The Development of High-Strength Steel of 980MPa Grade with Higher Hole Expansibility

K.C. YANG*, T.H. WANG, J.F. TU*, L. J. CHIANG*, W.J. CHENG* and C. Y. HUANG***

**Iron and Steel Research & Development Department*
***Metallurgical Department*
China Steel Corporation

Recently, due to the requirements for lightweight and safer automobile structures, the grade of 980MPa high-strength steel has the demand of high hole expansibility and high yield strength. Due to the large difference in hardness between the soft ferrite and hard martensite, the traditional DP980Y dual phase steel has poor hole expansibility. In order to improve the hole expansibility of DP980Y dual phase steel, the best way is to modify the microstructure into a single-phase to eliminate the large difference in hardness. In this paper, the steel of nearly full bainite microstructure with a small amount of ferrite and martensite-austenite (M/A) constituents was studied. Compared to the DP980Y dual phase steel, it was found that this modified steel with a single-phase microstructure has the same grade of 980MPa of tensile strength, but can achieve the demand of higher yield strength and hole-expansion ratio. This study shows that reducing the amount of ferrite can increase the homogeneity of the matrix with the single phase to improve the hole expansibility. In addition, the use of a lower bainite transformation temperature and lower carbon content has the higher hole-expansion ratio due to a lesser amount of M/A constituents.

Keywords: High Strength Steel, Hole Expansibility, Bainite

1. INTRODUCTION

Recently, light-weight and energy-saving requirements for the automobile industry are extremely important in order to protect the environment by a reduction in the emission of CO_2. In order to simultaneously satisfy these requirements, dual phase steels have attracted much attention due to their superior properties(1-5). Dual phase steels whose microstructure mainly consists of ferrite and martensite, exhibit continuous yielding, high strength, good ductility and a high work hardening rate which provide good press formability.

A statistic from the World Auto Steel (WAS) is that a 10% reduction in mass can result in a 6 to 8% reduction in fuel consumption and reduce 5-6% of greenhouse gas emissions(6). According to a proposal of the Future Steel Vehicle (FSV) by WAS, it has been predicted that the ultra high strength steel (UHSS, tensile strength≧980MPa) will be used in about 50% of car bodies before 2020(7). Recently, the UHSS has gradually had the requirements of high hole-expansibility and high yield strength(8). However, the dual phase steel has the characteristic of low hole-expansibility due to the large difference in hardness of ferrite and martensite which easily results in micro-cracks propagating along the interfaces during hole-expanding(9). The volume change during transformation of austenite to martensite creates a high density of unpinned dislocations of adjacent ferrite grains(10, 11). These dislocations are assumed to be mobile during the early stages of deformation and contribute to the absence of Lüders bands and a high rate of work hardening with the property of low yield strength in dual phase steel(12).

In order to solve the issues of low hole- expansibility and yield strength, one of the best ways is to modify the dual phase into the single phase to eliminate the hardness difference, such as the microstructure of full bainite and martensite(9). The homogeneity of single microstructure will influence the forming and mechanical properties(13,14). In this study, the high-strength steel of 980MPa grade with higher hole expansibility has been developed by optimizing chemical composition and process to modify the microstructure of dual phase into the nearly full bainite. Moreover, the relationship between hole-expansibility and a small amount of ferrite as well as martensite-austenite (M/A) constituent was investigated.

2. EXPERIMENTAL METHOD

2.1 Heat treatments

Table 1 shows the chemical compositions of two

Table 1 Chemical composition (in wt.%) of the steels used in this study

Steel	C	Si	Mn	others
High carbon content	0.16	0.3	1.8	Cr, Mo
Low carbon content	0.13	0.3	1.8	Cr, Mo (the same content as the upper row)

steel sheets used in this study with a thickness gauge of 1.4 mm. Steel sheets through several heat treatments were applied after cold rolling. These cold-rolling samples were rapidly heated to 860°C and soaked for 150s followed by cooling to an isothermal temperature for 600s below the Bs temperature (bainite strat temperature), and then slow cooled to room temperature (Fig.1). The various isothermal temperatures were applied from 440°C to 350°C.

