



Effect of austenitizing and tempering temperature and holding time on mechanical properties of advanced high-strength steels

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ABSTRACT

Reducing CO₂ emissions is an urgent mission worldwide. Notably, 25% of CO₂ emissions derive from the transport sector. Thus, reducing the weight of steel components in automotive parts was considered a way to lower CO₂ emissions. To this end, advanced high-strength steels (AHSS) were researched and applied in automotive sheet steel. The present study investigates the mechanical properties of AHSS produce by different heat treatment processes of steel plates makes from a JIS-SCM435. Three different heat-treated processes were performed: (1) The steel was homogenised at 880°C for 30 min and then austenitised at 900°C for 15 min, followed by water quenching. Subsequently, the steel was tempered at 400°C for 30 min; (2) The steel was annealed at about 770°C for 30 min, followed by water quenching, and then tempered at 200°C for 30 min; (3) The steel was annealed at about 900°C for 30 min, followed by water quenching, then tempered at 200°C for 30 min. The results showed that heat-treated processes (1); and (3) obtained martensite phase steel with the ultimate tensile strength (UTS) of 2,150 MPa and 1,400 MPa, respectively. Dual-phase steel was obtained from the second process with a UTS of 1,900 MPa. The elongations of these heat-treated steels showed an insignificant difference.

1. INTRODUCTION

Reducing CO₂ emissions is an urgent mission worldwide. Notably, 25% of CO₂ emissions derive from the transport sector. Thus, reducing the

weight of steel components in automotive parts was considered a way to lower CO₂ emissions. The use of AHSS can allow significant weight reduction and improved crash performance of

vehicles to provide better fuel economy and higher safety (Zhu & Ma, 2004).

Martensitic advanced high-strength steels (MS-AHSS) gained significant attention for use in lightweight and crashworthy automotive structures due to their excellent strength and cost-effective manufacturability (Bouaziz et al., 2013). When carbon steel was rapidly cooled (quenched), austenite transforms into martensite without diffusion through a displacive transformation that was the face-centred cubic (fcc) structure of the austenite transforms into a quadratic mesh by shear and dilatation (called the Bain transformation) (Krauss, 1999; Thewlis, 2004). This created a fine and complex microstructure composed of fine laths or thin plates with sub-micrometric and many dislocations, which resulted in high yield strength but low ductility. The cooling temperature determined the amount of martensite formed. The austenite transformed to martensite at a temperature denoted as M_s , which depended on carbon and alloy content (Van Bohemen, 2012).

Dual-phase advanced high-strength steels (DP-AHSS), initially developed for industrial use due to the ease of quenching thin sheets, consist of a ferrite matrix with martensite islands, whose volume can range from 10% to nearly 100%. Their microstructure was formed by annealing cold-rolled sheets in the intercritical temperature range, allowing carbon diffusion and subsequent martensite formation upon quenching. Proper heating and cooling rates led to fine microstructures, enhancing strength. DP-AHSS were also produced from hot-rolled sheets for thicker parts, enabled by advanced rolling and cooling technologies. For optimal strength–ductility balance in thinner sheets, a martensite content of 10–20% yielded a 300–700 MPa yield

stress, UTS over 1000 MPa, and good elongation (Kuziak et al., 2008).

This study investigates the mechanical properties and microstructural characteristics of MS-AHSS and DP-AHSS produced through three different heat-treatment processes applied to steel plates manufactured from JIS-SCM435.

2. MATERIALS AND METHODS

In this study, an AHSS steel plate was made from a 50 mm diameter JIS-SCM435 steel bar. Table 1 shows the detailed chemical composition of the steel. The steel bar was cut into plate specimens by electrical discharge machining (EDM); the steel plate geometry is shown in Fig. 1a.

Table 1. Chemical composition of JIS-SCM435

Components	Content (wt.%)
Cr	0.36
Si	0.22
Mn	0.79
P	0.12
S	0.13
Ni	0.10
Cr	0.96
Mo	0.15
Cu	0.16
Fe	Balance

Three different heat-treated processes were performed to conduct MS-AHSS and DP steels. The Koyo heat-treatment furnace was used to temper samples. The heat-treated processes were as follows:

- Heat-treated process 1 (denoted as HT1): The steel was homogenised at 880°C for 30 min and then austenitised at 900°C for 15 min, followed by water quenching. Subsequently, the steel was tempered at 400°C for 30 min.

