooled |
| LB2 | Austenize at 930℃ (15 min), predeformed (20%) and Austemper at 370℃ (50 min), Air cooled |
| UB | Austenize at 930℃ (15 min), predeformed (20%) and Austemper at 420℃ (30 min), Air cooled |
| UQ | Austenize at 930℃ (15 min) , predeformed (20%), Quenched at 320℃ (1 min) and Austemper at 400℃ (30 min), Air cooled |

All the specimens were heat treated in salt bath furnace. The as-received sample and different heat treatment schedules are referred to hereafter as “AR’, “LB1”, “LB2”, “UB” and “UQ” (Table 2), respectively.

The samples for microstructural examinations were mechanically polished according to the standard procedure and then etched with Nital 2%. The hardness values were obtained using Rockwell tester under a major load of 150 kgf.

Uniaxial tensile test specimens, 100 mm long and 10 mm wide prepared from the heat treated samples, were pulled to fracture at a crosshead speed of 5 mm/min, producing an average strain-rate of $10^{-3}$/s as the specimen extended. Load-extension curves were obtained with the aid of a 25 mm gauge length extensometer, from which the nominal stress-strain curves were calculated.

## 3. Results

The steel has an initial martempered structure as is shown in Fig. 1. According to Fig. 1, it is obvious that fine globular carbide particles dispersed homogenously within the microstructure. The mechanical properties of the as received compressor disk at room temperature are listed in Table 3.

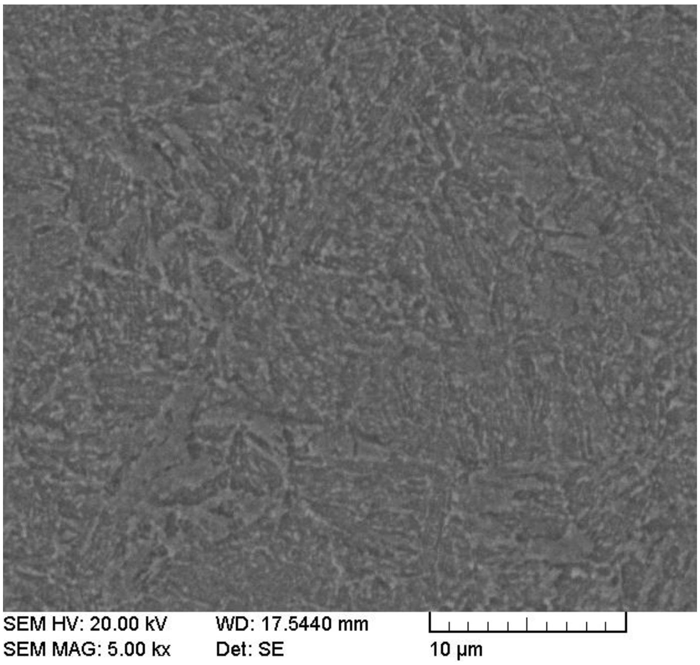

Fig. 1. The initial martempered structure of the starting material.

Table 3. Mechanical properties of as received AMS6305.

| YS (MPa) | UTS (MPa) | El (%) | Hardness (HRC) |
|---|---|---|---|
| 875 | 1087 | 12.83 | 34 |

Figure 2 shows engineering stress strain curves for samples with different bainitic structures. The same elastic modulus observed for all curves indicates the independency of the elastic modulus to heat treatment schedule. Concerning Fig. 2, the mechanical properties of different samples are listed in Table 4.