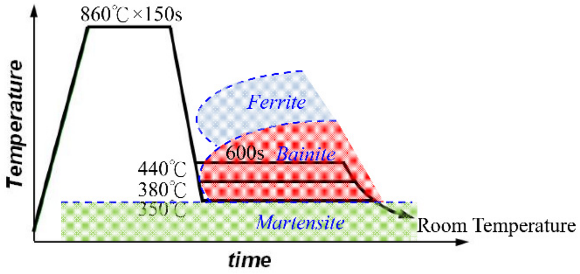


Fig.1. Schematic illustration of heating cycle of the tests

2.2 Mechanical Characterizations

Samples were cut perpendicular to the rolling direction from the steel sheets with various heat treatments. These samples were processed into the tensile specimens with the specification of JIS No.5. Afterwards, they were examined by a tensile test to measure their mechanical properties. Besides, some heated samples were prepared for the hole-expanding test standardized by JFS T1001 to evaluate hole expansibility.

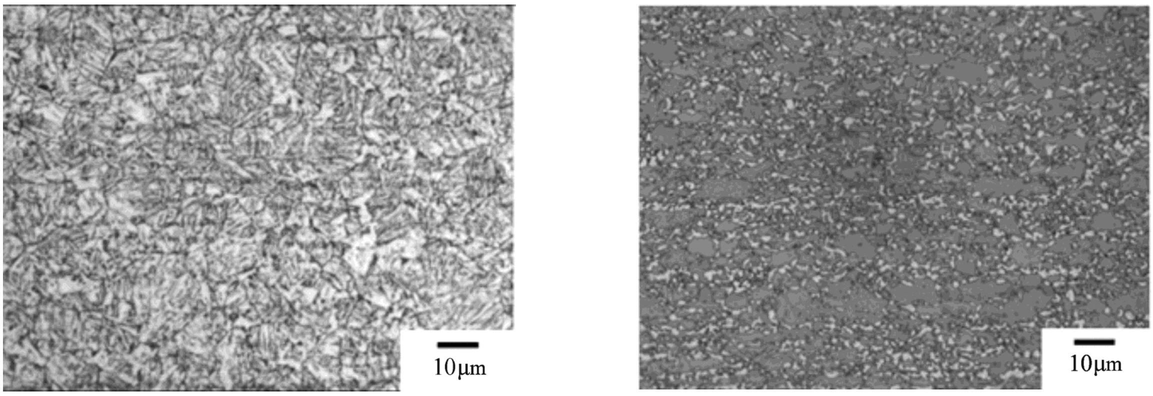
2.3 Analysis of Microstructure

Samples with various heat treatments for metallographic examination were cut along their rolling direction. After being ground, polished and etched in 3% nital solution, these samples were analyzed by OM (Optical Microscope), SEM (Scanning Electron Microscope) and EBSD (Electron Back Scatter Diffraction) to observe the microstructure and the distribution of phase.

3. RESULTS AND DISCUSSION

3.1 Comparison of DP980Y dual-phase steel

Steel A with a high carbon content of 0.16wt.% (Table 1), experiencing heat treatment with an isothermal temperature of 440°C (Fig.1), shows the microstructure as full bainite (Fig.2a). Compared to the DP980Y dual phase steel whose microstructure mainly consists of ferrite and martensite (Fig.2b), steel A shows the same tensile strength of grade 980MPa, but it has higher hole expansibility and yield strength (Table 2). It has been deuced that the modification of the microstructure



(a) Steel A with microstructure of full bainite

(b) DP980Y dual phase steel

Fig.2. Optical microstructure of two steels: (a) the studied Steel A with microstructure of full bainite; (b) the comparison of traditional DP980Y with microstructure of ferrite (gray) and martensite (white).

Table 2 The mechanical properties of traditional DP980Y dual phase steel and Steel A with the microstructure of full bainite

Steel	YS (MPa)	TS (MPa)	EL (%)	λ (%)
DP980Y dual phase steel	633	1012	15	30
Steel A with the microstructure of full bainite	863	1021	13	67

should effectively solve the issues of large differences in hardness of ferrite and martensite as well as a high density of unpinned dislocations in ferrite(9-12).

