MECHANICAL PROPERTIES OF 0.15 Wt%C - 0.37 Wt%Mn - 0.24 Wt%Si STEEL QUENCHED TO ROOM TEMPERATURE AFTER SINGLE PHASE AUSTENITIZATION

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Abstract

Mechanical properties of 0.15 wt%C - 0.37 wt%Mn - 0.24 wt%Si steel quenched to room temperature after single phase austenitization and those tempered after quenching were studied. Forty eight steel samples were prepared for mechanical properties analyses and heat treated at 850°C, 870°C, 890°C, 910°C, 930°C, 950°C, 970°C and 990°C for 1hr at each temperature in a laboratory muffle heat treatment furnace. The heat treated samples were quenched to room temperature in plain water. Twenty four samples from the quenched samples were further subjected to a low temperature tempering at 200°C for 1 hr and air cooled to room temperature. Lower single phase austenitization temperatures gave higher strength and hardness values but lower ductility and notch impact toughness values compared to higher single phase austenitization temperatures. The results revealed that tensile strength and hardness values decreased from 571.27N/mm^2 at 850°C to 412.31N/mm^2 at 990°C for tensile strength and from 250 BHN at 850°C to 206 BHN at 990°C for hardness while ductility and notch impact toughness increased from 4.57% at 850°C to 11.61% at 990°C and from 10.24 J/cm^2 at 850°C to 23.69 J/cm^2 at 990°C respectively with single phase austenitization temperatures. Tempered steel has yield strength values which decreased with single phase austenitization temperatures from 383.34 N/mm^2 at 850°C to 222.76 N/mm^2 at 990°C. From the values it was observed that tempering gave rise to a decrease in tensile strength (from 571.27 N/mm^2 at 850°C after quenching to 552.03 N/mm^2 at 850°C after tempering) and hardness (from 250 BHN at 850°C after quenching to 239 BHN at 850°C after tempering) and an increase in ductility (from 11.61% at 990°C after quenching to 28.04% at 990°C after tempering) and notch impact toughness (from 23.69 J/mm^2 at 990°C after quenching to 84.60 J/mm^2 at 990°C after tempering) of the as-quenched steel.

Keywords: quenching, tempering, mechanical properties, single phase austenitization temperatures

Symbol notation

σ_t	tensile strength
σ_y	yield strength
δ	ductility
H	hardness
BHN	Brinnel hardnes number
a_n	notch impact toughness
q_s	quenched sample
t_s	tempered sample

1. Introduction

Since the nineties of 20th century, automotive industry has reported high demands for steels possessing high strength and plastic properties as well as cold formability. A great contribution in the development of new generation of steels emanated from international projects with participation of numerous steel industries. The basic goal was to collaborate and produce components from high strength steels, using modern methods of forming and processing for the production of body parts of a vehicle [1]. The expectations of automotive industry were brought to lime light by the introduction of multiphase steels, consisting of soft ferritic matrix containing islands of martensite, bainite or bainitic-austenitic islands. Steels with such microstructure have characteristics of a composite material, perfectly combining high strength with required plasticity [2 - 4].

The final mechanical properties depend upon kinetics of austenite to martensite transformation, which is strictly connected with austenite phase stability, mostly dependent on carbon concentration in austenite [5-7], the size and arrangement of particles of this phase as well as its strength and the present state of stress [8, 9]. The optimization of alloy contents in the iron - carbon alloy system combined with different mechanical and heat treatments lead to immense opportunities for parameter variations and these are continuously being developed [10-12]. The development of new structural materials with good strength, impact and plasticity, which allow for weight reduction of cars, is still an open task for manufacturers [13].

Table 1: Chemical composition of the steel used (wt %) with its critical temperature (calculated).

C	Mn	Si	Ni	Al	S	AC_3 (°C)
0.15	0.37	0.24	0.04	0.01	0.002	832

Table 2: Mechanical properties of steel used.

σ_y (N/mm^2)	σ_t (N/mm^2)	δ (%)	H (BHN)	a_n (J/cm^2)
213.86	367.31	34.49	148	72.41

2. Objectivies of the Study

The objectives of this work are to study the effects of various single phase austenitization temperatures and tempering on the mechanical properties of 0.15 wt%C - 0.37 wt%Mn - 0.24 wt%Si steel. So the goal of this work is to find the single phase austenitization temperature or temperature interval from which quenching results in better mechanical properties when combined with low temperature tempering.

