Effects of The Tempering Temperature on Mechanical Properties of Dual Phase Steels

Thipwipa SIRINAKORN[1], Vitoon UTHAISANGSUK[1*] and Sompong SRIMANOSAOWAPAK[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bang Mod, Bangkok 10140, Thailand
[2]National Metal and Materials Technology Center, National Science and Technology Development Agency, Khlong Luang, Pathum Thani 12120, Thailand

Abstract

Dual Phase (DP) steels have been gradually used in the automotive industries because of their distinguished strength and ductility properties. Principally, microstructure of the DP steels contains defined amount of hard martensite islands dispersed in soft ferrite matrix. This microstructure characteristic and corresponding mechanical properties of the DP steels with 35% martensite phase fraction can be adjusted by heat treatment. In this work, effects of tempering temperature and time on tensile properties of DP steels were investigated. Continuous yielding behavior of tempered DP steels was observed up to around a temperature of 300°C. At higher tempering temperature, DP steels showed distinct increased yield point. Furthermore, ultimate tensile strength decreased and elongation increased, when the tempering temperature and time were elevated. The investigated DP steel, which was tempered at 200ºC for 60 minutes, exhibited optimal combination of strength and ductility. Additionally, stretch-flangeability of the DP steels was examined. Three types of hole manufacturing process, namely, drilling, blanking and wire cut, were taken into account. It was found that formability of the DP steel sheets was significantly affected by quality of the hole edge. The samples prepared by wire cutting resulted in highest hole expansion ratio, since it caused the least prior damage.

Keywords: Dual Phase steels, Tempering, Microstructures, Hole expansion test
DOI : 10.14456/jmmm.2014.3

Introduction

Recently, automotive industries have aimed to reduce weight of vehicles in order to decrease fuel consumption and resolve environmental pollution. Therefore, new technologies of material processing were expanded for improving mechanical properties of steels. The objectives are thickness reduction of steel sheet, but superior safety demand. Dual Phase (DP) steel grade are a type of Advanced High Strength (AHS) steels that has been continuously developed for responding the requirements of high ultimate tensile strength with high fracture strain and excellent formability.[1,2] Typical characteristics of mechanical properties of DP steels are low yield strength, high strain hardening and continuous yielding behavior. Due to relative high hardening rate of DP steels reasonable combination of formability and strength is provided. Microstructure of the DP steels basically consists of hard martensite islands embedded in soft ferritic matrix. It has been shown that flow behavior of the DP steels was controlled by martensite volume fraction, morphology of martensite, martensite distribution and ferrite grain size. Strength of DP steels could be enhanced not only by ferrite but also martensite properties, for example, finer ferrite grain size, higher martensite volume fraction and high carbon content in martensite.[3-6] Effects of microstructure on mechanical behavior of DP steels were studied in numerous investigations. An optimum combination of high strength and ductility with high impact toughness was found in finely dispersed ferrite and martensite phase.[7]

To improve elongation and formability of high strength DP steels, tempering process could be proposed. During tempering, microstructure changes occur leading to property enhancement of both martensitic and ferritic phases.[8,9] It activates carbon diffusion and affects redistribution of carbon in the microstructure. Hardness of martensite decreases with increasing temperature due to the diffusion of carbon atoms from their stressed interstitial lattice sites to form second-phase carbide precipitates. Generally, tempering was conducted by including

*Corresponding author E-mail : vitoon.uth@kmutt.ac.th (V. Uthaisangsuk)

an additional heat treatment step, after DP steel was produced and cooled to ambient temperature. In Kamp et al.[10] tempering temperatures between 200ºC and 450ºC and tempering times ranged from short time scales up to 10 minutes were investigated. The short tempering time leaded to a decrease in tensile elongation and an increase in hole-expansibility and bendability. Effects of tempering temperatures on microstructure and corresponding mechanical properties of DP steels were studies as well by Anazadeh et al.[8] It was found that at tempering temperature of 200ºC, fine carbides occurred in the martensitic phase. The amount of carbides increased and it led to depleted carbon in martensite when tempering temperature was higher. Moreover, uniform elongation (UEL) and total elongation (TEL) slightly increased with increasing tempering time.