3.2 The effect of the amount of ferrite

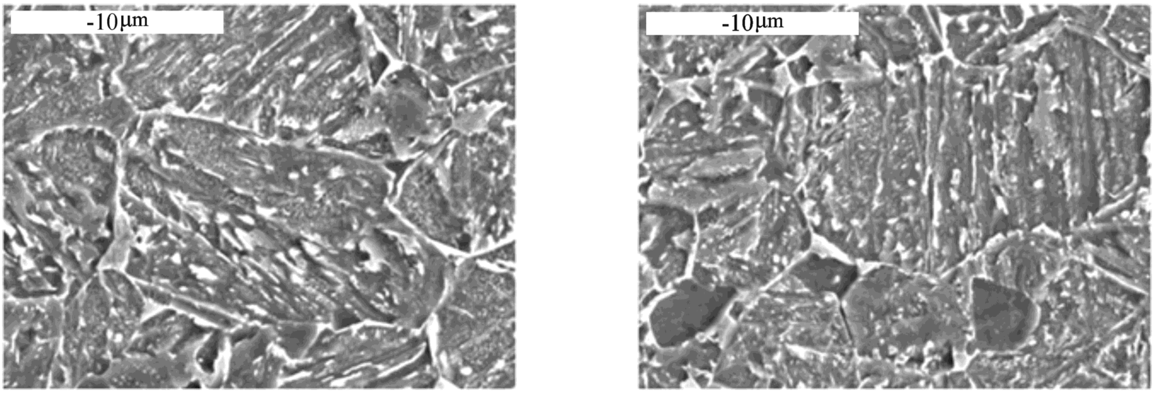
Steel B with a high carbon content of 0.16wt.% (Table 1), also experiencing the same heating cycle (Fig.1) with an isothermal temperature of 440°C, shows almost the same mechanical properties as Steel A, but different hole expansibility (Table 2 & Table 3). The hole expansion ratio of Steel A reaches 67% which is higher than that of steel B (λ=40%). Comparing the microstructure of these two steels, both have the same matrix of bainite with different amounts of ferrite (Fig.3). In order to study the relationship of hole expansibility and the amount of ferrite, an EBSD was further applied. Steel A with the higher hole expansibility has a lesser amount of ferrite at about 13.5% compared to that of Steel B with the lower hole expansibility at about 22.5% (Fig.4). Because the higher the homogeneity of a microstructure, the better the hole expansibility can be obtained, Steel A being closer to the bainite single phase has an enhanced hole expansibility(13).

3.3 The effect of the amount of M/A constituents

Another two steel samples with a high carbon content of 0.16wt.% (Table 1), experiencing the same heating cycle with an isothermal temperature of 440°C, showed almost the same mechanical properties, but different hole expansibility (Table 4). Comparing these two steels, both types of steel also had the same matrix of bainite as the steel in Fig.3, but they have different amounts of the M/A constituents (Fig.5). Steel C with the higher hole expansibility (λ=62%) has a lesser amount of M/A constituents compared to that of Steel D with the lower hole expansibility (λ=44%). The M/A

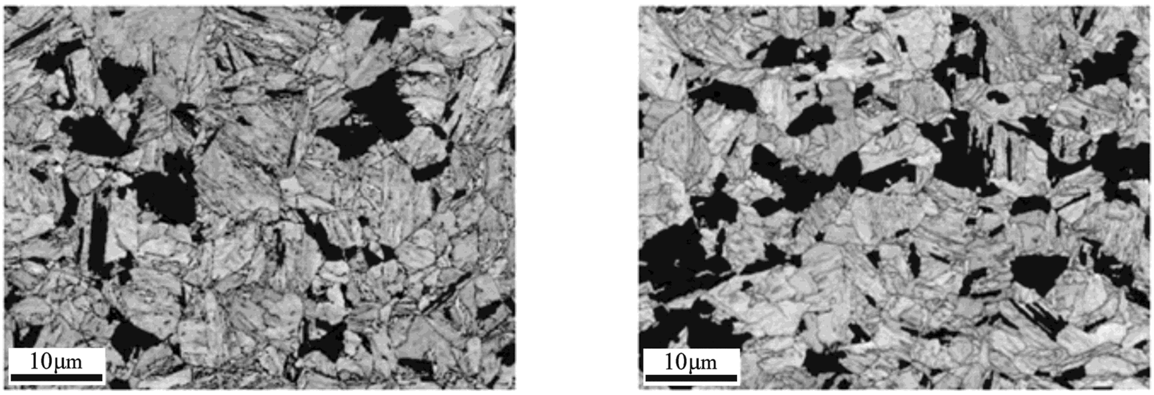
Table 3 Steel B has almost the same mechanical properties as Steel A (refer to Table 2), but lower hole expansibility. Both of Steel B and Steel A have the same carbon content (0.16wt.%) and experience the same heating cycle.