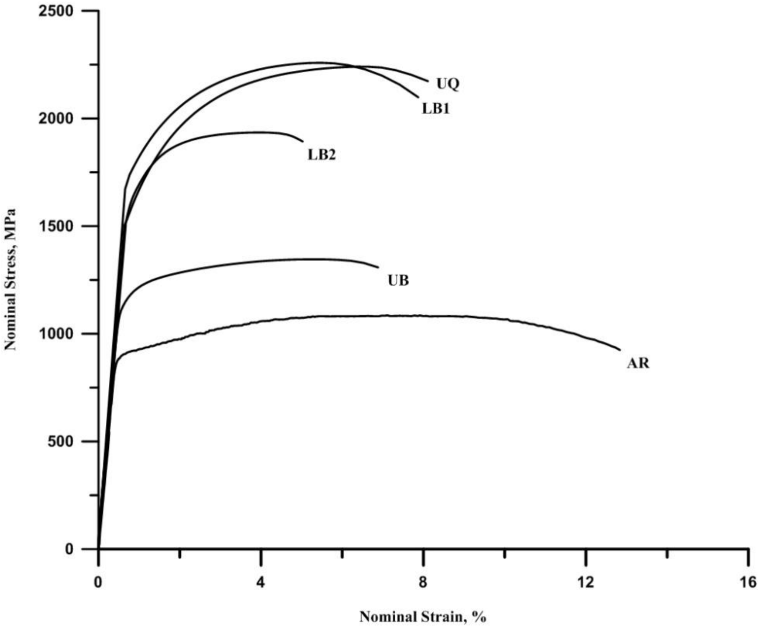

Fig. 2. Nominal stress-strain curves for different samples.

Table 4. Tensile properties of samples at room temperature.

| sample | Yield strength (MPa) | UTS (MPa) | El (%) | YS/UTS |
|---|---|---|---|---|
| AR | 875 | 1085 | 12.83 | 0.80 |
| LB1 | 1672 | 2258 | 7.87 | 0.74 |
| LB2 | 1406 | 1874 | 4.68 | 0.75 |
| UB | 1067 | 1346 | 6.88 | 0.79 |
| UQ | 1503 | 2240 | 8.2 | 0.67 |

The strain hardening exponent $(n)$ is an index which shows the ability of material to deform homogenously. For metals, the values of $n$ vary between 0.1 and 0.6 and decreases with increasing strength. So, it is an important factor for determining the workability and formability of materials. The values of strain hardening exponent for different samples are shown in Fig. 3. And the hardness values for different samples are shown in Fig. 4.

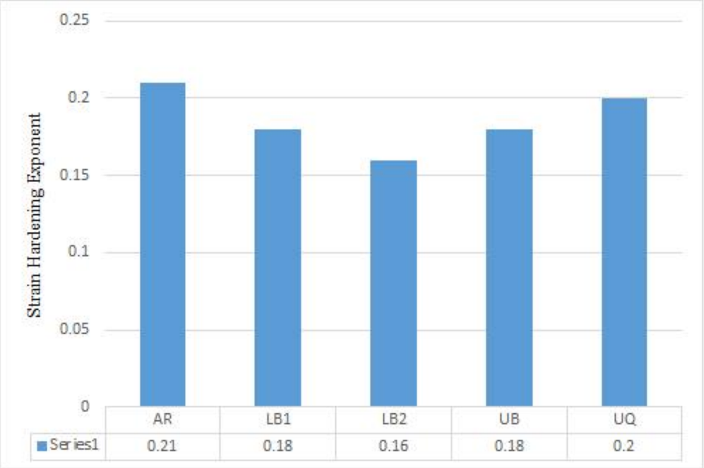

Fig. 3. Strain hardening exponent values for different samples.