Bending is one of the most frequently used sheet-forming operations in the automotive industry to produce structural and safety parts such as bumper beams and lateral reinforcement beams.[11] Bending of sheet metal is governed by an inhomogeneous multi-axial state of stress and strain, by which tensile stress takes place on the outer and compressive stress on the inner surface of the bending zone. Damage and failure most likely occurs at the outer fiber caused by the tensile stress.[12] Abbas et al.[13] studied fracture in a bending of monolithic sheets and machined tailor-made blanks made of high strength aluminum alloys commonly used in the aircraft industry. Effects of sheet thickness and thickness difference on forming limits were investigated. Minimum bending ratio was increased by increasing the thickness.

Hole expansion test has been commonly used to evaluate edge cracking in flanging of AHS steels. In the automotive industries, holes in sheet metal parts were expanded during forming operations. During the test, hole in the middle of sheet sample is stretched to increased diameter.[14] Obviously, edge cracking could occur at significantly lower strains than those predicted by the Forming Limit Diagram (FLD) of material. Furthermore, edge quality of hole had a considerable influence on the edge cracking.[15] Chung et al.[16] investigated high strength steels using hole expansion test. The holes were manufactured by punching and milling process. Macro cracks at the hole edge surface were examined and main cracks developed through sample thickness were observed.

In this work, DP steels with a defined martensite fraction were produced by intercritical annealing. The generated DP steels were tempered using different temperatures and holding times. Afterwards, metallography examinations and tensile tests were carried out. The resulted stress-strain curves of different tempering conditions were compared. Mechanical properties of the DP steels after tempering were then evaluated in order to identify optimal conditions for forming processes. In addition, bending test and hole expansion tests were performed for the DP steels. Samples for the hole expansion test were prepared by drilling, piercing and wire cutting. The effects of tempering and hole edge surface were studied.

Materials and Experimental Procedures

Material

A laboratory heat treatment was performed aiming to produce DP steels with 35% martensite phase fraction, which is the typical amount of martensite in commercial DP780 steel. An as-received hot rolled steel plate with a thickness of 2 mm was taken. Chemical composition of the steel was determined by using vacuum emission spectroscopy, as shown in Table 1. The steel plate was cold rolled to a thickness of 1.4 mm. Then, steel sheet samples were immersed in a salt bath at the intercritical temperature of 770ºC. This temperature was calculated by ThermoCalc considering chemical composition of the used steel. The holding time after reaching the intercritical temperature was 5 minutes. Subsequently, the samples were quenched in water to room temperature, by which phase transformation from austenite to martensite took place. Finally, the samples were tempered at three different temperatures of 200ºC, 300ºC and 400ºC with the holding times of 5 minutes and 60 minutes.

Microstructure analysis

All DP steel sheets undergoing heat treatment and tempering process were prepared for metallography analysis. The samples were grounded by silicon carbide paper with a grit size of 400, 600, 1200 and 2000 in sequence and polished with 0.03 µm alumina. Then, the samples were etched by 2% Nital solution (2 ml HNO_3 in 98 ml ethanol). For each testing condition, micrographs were taken by Light Optical Microscopes (LOM), were later converted into black and white color images. The bright regions were identified as ferrite and the dark region as martensite

Table 1: Chemical composition of the investigated DP steels (in wt.%)

Fe	C	Si	Mn	P	S	Cr	Al	Nb
Balance	0.116	0.077	1.338	0.020	0.006	0.020	0.011	0.037

Tensile test

DP steel samples obtained from each tempering condition were investigated by tensile test. Tensile samples were prepared according to DIN EN 10002. The tensile sample with a nominal gauge length and nominal width of 25 mm and 5 mm, respectively, was used. The tensile tests were performed parallelly to the rolling direction. The specimens were elongated under uniaxial condition at a strain rate of 0.002 s^{-1} that was in the range of quasi-static condition. During the test, force and displacement were recorded by mechanical extensometer. Then, the resulted data were calculated to stress and strain values.