Steel	YS (MPa)	TS (MPa)	EL (%)	λ (%)
Steel B with the lower hole expansibility	855	1048	13	40



(a) Steel A with λ=67% (b) Steel B with λ=40%

Fig.3. SEM images taken from the two steels have the same matrix of bainite with different amounts of ferrite. These two steel with the same carbon content (0.16wt.%) experienced the same heating cycle.

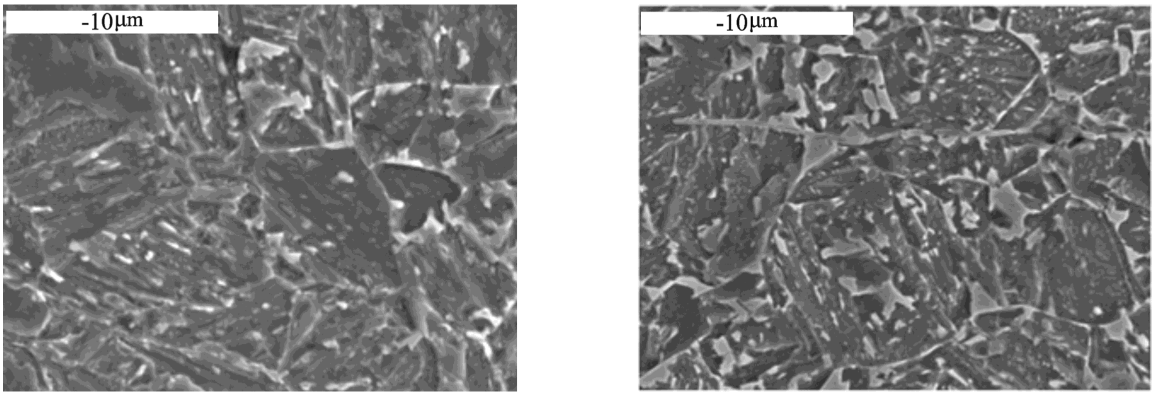


(a) Steel A, the amount of ferrite=13.5% (b) Steel B, the amount of ferrite=22.5%

Fig.4. The EBSD technique was applied to observe the amount of ferrite in the two steels. These two steels with the same carbon content (0.16wt.%) experienced the same heating cycle.

Table 4 Another two steels have almost the same mechanical properties, but different hole expansibility. They have the same carbon content (0.16wt.%) and experience the same heating cycle.

Steel	YS (MPa)	TS (MPa)	EL (%)	λ (%)
Steel C with the higher hole expansibility	905	1087	13	62
Steel D with the lower hole expansibility	892	1084	13	44