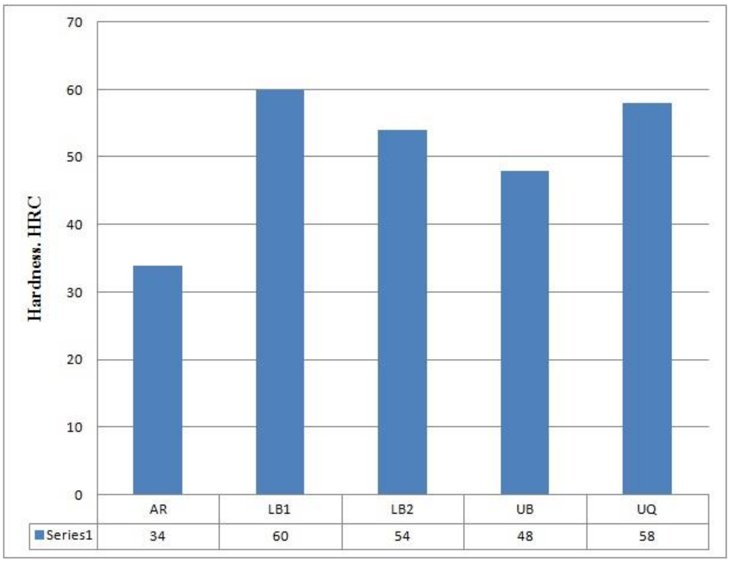

Fig. 4. Hardness results for the austempered specimens.

## 4. Discussion

Considering stress strain curves, LB1 structure shows a very good combination of strength and ductility and also the ratio of YS to UTS is reasonable. This is a result of the austempering condition and predeformation effects that result in bainitic microstructure with high aspect ratio of bainitic ferrite laths. It has been shown that the applied stress and predeformation in general accelerates the overall bainite transformation kinetics, though the final amount of bainite may be reduced. Increased stored energy at the grain boundary of austenite phase is believed to accelerate the bainite transformation [17,18]. The quantitative examination of the effect of predeformation requires at least two different straining procedures, however in the present study, we perform all experiments by the same initial predeformation, though the post treatments are different. The optical microstructure of LB1 specimen is shown in Fig. 5a.

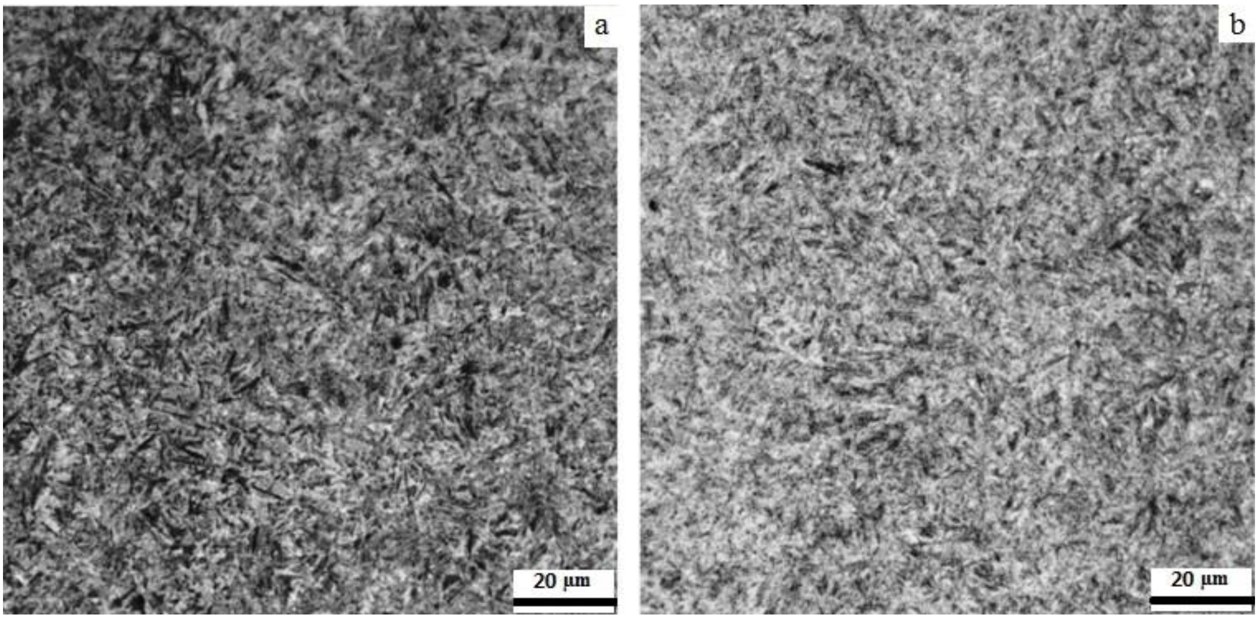

Fig. 5. Micrograph of (a) LB1 and (b) LB2 specimens.