Bending test

Free bend tests were performed for the DP steels regarding two conditions, without tempering and with tempering at 200ºC and holding time of 60 minutes. The bending specimen had a dimension of 12mm×60mm and a bending radius of 1 mm was used. The specimens were bended perpendicularly to the rolling direction until different bend angles of 90º, 105º, 120º and 130º. Then, sample surfaces in vicinity of the bending area were examined with respect to bendability of material.

Hole expansion test

Similar to the bending test, DP sheet samples experiencing tempering at the temperature of 200ºC and holding time of 60 minutes were used for the hole expansion test. Here, hole of the specimens was manufactured by three different procedures, drilling, blanking and wire cutting. It was intended to study effects of surface condition of hole edge on material formability. The initial diameter of the hole was 25 mm. By the test, hole was expanded and sample was deformed by a conical punch until a primary crack appeared. Schematic of the hole expansion test was shown in Figure 1. The cone angle of the punch was 60 degrees. Punch speed of 90 mm/min and blank holder force of 60 kN were employed. During the hole expansion test, penetration force and penetration depth were recorded. Hole Expansion Ratio (HER) of the DP steel sheets of different conditions were calculated by Eq. 1.

$$HER(\%) = \left(\frac{d_f - d_h}{d_h} \right) \times 100 \quad (1)$$

Where d_h is the initial diameter of hole and d_f is the expanded hole diameter.

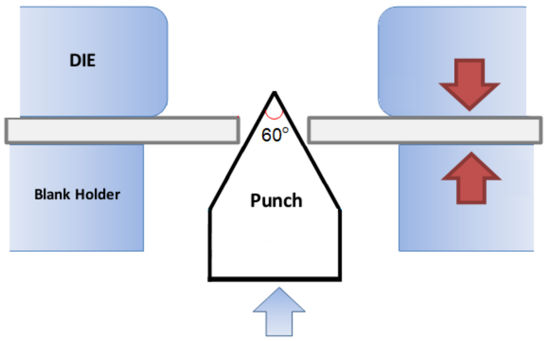

Figure 1: Schematics of hole expansion test.

Results and Discussion

Microstructures

Microstructures of the investigated DP steels after various tempering conditions were investigated by LOM, as shown in Figure 2. It could be observed that resulted microstructures of all tempered DP steels contained ferrite, martensite and fine carbides. Before tempering, the DP steels exhibited 35% martensite phase fraction. Thus, carbon content in martensite could be calculated to be 0.29 wt% by using rule of mass balance. In case of tempering at the temperatures of 200ºC and 300ºC for 5 minutes, obtained DP microstructures were similar to the DP steel without tempering, as seen in Figure 2c and 2d. Since tempering time was relatively short, no noticeable structure change occurred. By tempering at the temperature of 400ºC for 5 minutes, more carbon diffusion from martensite took place and resulted in tempered martensite including fine carbide (Fe_3C) and ferrite (α-Fe), as depicted in Figure 2e that was according to Anazadeh et al.[8] Additionally, the fine carbides were observed in both ferrite and martensite, as shown in Figure 3d and 3e. Generally, at lower temperature saturated carbon in ferrite precipitated out due to aging effect. When the DP steel was tempered at 200°C with longer holding time of 60 minutes, martensite character was altered because of more carbide precipitation, as observed in Figure 3b. The diffusion of carbon atoms increased by increasing tempering time and temperature. The same manner was found for the DP steel with tempering at 400°C for 5 minutes.