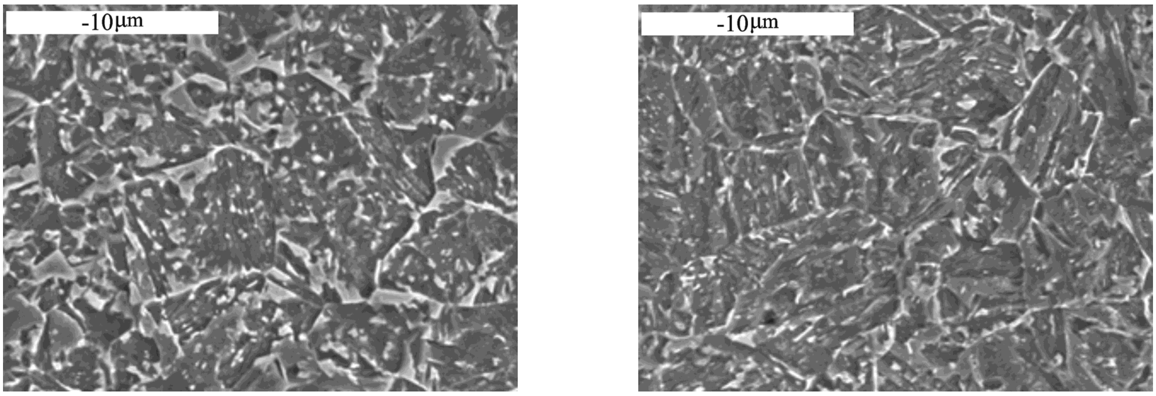
(a) Steel C with λ=62% (b) Steel D with λ=44%

Fig.5. SEM images taken from Steel C and Steel D show the same matrix of bainite with different amounts of M/A constituent. These two steels with the same carbon content (0.16wt.%) experienced the same heating cycle.

constituents are a harder second phase compared to the matrix of bainite. The interface between the M/A constituents and matrix is a source of cracks since stress concentration easily takes place in these areas. Hence, the deterioration of toughness with increasing fractions of M/A constituents occurs in any grade of steel$^{(15, 16)}$, so does the hole expansibility.

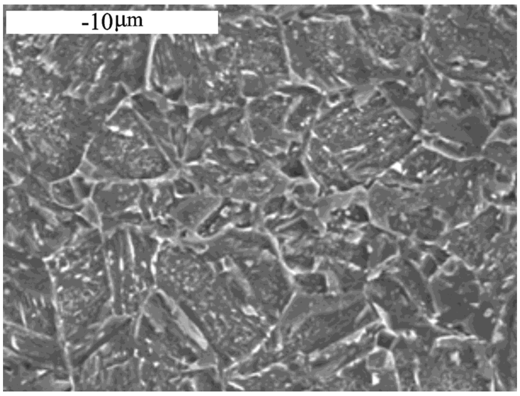
3.4 The prevention of a greater amount of M/A constituents

In order to avoid the formation of a greater amount of M/A constituents, the isothermal temperature and carbon content were studied. Steel with a high carbon content of 0.16wt.% (Table 1), experiencing different heating cycles with various isothermal temperatures from 440°C to 350°C (Fig.1), Fig.6 shows that lowering isothermal temperatures can decrease the amount of M/A constituents and also reduce the size of M/A constituents. Reducing the carbon content from 0.16% to 0.13%



(a) Isothermal temperature=440℃

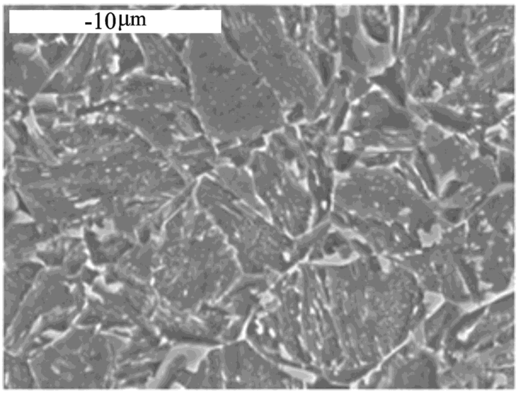
(b) Isothermal temperature=380℃



(c) Isothermal temperature =350℃

Fig.6. SEM images taken from different isothermal temperatures show the amount of M/A constituent decrease. The carbon content is 0.16wt.%.

while keeping the same heat treatment, the amount of M/A constituents is also decreased (Fig.7) to improve the hole expansion ratio to 58%. The formation of M/A constituents is dependent on carbon diffusion in steel. According to thermodynamics and kinetics analysis, the stability of carbon super-saturation is lower and the carbon diffusion rate is also lower at a lower temperature, which avoids the formation of M/A constituents(17). Thus, lowering the isothermal temperature during bainite transformation and reducing the carbon composition are recommended.