- Heat-treated process 2 (denoted as HT2): The steel was annealed at about 770°C for 30 min, followed by water quenching, and then tempered at 200°C for 30 min.

- Heat-treated process 3 (denoted as HT3): The steel was annealed at about 900°C for 30 min, followed by water quenching, then tempered at 200°C for 30 min.

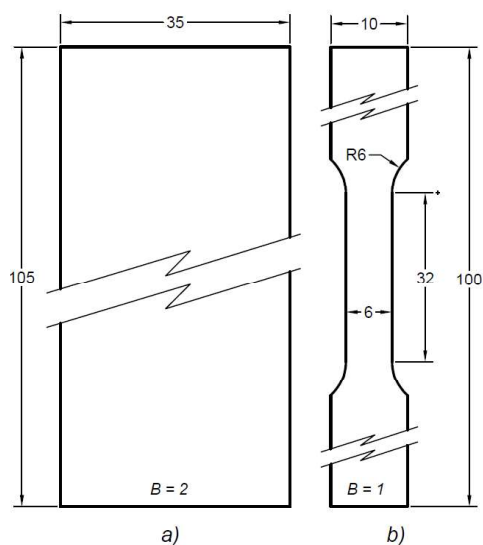


Figure 1. Specimen geometries (units mm). a) Heat treatment specimen, b) Tensile specimens

The heat-treated specimens were polished to a thickness of 1 mm and then cut into tensile specimens by EDM. The tensile specimen geometry is schematically shown in Fig. 1b. The tensile tests were conducted using an electro-hydraulic testing machine. The specimen geometry and tensile test were followed by E8/E8M-13a ASTM standard. The samples were etched in 5% Nital etchant for about 3 minutes to observe heat-treated microstructures. The microscopic pictures were then observed by field emission scanning electron microscopy (FE-SEM) at an accelerating voltage of 15 kV.

3. RESULTS AND DISCUSSION

3.1 Microstructure observation

Figs. 2, 3, 4 and 5 show the SEM images of the etched microstructures of SCM435, MS-AHSS (HT1), DP-AHSS (HT2), and MS-AHSS (HT3) materials, respectively.

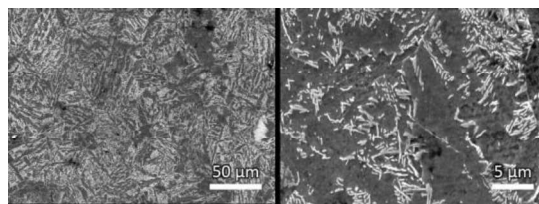


Figure 2. JIS-SCM435 microstructure

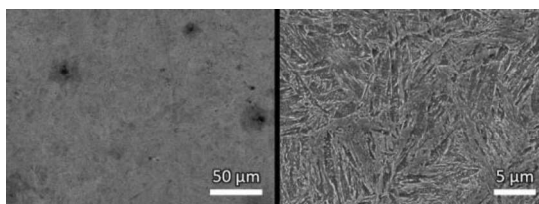


Figure 3. MS-AHSS (HT1) microstructure

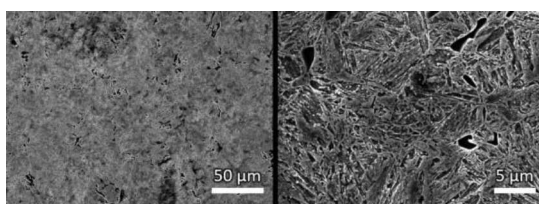


Figure 4. DP-AHSS (HT2) microstructure

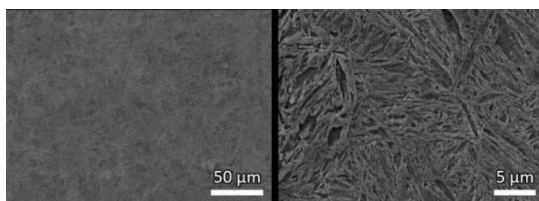


Figure 5. MS-AHSS (HT3) microstructure

Fig. 2 shows microscopic figures of JIS-SCM435 material in low and high magnifications. The microstructure consists of a refined mixture of ferrite and pearlite. Ferrite is a ductile phase and appears in light regions under optical microscopy. Pearlite is a lamellar mixture of ferrite and cementite and appears in darker, banded or layered regions. Dispersedly distributed carbides are observed in Fig. 2 (Saha et al., 2016; Thakare et al., 2019; Wen et al., 2016)