Tensile properties

Effect of tempering temperature was firstly examined by tensile test. Three different temperatures of 200ºC, 300ºC and 400ºC with a holding time of 5 minutes were considered. The obtained stress-strain curves from different tempering temperatures were compared and illustrated in Figure 4. It could be seen that the DP steel without tempering exhibited continuous yielding behaviour. The continuous yielding was observed as well for the DP samples tempered at the temperature of 200ºC and 300ºC. This continuous flow character of the DP steels was due to interaction between soft ferrite and hard martensite and high dislocation density in ferrite. The dislocations were produced by enlarged martensite volume during phase transformation from austenite to martensite.[17] In case of the tempering temperature of 400ºC, considerable yield point was found. At sufficient temperature interstitial solute carbon atoms diffused to dislocations generated during phase transformation.[8,9] Stress-strain curve of the DP steel without tempering was highest. For the tempered DP steel stress-strain curves became lower with increasing temperature. Yield Strengths (YS) of the samples tempered at 200ºC and 300ºC were slightly increased because of diffusion of carbon atoms causing dislocation pinning and formation of carbides in the martensite and ferrite.[10] Otherwise, for both tempering temperatures, Ultimate Tensile Strengths (UTS) were slightly lower than that of the DP steel without tempering as depicted in Table 2. Additionally, a bit increased elongations were noticed at these temperatures. By higher tempering temperature of 400ºC, fine carbides were replaced by cementite.[9] Thus, for this temperature, strain hardening was significantly decreased resulting in a much lower UTS value, since martensite was softened. The matrix structure of the tempered martensite transformed to Body Center Cubic (BCC) lattice and carbon concentration of the matrix approached that of the ferrite. Furthermore, strength difference between ferrite and the tempered martensite was reduced[8], the strength of ferrite was increased by dislocation pinning by carbon atom and fine carbide, whereas the strength of martensite was decreased by reduction of carbon saturation.[10] With higher tempering temperature, both YS and UTS values decreased and higher elongation was certainly provided. Figure 4 showed that the DP sample tempered at 400ºC had the highest elongation. Nevertheless, to evaluate ability of energy absorption of the steel during deformation, properties in term of both strength and ductility must be considered. In this work, the energy absorption capabilities of the DP steels were determined by calculating total area below the stress-strain curve.[18] In comparison, the DP steel tempered at the temperature of 200ºC exhibited the highest energy absorption capability, as given in Table 2. Thus, this temperature was taken into account for further studies.

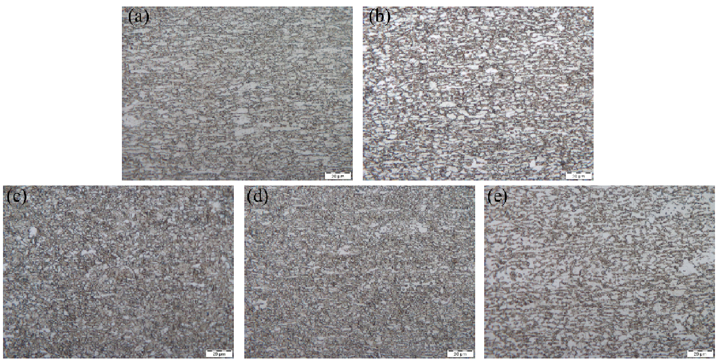

Figure 2. Optical micrographs of the investigated DP steels under conditions: (a) without tempering, (b) tempering at 200ºC for 60 minutes, (c) tempering at 200ºC for 5 minutes, (d) tempering at 300ºC for 5 minutes, and (e) tempering at 400ºC for 5 minutes

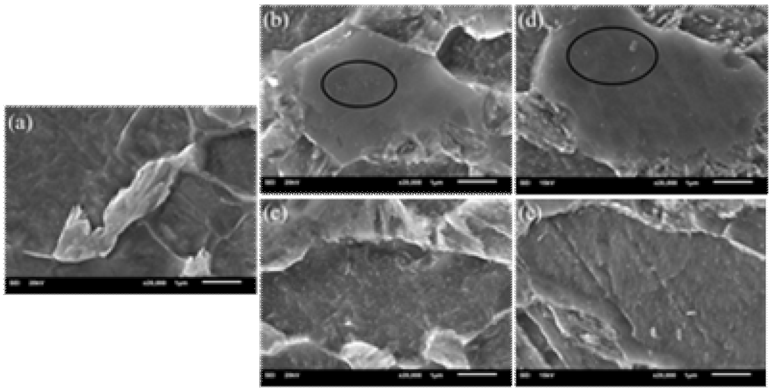

Figure 3. SEM micrographs of the investigated DP steels under conditions: (a) without tempering, tempering at 200ºC for 60 minutes of (b) martensite and (c) ferrite, and tempering at 400ºC for 5 minutes of (d) martensite and (e) ferrite.