Steel with low carbon content, λ=58%

Fig.7. SEM image taken from the steel with a lower carbon content (0.13wt.%) shows a lesser amount of M/A constituent. This steel experienced the heating cycle with an isothermal temperature of 440℃.

4. CONCLUSIONS

The modification of microstructure into a single phase with full bainite is effective to improve hole expansibility and yield strength. In order to investigate the relationship of the amount of ferrite and M/A constituents on the hole expansibility of ultra high strength steel (UHSS) with 980MPa grade, the microstructure of samples were studied by OM, SEM and EBSD observation. Reducing the amount of ferrite can increase the homogeneity of the matrix with the single phase to improve the hole expansibility. Moreover, reducing the amount of M/A constituents can lower the cracking source at the interface between the M/A constituent and matrix. It helps the improvement of hole expansibility by lowering the isothermal temperature and carbon composition.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Delphic Chen for the operation and analysis of EBSD.

REFERENCES

1. S. Traint, E.A. Werner, A. Pichler and P. Stiaszny: ”Microstructure-Property Relationships for Dual-Phase and Multiphase Steel Strip”, pp. 25-36 in Proc. 41st MWSP Conf., Vol. XXXVII, Baltimore, USA, Oct. 24-27, 1999.
2. A. Pichler, G. Hribernig, E. Tragl, R. Anngerer, K. Radlmayr, J. Szinyur, S. Traint, E. Werner and P. Stiaszny: “Aspects of the Production of Dual Phase and Multiphase Steel Strips”, pp. 37-60 in Proc. 41st MWSP Conf., Vol. XXXVII, Baltimore, USA, Oct. 24-27, 1999.
3. K. Kynoo, T. Shimizu, K. Sakata and C. Kato: ”Development of Strength Grade Galvannealed Sheet Steels”, pp. 121-128 in Galvatech’01, Brussels, Belgium, Jun. 26-28, 2001.
4. B. Mintz: ”Review on the Hot Dip Galvanisability of Low Si TRIP and Dual Phase Steels with 590MPa Strengths”, pp. 551-559 in Galvatech’01, Brussels, Belgium, Jun. 26-28, 2001.
5. J.S. Rege, T. Inazumi, Y. Nagataki, T. Urabe, G. Smith, B. Zuidema and S. Denner: ”Development of HDGI/HDGA Dual Phase Steel Family (DP500, DP600, DP800, DP1000) at National Steel Corporation”, pp. 391-404 in Proc. 44th MWSP Conf., Vol. XL, Orlando, USA, Sep. 8-11, 2002.
6. Website:http://www.worldautosteel.org/steelyourworld/ fuel-efficiency/
7. Website:http://www.worldautosteel.org/projects/future-steel-vehicle/phase-2-results/
8. T. Mega, K. HASEGAWA and H. Kawabe: JFE technical report, 2004, N4, 38-43.
9. K. Hasegawa, K. Kawamura, T. Urabe and Y. Hosoya: ISIJ international, 2004, Vol. 44 , 603-609.
10. R. G. Davies: Metall. Trans. A, 1979, Vol. 10, 1549-1555.
11. M.S. Rashid: “Relationship between steel microstructure and formability”, pp. 1-24, in Formable HSLA and dual-phase steels, Illinois, Chicago, Oct. 26, 1979.
12. J. Kadkhodapour, S. Schmauder, D. Raabe and S. Ziaei-Rad: Acta Mater., 2011, Vol. 59, 4387-4394.
13. M. Takahashi: Nippon Steel Technical Report, 2003, N88, 2-7.
14. J.C. Hell, M. Dehmas, S. Allain, J.M. Prado, A. Hazotte, J.P. Chateau: ISIJ international, 2011, Vol. 5, 11724-1732.
15. F. Matsuda, K. Ikeuchi, H. OKADA:Trans. JWRI, 1994, Vol. 23, 231-238.
16. F. Matsuda, K. Ikeuchi, Y. Fukada, Y. Horii; H. Okada, T.Shiwaku, C. Shiga: Trans. JWRI , 1995, Vol. 24, 1-24.
17. X. Liang, The complex phase transformation of austenite in high strength linepipe steels and its influence on the mechanical properties, Ph. D Thesis, University of Pittsburgh, 2012. □