3. Materials and Methods

3.1. Materials

Hot-rolled 16mm (5/8 inch) steel rod of chemical composition (wt %) shown in Table 1 was used for the experimental work. The mechanical properties of the experimental steel in its original as hot-rolled state are given in Table 2.

3.2. Methods

The samples used for the experimental work were machined from the as-hot-rolled steel rod. Forty eight steel samples were prepared for mechanical properties analyses and heat treated at 850°C, 870°C, 890°C, 910°C, 930°C, 950°, 970°C and 990°C for 1hr at each temperature in a laboratory muffle heat treatment furnace. The heated treated samples were quenched to room temperature in plain water. Twenty four samples from the quenched samples were further subjected to a low temperature tempering at 200°C for 1 hr and air cooled to room temperature to improve ductility and notch impact toughness.

The upper critical temperature AC3 was calculated using empirical equation developed by Andrews [14-16].

After the heat treatment of the test samples, tensile tests were carried out at room temperature using 10 ton universal testing machine. Brinell hardness testing method was used to determine hardness while the Charpy impact testing machine was used for the determination of the notch impact toughness.

4. Results and Discussions

The results of measurements made are tabulated in tables 3.

Table 3 shows the strength and ductility – temperature relationships of the steel samples prepared for quenching and those prepared for quenching and then tempering after single phase austenitization at 850°C, 870°C, 890°C, 910°C, 930°C, 950°C, 970°C and 990° for 1hr in a laboratory muffle heat treatment furnace and quenched to room temperature in plain water. The steel samples prepared for quenching and then tempering were further subjected to a low temperature tempering at 200°C for 1 hr and air cooled to room temperature. The table also shows profoundly that single phase austenitization temperature and low temperature tempering had noticeable effects on the strength and ductility values. Steel samples quenched in plain water had higher tensile strength values (from 571.27N/mm^2 at 850°C to 412.31N/mm^2 at 990°C) than those subjected to low temperature tempering after plain water quenching (from 552.02N/mm2 at 850°C to 389.90N/mm^2 at 990°C). On the other hand, steel samples tempered after plain water quenching had higher ductility values (from 28.04% at 990°C to 16.27% at 850°C) than those quenched in plain water but not tempered (from 11.61% at 990°C to 4.57% at 850°C). Lower single phase austenitization temperatures gave higher strength and hardness values but lower ductility and notch impact toughness values compared to higher single phase austenitization temperatures. The results show that lower single phase austenitization temperatures gave higher tensile strength values (571.27N/mm^2 at 850°C to 412.31N/mm^2 at 990°C) but lower ductility values (from 11.61% at 990°C to 4.57% at 850°C) compared to higher single phase austenitization temperatures. It is also of note that the yield strength values decreased with single phase austenitization temperatures (from 222.76N/mm^2 at 990°C to 383.34N/mm^2 at 850°C).

Perhaps the most fascinating aspect of steel is that it may be strengthened to amazingly high levels by quenching. The strength levels are higher than the strongest commercial alloys of aluminum, copper and titanium by factors of roughly 4.7, 2.2 and 2.1 respectively [17]. Increased strengths do not occur unless the hot steel contains the austenite phase. The very rapid cooling prevents the austenite from transforming into the preferred ferrite + cementite structure. A new structure called martensite is formed instead, and this martensite phase is responsible for the very high strength levels [17]. Most martensites are tempered by heating to low temperatures. The tempering causes very small carbides to form in the martensite which reduces strength but enhances ductility. It also makes tempered martensite etch dark in the optical microscope [17].

Furthermore, Table 3 shows the hardness and notch impact toughness versus temperature relationships of the steel samples prepared for quenching and those prepared for quenching and then tempering after single phase austenitization at 850°C, 870°C, 890°C, 910°C, 930°C, 950°C, 970°C and 990°C for 1hr in a laboratory muffle heat treatment furnace and quenched to room temperature in plain water. The steel samples prepared for quenching and then tempering were further subjected to a low temperature tempering at 200°C for 1 hr and air cooled to room temperature. Table 3 also shows profoundly that single phase austenitization temperature and low temperature tempering had noticeable ef-

Table 3: Strength properties of the heat treated steel specimens..