Table 2: Determined mechanical properties and energy absorption of the investigated DP steels.

Materials	YS (MPa)	UTS (MPa)	UEL (%)	TEL (%)	Energy absorption ($MJ{\cdot}m^{-3}$)
DP steels without tempering	480	960	6.76	9.10	81.0
DP steels tempering at 200ºC for 5 min	520	885	7.26	10.32	85.1
DP steels tempering at 300ºC for 5 min	529	818	7.45	10.90	83.0
DP steels tempering at 400ºC for 5 min	486	605	7.54	11.73	65.3
DP steels tempering at 200ºC for 60 min	650	848	8.52	12.83	102.0

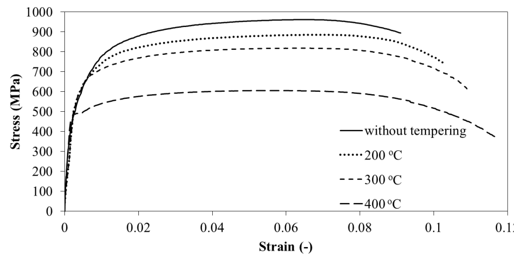

Figure 4: Determined stress-strain curves of the investigated DP steels without tempering and with tempering at different temperatures for 5 minutes.

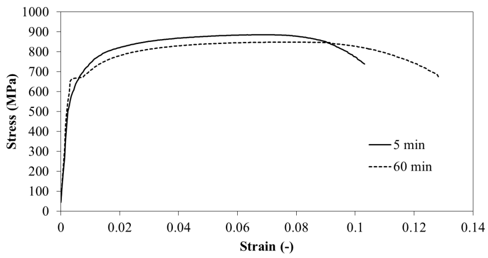

Figure 5: Determined stress-strain curve of the tempered DP steels at 200ºC for 5 and 60 minutes.

Effect of tempering time was also investigated. The stress-strain curves obtained from the DP samples tempered at the temperature of 200ºC with the holding time of 5 minutes and 60 minutes were illustrated in Figure 5. By the same manner, stress-strain response of the DP sample tempered with the holding time of 1 h showed discontinuous yielding. This was due to carbide appearance and affected precipitation strengthening. Dislocation movement was blocked by accumulation of carbon atoms and precipitation in the dilated tension field of the existing dislocations. Obviously, increased tempering time at 200°C led to both higher YS and elongation, by which UTS value slightly decreased. Therefore, energy absorption capability of the steel under this condition was highly increased, as shown in Table 2. In this work, tempering at the temperature of 200°C for 60 minutes was considered as the optimum tempering parameters for the investigated DP steel.

Bendability

Figure 6 depicted surfaces of outer bending area of the DP sample without tempering and with tempering at the temperature of 200°C for 60 minutes by different bending angles. It can be seen that the DP steel without tempering could be bent until 90º without visible crack. When the bending angle was increased to 105º, macro crack was initiated from the edge of the specimen. The crack propagated through width and thickness of the specimen when increasing bending angle to 120º. At the bending angle of 130º crack was observed on the entire outer bending area of the sample. In this area, high local tensile stress occurred. For the tempered DP steel, no macro crack was detected and the sample could be deformed up to the bending angle of 130° or even higher. The considered tempering process could be applied to provide a DP steel with better bendability.