Figs. 3 and 5 show the microstructure of MS-AHSS materials heat-treated by HT2 and HT3,

respectively. A needle-like and lath-like pattern characterises the microstructure of these steels. Fig. 4 shows typical lath martensite, from which the packets, blocks and martensitic laths can be distinguished clearly. However, the microscopic figure shows in Fig. 2 is slightly different, in which the lath martensitic structure is bigger and broader compared to that shows in Fig. 4. These microstructures were consistent with previous observation that elevated tempering temperatures lead to coarsening of martensitic laths and blocks (Krauss, 2017; Wang et al., 2023; Zhao et al., 2019).

Fig. 4 shows the SEM images of the etched microstructures of DP-AHSS, which are characterised by a microstructure comprising a rugged martensitic phase interspersed with ferritic matrix islands (Ren et al., 2023).

3.2 Strength of materials

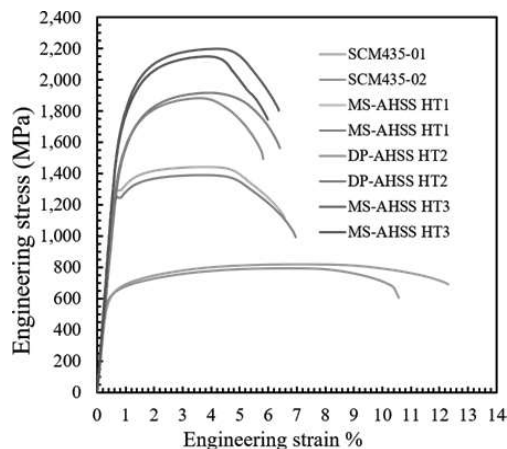


Figure 6. Engineering stress–strain curves of received and heat-treated materials

Fig. 6 shows the engineering stress-strain curves of received and heat-treated materials. The strength of these materials shows a significant difference, but there is little difference in elongation.

The MS-AHSS (HT3) had the highest UTS, about 2,150 MPa. The MS-AHSS (HT1) revealed the smallest UTS of about 1,400 MPa, while the

elongation of this material was significant compared to that of MS-AHSS (MT3) and DP-AHSS (MT2). The UTS of DP-AHSS (MT2) is about 1,900 MPa and is higher than that of MS-AHSS (MT1), but is lower than that of MS-AHSS (MT3). The elongations of these heat-treated materials seem to be reduced by about 50% compared to the received SCM435 material.

As shown in Figs. 3 and 5, and the UTS of MS-AHSS (MT1) and MS-AHSS (MT3), tempering temperature significantly influences the size and morphology of laths and blocks in martensitic steels, affecting their mechanical properties. Previous studies underscored the critical role of tempering temperature in dictating the microstructural evolution of martensitic steels, which governed their mechanical behaviour. Elevated tempering temperatures lead to coarsening of martensitic laths and blocks, contributing to decreased hardness and strength of material (Krauss, 2017; Saha et al., 2016; Wang et al., 2023; Zhao et al., 2019).

The fraction and characteristics of the ferrite phase significantly influenced the mechanical properties of DP-AHSS steels. An increased ferrite content generally enhanced ductility due to the softer nature of ferrite, facilitating easier deformation; conversely, a higher martensite fraction boosts strength but can reduce ductility (Liu et al., 2023). The size and morphology of laths and blocks of martensite show in Fig. 4 seem to be narrower than those shown in Fig. 3; this can contribute to the DP-AHSS (HT2) having higher UTS than MS-AHSS (HT1) despite the contribution of a small fraction of ferrite in DP-AHSS (HT2). Based on these results, HT3 is the first suggestion to get the highest UTS and acceptable elongation. The HT1 is recommended

for heat treatment of the present materials to achieve high elongation and an acceptable UTS.

4. CONCLUSION

The present study investigates the mechanical properties of AHSS produced by three different heat treatment processes of steel plates made from a JIS-SCM435. Three different heat-treated processes are performed. The results show as follows: (a) Heat-treated processes (1) and (3) obtain MS-AHSS with the UTS of 2,150 MPa and 1,400 MPa, respectively; (b) DP-AHSS is obtained from the heat-treated processes (2) with a UTS of 1,900 MPa. The elongations of these heat-treated steels show an insignificant difference. The elongation of heat-treated materials is reduced by about 50% compared to the as-received SCM435 material.