T °C	σ_{yqs} N/mm^2	σ_{yts} N/mm^2	σ_{tqs} N/mm^2	σ_{tts} N/mm^2	q_s %	t_s %	H_{qs} BHN	H_{ts} BHN	a_nq_s J/cm^2	a_nt_s J/cm^2
850	-	383.34	571.27	552.03	4.57	16.27	250	239	10.24	56.27
870	-	367.11	549.71	538.15	4.81	18.31	240	228	11.97	58.33
890	-	346.63	532.29	515.16	5.93	20.01	35	221	13.77	62.17
910	-	339.04	507.04	486.29	6.45	21.62	229	215	14.16	65.93
930	-	320.47	482.92	468.75	8.12	23.75	222	207	15.21	70.45
950	-	305.11	460.44	443.62	9.84	25.44	215	194	17.6	74.5
970	-	265.39	436.41	417.84	10.41	25.78	210	182	20.38	80.87
990	-	222.76	412.31	389.9	11.61	28.04	206	173	23.69	84.6

fects on the hardness and notch impact toughness values. Steel samples quenched in plain water had higher hardness values (from 250 BHN at 850°C to 206 BHN at 990°C) than that subjected to tempering after plain water quenching (from 239 BHN at 850°C to 173 BHN at 990°C). On the other hand, steel samples tempered after plain water quenching had higher notch impact toughness values (from 84.60 J/cm^2 at 990°C to 56.27 J/cm^2 at 850°C) than that quenched in plain water but not tempered (from 12.24 J/cm^2 at 990°C to 23.69 J/cm^2 at 850°C). In the same vein, the results show that lower single phase austenitization temperatures gave higher hardness values (from 250 BHN at 850°C to 206 BHN at 990°C) but lower notch impact toughness values (from 23.69 J/cm^2 at 990°C to 10.24 J/cm^2 at 850°C) compared to higher single phase austenitization temperatures (see Table 3). By the tempering process, the properties of quenched steel could be modified to decrease hardness and increase ductility and impact strength gradually [10]. Coarsening of austenite microstructure with higher temperature prior to quenching is responsible for the observed trends. It should be noted that in accordance with the Hall-Petch equation, smaller grain size usually leads to increased yield strength and impaired technological ductility of steel [18]. Raising the austenitization temperature (thus, increasing austenitic grain growth) can be considered promising and effective method of increasing the strength of grain boundaries due to reduction of impurity segregation. It is known that raising the austenitization temperature leads to higher residual elastic stresses and also to higher local peak microstresses that occur when the martensite crystals encounter grain boundaries. For this reason, it is possible for the positive effect resulting from weakening of segregation embrittlement of grain boundaries after high temperature austenitization to be offset by the negative effect of structural microstresses. To reduce metal consumption and the weight of structures it is necessary to broaden the use of high strength steels and alloys. The increase in strength resulting from quenching to produce martensite is inevitably accompanied by low resistance to brittle fracture the most important characteristic of structural strength [19, 20]. Dual phase steels have been designed to have low carbon with or without alloying elements and heat treated or hot rolled to have martensite volume fractions rarely exceeding 15%, because beyond this percentage, formability of dual phase steels is badly affected [21]. The advantages gained by heat treatments that use austenitization, quenching to martensite and then tempering the martensite are that the desired microstructure can be obtained either throughout the part or at selected locations. Obtaining the desired microstructure means that the proper mechanical properties can be obtained where required. All of this is true provided that the part being heat treated can indeed be converted to martensite when the austenite is cooled. If it cannot be so trans-formed then the required microstructure cannot be produced [13, 15].

5. Conclusions

The following conclusions can be drawn.

- Strength and hardness values decreased with increase in single phase austenitization temperatures.
- Ductility and notch impact toughness increased with increase in single phase austenitization temperatures.
- Tempered steel has yield strength values which decreased with increase in single phase austenitization temperatures. As quenched steel has no yield strength values.
- Tempering gave rise to a decrease in tensile strength and hardness and an increase in ductility and notch impact toughness of the as hot rolled steel.
- Tempered steels presented the better compromise between strength, hardness, ductility and notch impact toughness.

References

1. Grajcar A. and Krzto H., Effect of isothermal bainitic transformation temperature on retained austenite fraction in C-Mn-Si-Al-Nb-Ti TRIP-type steel, *Journal of Achievements in Materials and Manufacturing Engineering* Volume 35 Issue 2 August 2009.