Stretch-flangeability

Before hole expansion test, hole edge surfaces of the specimens, which were prepared by drilling, blanking and wire cutting, were examined by LOM, as shown in Figure 7. For the drilling process, hole surface was very rough and not plane-parallel. The pierced hole surface was clearly separated into two zones. The upper burnish zone was a work-hardened area and smooth. The lower fracture zone was rough and micro crack could initiate here. This micro crack possibly occurred during piercing could develop rapidly into crack when the sample was subjected to stretching or bending. Basically, a sufficient burnished depth must be set by adjusting clearance in order to keep the fractured depth to be minimal. The edge surface prepared by wire cutting was most homogeneous and flat. After the hole expansion tests, characteristics of macro crack occurred on each surface condition were investigated. All macroscopic crack appearances were similar, as illustrated in Figure 8.

The cracks initiated at the hole edge and extended through the samples along punching direction. Determined forming forces and penetration depths were shown for each edge surface condition in Figure 9. The DP samples with different edge surfaces exhibited likewise force-displacement behaviour. However, the wire cut sample provided the highest penetration depth, while the drilled sample the lowest one. Subsequently, engineering strain in tension mode was defined by HER, which was comparable with the total elongation from tensile test.[16] The HER values of the DP steels with and without tempering were calculated for each surface conditions and compared in Figure 10. The HER value was directly related to the surface condition or prior damage of the sample before testing. If more prior damage or stress concentration being present at the hole edge, HER value will be lower. The similar tendency was found for both DP steels with and without tempering. In case of pierced specimens, hole edge surface was less rough than drilled specimens that led to higher HER value. The samples with wire cut hole surface showed the largest HER value of almost 100%. Nevertheless, wire cut process is not appropriate for industrial application. Thus, blanking process must be optimized in order to obtain an acceptable hole edge surface and to achieve entire formability of the DP steel. However, for all surface conditions, the HER values of the DP steels with tempering were higher than those of the DP steels without tempering that was related to the bendability.

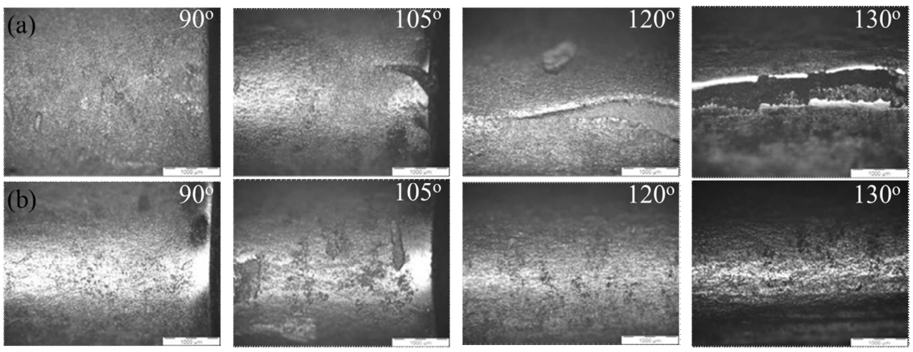

Figure 6. Bending surfaces at different bending angles of the DP steels (a) without and (b) with tempering at the temperature of 200°C for 60 minutes.

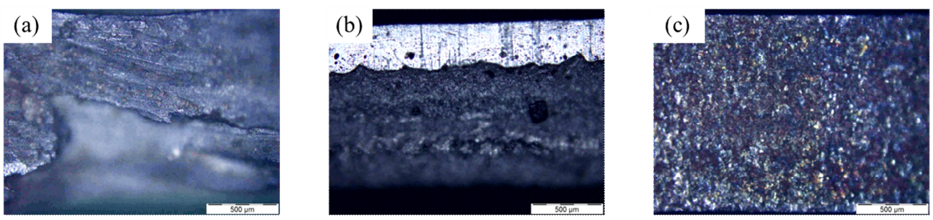

Figure 7. Hole edge surface prepared by (a) drilling, (b) piercing and (c) wire cutting.