Although the recognition between bainite and martensite phases is difficult, it can be observed that the bainite is the dominant phase in the microstructure. It is clear that parallel acicular bainite blades with different orientation are produced in some regions. Moreover, the austenitization temperature (930°C) is lower than the solving temperatures of some common carbide in the initial martempered microstructure (for example alloying of vanadium steel with nickel or chromium accelerates the solution of vanadium carbides at 1000-1150°C [19]). The presence of carbides such as vanadium carbides which not solved during heat treatment reduces the carbon content in the solid solution. Thus, the bainite transformation temperature is increased. It results in maximizing the fraction of bainite [20]. Furthermore, the cementite precipitates which have an adverse effect on mechanical properties are minimized. On the other hand, these carbides can affect the austenite recrystallization and the growth of austenite grains [21, 22].

SEM microstructure of LB1 specimen is shown in Fig. 6. It is clear that very fine globular carbide particles can be observed within the microstructure. The values of strength and ductility reduced with increasing austempering time. This can be related to thickening of bainitic blade size and increasing in cementite precipitation (Fig. 5b).

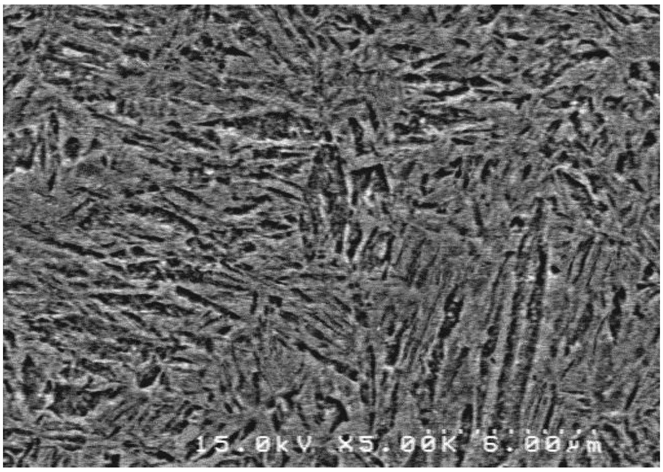

Fig. 6. SEM micrograph of LB1 specimen.

A significant decrease in strength and hardness is occurred when the transformation temperature is increased from 380°C to 420°C. This is due to the change of bainitic morphology (thickening of bainitic blade size) with temperature. The cementite precipitation is also increased with increasing temperature, though it is associated with decreasing the aspect ratio of carbides (Fig. 7).

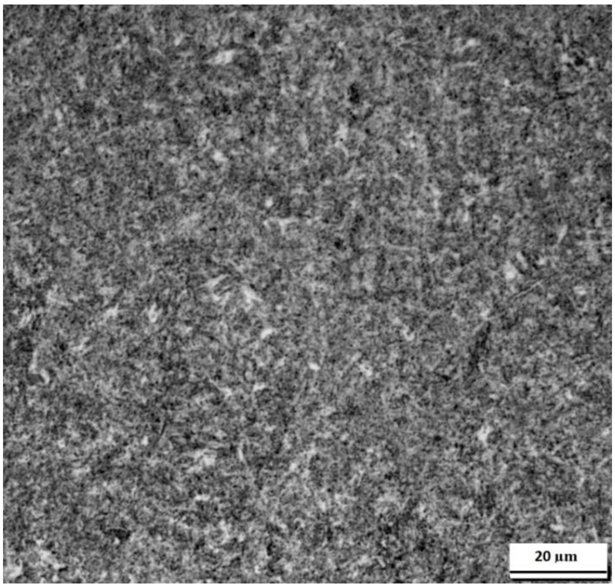

Fig. 7. Micrograph of UB specimen.