2. V. Flaxa, J. Shaw, Material applications in ULSAB-AVC, *Steel Grips* 1/4 (2003) 255-261.

3. M. Mehrkens, J. Frber, Modern multi-phase steels in the BMW of the Porsche Cayenne, *Steel Grips* 1/4 (2003) 249-251.

4. R. Kuziak, R. Kawalla, S. Waengler, Advanced high strength steels for automotive industry, *Archives of Civil and Mechanical Engineering* 8/2 (2008) 103-117.

5. W. Shi, L. Li, Ch. Yang, R.Y. Fu, L. Wang, P. Wollants, Strain-induced transformation of retained austenite in low-carbon low-silicon TRIP steel containing aluminum and vanadium, *Materials Science and Engineering A* 429 (2006) 247-251.

6. Y.K. Lee, H.C. Shin, Y.C. Jang, S.H. Kim, C.S. Choi, Effect of isothermal transformation temperature on amount of retained austenite and its thermal stability in a bainitic Fe-3%Si-0.45%C-X steel, *Scipta Materialia* 47 (2002) 805-809.

7. H.B. Ryu, J.G. Speer, J.P. Wise, Effect of thermomechanical processing on the retained austenite content in a Si-Mn Transformation-Induced-Plasticity steel, M*etallurgical and Materials Transactions A* 33A (2002) 2811-2816.

8. G.N. Haidemenopoulos, A.I. Katsamas, N. Aravas, Stability and constitutive modelling in multiphase TRIP steels, *Steel Research International* 77 (2006) 720-726.

9. I.B. Timokhina, P.D. Hodgson, E.V. Pereloma, Effect of deformation schedule on the microstructure and mechanical properties of a thermomechanically processed C-Mn-Si transformationinducedplasticity steel, *Metallurgical and Materials Transactions A* 34A (2003) 15991609.

10. Bello, K.A., *Effect of Intercritical and Tempering heat treatment on the microstructure and mechanical properties of a high martensite dual - phase steel*, MSC, ABU, Zaria, 2007.

11. Lis, J., Lis, A.K. and Kolan, C., Processing dual-phase microstructure, *13th International scientific conference on Achievements in Mechanical and Materials Engineering*, Gliwice-Wisla, Poland, 2005, pp: 395 398.

12. Khamedi, R., Fallahi, A. and Zoghi, H., The Influence of Morphology and volume during tensile loading of dual-phase steels, *International journal of recent trends in Engineering*, vol.1, No 5,2009 pp. 30-34.

13. Bag, A., Ray, K.K. and Dwarakadasa, E.S., Influence of Mertensite content and morphology on tensile and impact properties of high - martensite dual - phase steels, *Metalt and Mater. Trans.* Vol. 30 (A), 1999, pp. 1193-1202.

14. Offor, P.O. *The Effect of Diverse Heat Treatment on the Mechanical Properties of Structural Steels*, M.Eng. Thesis, ESUT Enugu, 1993.

15. Leslie, W.C., *The Physical Metallurgy of Steels*. McGraw-Hill, International: New York, 1983, 219 -257.

16. Birgani, E.N. and Pouranvari, M., *Effect of martensite volume fraction on the work hardening behavior of dual-phase steels*, Hradec nad Moravici, 19-215. 2008, pp. 107.

17. Verhoeven, J. D., *Metallurgy of Steel for Bladesmiths & Others who Heat Treat and Forge Steel*, Iowa State University, 2005.

18. Fonshtein, N. M., Effect of the Structure on Indices of Technological Ductility of Cold-Rooled-Alloy Steels with Improved Strength, *Metal Science and Heat Treatment* Vol. 28, 1987 pp. 625 - 628

19. Arain (Ayooq), A., *Heat treatment and toughness behavior of tool steels (D2 and H13) for cutting blades*, M. AS. Thesis, University of Toronto, 1999.

20. Romaniv, O. N., Structural Strength of Steels with a Structure of Temper Martensite, *Metal Science and Heat Treatment*, vol. 28,1982.

21. Abouei, V., Saghafian, H., Kheirandish, Sh. and Ranjbar, Kh., A Study on the Wear Behaviour or Dual Phase Steels, *J. Mater. Sci. Technol.*, Vol.23 No.1, 2007, pp. 107-110.