REFERENCES

- Bouaziz, O., Zurob, H., & Huang, M. (2013). Driving force and logic of development of advanced high strength steels for automotive applications. *Steel Research International*, 84(10), 937–947.
<https://doi.org/10.1002/SRIN.201200288>
- Krauss, G. (1999). Martensite in steel: strength and structure. *Materials Science and Engineering: A*, 273–275, 40–57.
[https://doi.org/10.1016/S0921-5093\(99\)00288-9](https://doi.org/10.1016/S0921-5093(99)00288-9)
- Krauss, G. (2017). Tempering of Lath Martensite in Low and Medium Carbon Steels: Assessment and Challenges. *Steel Research International*, 88(10), 1700038.
<https://doi.org/10.1002/SRIN.201700038>
- Kuziak, R., Kawalla, R., & Waengler, S. (2008). Advanced high strength steels for automotive industry: A review. *Archives of Civil and Mechanical Engineering*, 8(2), 103–117.
[https://doi.org/10.1016/s1644-9665\(12\)60197-6](https://doi.org/10.1016/s1644-9665(12)60197-6)
- Liu, L., Li, L., Liang, Z., Huang, M., Peng, Z., Gao, J., & Luo, Z. (2023). Towards ultra-high strength dual-phase steel with excellent damage tolerance: The effect of martensite volume fraction. *International Journal of Plasticity*, 170, 103778.
<https://doi.org/10.1016/J.IJPLAS.2023.103778>
- Ren, Q. Q., Baik, S. Il, An, D., Isheim, D., Zhu, M., Krakauer, B. W., & Seidman, D. N. (2023). The effects of heat-treatment parameters on the mechanical properties and microstructures of a low-carbon dual-phase steel. *Materials Science and Engineering: A*, 888, 145801.
<https://doi.org/10.1016/J.MSEA.2023.145801>
- Saha, D. C., Biro, E., Gerlich, A. P., & Zhou, Y. (2016). Effects of tempering mode on the structural changes of martensite. *Materials Science and Engineering: A*, 673, 467–475.
<https://doi.org/10.1016>
- Thakare, A. S., Butee, S. P., Dhanorkar, R., & Kambale, K. R. (2019). Phase transformations and mechanical properties of thermomechanically processed 34CrMo4 steel. *Heliyon*, 5(5), e01610. <https://doi.org/10.1016>
- Thewlis, G. (2004). Materials perspective: Classification and quantification of microstructures in steels. *Materials Science and Technology*, 20(2), 143–160.
<https://doi.org/10.1179>
- Van Bohemen, S. M. C. (2012). Bainite and martensite start temperature calculated with exponential carbon dependence. *Materials Science and Technology*, 28(4), 487–495.
<https://doi.org/10.1179>
- Wang, Z., Sun, H., Guo, X., Wang, P., Liu, N., Yu, D., & Zhang, H. (2023). Tempering

mechanism of lath martensite induced in IF steel under high pressure. *Journal of Materials Science & Technology*, 160, 148–160.

<https://doi.org/10.1016/J.JMST.2023.02.054>

Wen, X. L., Mei, Z., Jiang, B., Zhang, L. C., & Liu, Y. Z. (2016). Effect of normalizing temperature on microstructure and mechanical properties of a Nb-V microalloyed large forging steel. *Materials Science and Engineering: A*, 671, 233–243.

<https://doi.org/10.1016/J.MSEA.2016.06.059>

Zhao, D., Zhang, S., Zhang, H., Li, S., Xiao, H., Wang, Y., & Wang, X. (2019). Effects of Tempering Temperature on the Microstructure and Mechanical Properties of T92 Heat-Resistant Steel. *Metals* 2019, Vol. 9, Page 194, 9(2), 194.

<https://doi.org/10.3390/MET9020194>

Zhu, X. D., & Ma, Z. H. (2004). Current status of high strength steel for auto-making and its development in Baosteel; Etat actuel des aciers a haute resistance pour l'automobile et leur developpement chez Baosteel. *Revue de Metallurgie (Paris)*.