The optimized strength and toughness was achieved by up quenching treatment. One criterion to evaluate toughness of a material is the value of the area under the strain-stress curve. Calculating the corresponding area under the strain-stress curves of as received material (with martempered microstructure), LB1 and UQ (Table 5) demonstrates that the toughness enhances following performing the proposed thermomechanical treatment compared to that of the as received material.

Table 5. the value of the area under the strain-stress curve.

| AS | LB1 | UQ |
|---|---|---|
| 13340.7 | 16039.2 | 16242.7 |

The difference between this specific heat treatment and common martempering is that the former consists of quenching at a temperature just below $M_S$, followed by tempering (austempering) at higher temperature. Thus, the final structure consists of tempered martensite and bainite while in martempering heat treatment, steel is quenched to a temperature slightly above the martensite start temperature ($M_S$) and is cooled to room temperature.

SEM microstructure of the UQ specimen is shown in Fig. 8, where prior austenite grain boundaries depicted with red lines. The bainitic parallel needle like blades can be observed in the prior austenite grains. Some of these grains are divided by bainitic sheaves. The martensite pockets are also obvious in microstructure (dark regions). These regions limit the plastic flow of lower bainite. So, the strength of steel is increased. On the other hand, the $n$ value (Fig. 3) of this microstructure is superior. Thus, the production of UHSS with good formability is possible by the presented method.

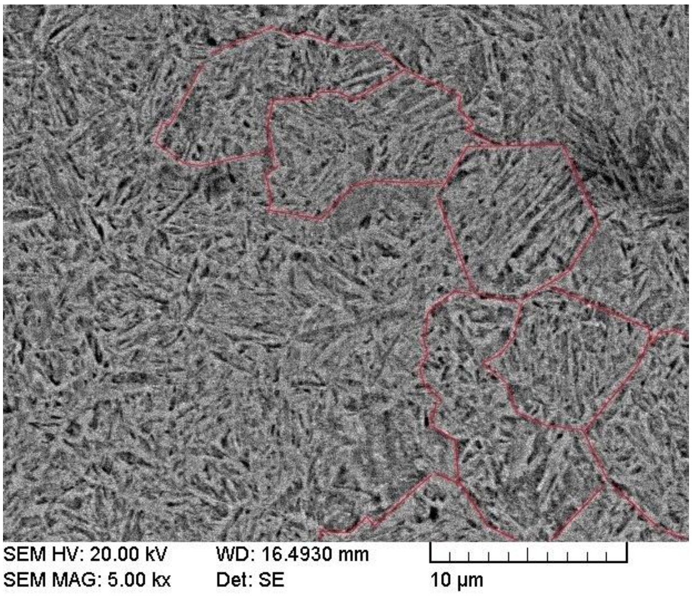

Fig. 8. SEM micrograph of UQ specimen.

## 5. Conclusion

In the present investigation, ultra-high strength compressor disk steel was produced by exploiting a bainitic structure. The increase in the toughness and strength could be ascribed to the austempering condition and predeformation effects that develop bainitic microstructure with high aspect ratio of bainitic ferrite laths. Therefore, austenitization time and temperature, as well as austempering time and temperature play a major role in achieving ultra-high strength bainitic steels. The optimized strength and toughness was achieved by up quenching treatment. This is due to partitioning of prior austenite grains by tempered martensite plates. Therefore, a combination of ultra-high strength and good toughness is obtained by the specific thermomechanical treatment.

## 5. References

[1] M. Jahazi and B. Eghbali, The influence of hot rolling parameters on the microstructure and mechanical properties of an ultra-high strength steel, *Journal of Materials Processing Technology*, 103(2000) 276-279.

[2] W.S. Lee and T.T. Su, Mechanical properties and microstructural features of AISI4340 high strength alloy steel under quenched and tempered conditions, *Journal of Materials Processing Technology*, 87(1999) 198-206.

[3] A.A. Barani, F. Li, P. Romano, D. Ponge and D. Raabe, Design of high-strength steels by microalloying and thermomechanical treatment, *Materials Science and Engineering A*, 463(2007) 138-146.

[4] K. Sato, Improving the toughness of ultrahigh strength steel [Dissertation] (in Japan), Kyoto, Kyoto University, (2002).

[5] S. Gunduz and R.C. Cochrane, Influence of cooling rate and tempering on precipitation and hardness of vanadium microalloyed steel, *Materials and Design*, 26(2005) 486-492.

[6] Y. Tomita, Effect of modified austemper on tensile properties of 0·52%C steel, *Materials Science and Technology*, 11(1995) 994-997.

[7] Z. Li and D. Wu, Effects of holding temperature for austempering on mechanical properties of Si-Mn TRIP steel, *Journal of Iron and Steel Researh*, 11(2004) 40-44.

[8] A.D. Basso, R.A. Martinez and J.A. Sikora, Influence of austenitizing temperature on microstructure and properties of dual phase ADI, *Materials Science and Technology*, 23(2007) 1321-1326.

[9] M. Takahashi and H.K.D.H. Bhadeshia, A model for the microstructure of some advanced bainitic steels, *Materials Transactions JIM*, 32(1991) 689-696.

[10] J. M. Tartaglia, K.A. Lazzari, G.P. Hui and K.L. Hayrynen, A comparison of mechanical properties and hydrogen embrittlment resistance of austempered vs quenched and tempered 4340 steel, *Metallurgical and Materials Transactions A*, 39(2008) 559-576.

[11] S.B. Singh and H.K.D.H. Bhadeshia, Estimation of bainite plate-thickness in low-alloy steels, *Materials Science and Engineering A*, 245(1998) 72-79.

[12] M.Y. Tu, C.A. Hsu, W.H. Wang, Y.F. Hsu, Comparison of microstructure and mechanical behavior of lower bainite and tempered martensite in JIS SK5 steel, *Materials Chemistry and Physics*, 107(2008) 418-425.

[13] A.R. Mirak and M. Nili Ahmadabadi, Effect of modified heat treatments on the microstructure and mechanical properties of a low alloy high strength steel, *Materials Science and Technology*, 20(2004) 897-902.

[14] C.D. Liu and P.W. Kao, Tensile properties of a 0.34C-3Ni-Cr-Mo-V steel with mixed lower bainite – martensite structure, *Materials Science and Engineering A*, 150(1992) 171-177.

[15] K. Zhu, O. Bouaziz, C. Oberbilling and M. Huang, An approach to define the effective lath size controlling yield strength of bainite, *Materials Science and Engineering A*, 527(2010) 6614-6619.

[16] ASM Metal Handbook, *Heat treatment*, 10th edition, Vol. 4(1990) Materials Park, OH.

[17] P.H. Shipway and H.K.D.H. Bhadeshia, The effect of small stresses on the kinetics of the bainite transformation, *Materials Science and Engineering A*, 201(1995) 143-149.

[18] M. Takahashi, Recent progress: kinetics of the bainite transformation in steels, *Current Opinion in Solid State and Materials Science*, 8(2004) 213-217.

[19] A.G. Rakhshtadt , K.A. Lanskaya and V.V. Goryachev, Solution and precipitation of carbide phase in medium-carbon steels, *Metal Science and Heat Treatment*, 23(1981) 98-103.

[20] C. Garcia-Mateo and F.G. Caballero, Ultra high strength bainitic steels, *ISIJ International*, 45(2005) 1736-1740.

[21] M. Gomez, S.F. Medina, A. Quispe and P. Valles, Static recrystallization and induced precipitation in a low Nb microalloyed steel, *ISIJ International*, 42(2002) 423-431.

[22] Y. Chen, D. Zhang, Y. Liu, H. Li and D. Xu, Effect of dissolution and precipitation of Nb on the formation of acicular ferrite/bainite ferrite in low-carbon HSLA steels, *Materials Characterization*, 84(2013) 232-239.