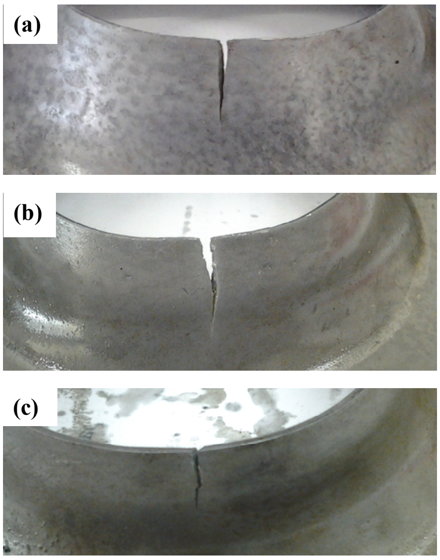

Figure 8. Macroscopic crack characteristics after hole expansion test of the DP samples prepared by (a) drilling, (b) blanking and (c) wire cutting.

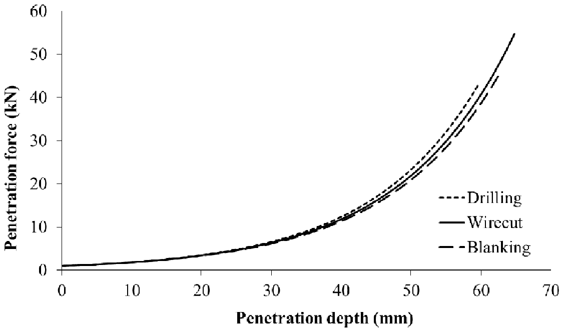

Figure 9. Relationship between penetration force-and penetration depth of the tempered DP steels with different surface conditions.

Conclusions

Effect of tempering on mechanical properties of the DP steels produced by intercritical annealing was investigated. In this work, the DP steels were tempered at the temperatures of 200°C, 300°C and 400ºC for 5 minutes and 60 minutes. The LOM analysis and tensile tests were carried out for the examined steels. It was found that microstructure of the tempered DP steels consisted of martensite islands dispersed in ferrite matrix with some carbide precipitations. Continuous yielding of the tempered DP steels was observed until the tempering temperature of 300ºC by shorter holding time. At higher temperature than 300°C distinct yield point occurred. For the tempering temperatures of 200°C and 300°C, the YS slightly increased, but the UTS slightly decreased. By higher temperature, the YS and UTS significantly decreased, whereas elongation became larger. Longer tempering time of 60 minutes led to definitely higher elongation and small alteration of strength. Therefore, the DP steels tempered at the temperature of 200ºC for 60 minutes exhibited the highest energy absorption ability. Additionally, hole expansion tests were performed for the DP steels with different surface conditions of the hole edge. The tempered DP steels significantly provided the better bendability and stretch-flangeability. It was also found that wire cut sample exhibited the highest HER value. The pierced sample gave a lower stretch-flangeability. The blanking process must be improved for obtaining an optimum material usage.

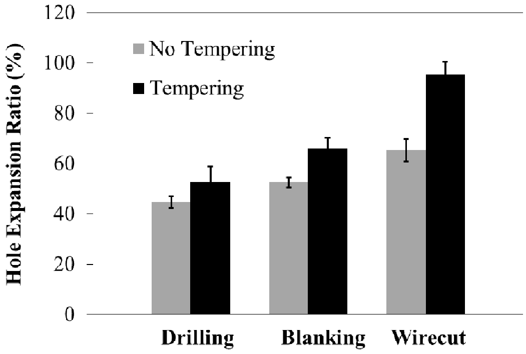

Figure 10. Determined hole expansion ration of the DP steels having different surface conditions for with and without tempering.

Acknowledgement

This research has been financially supported by National Metal and Materials Technology Center, Thailand (MTEC), Office of the Higher Education Commission, the Thailand Research Fund (TRF) and King Mongkut's University of Technology Thonburi (KMUTT) (MRG5580219).

References

1. Kadkhodapour, J., Butz, A., Ziaei-Rad, S. and Schmauder, S. (2011). A micro mechanical study on failure initiation of dual phase steels under tension using single crystal plasticity model. *Int. J. Plas.* **27(7)** : 1103-1125.

2. Prawoto, Y., Fanone, M., Shahedi, S., Ismail, M.S. and Wan Nik, W.B. (2012). Computational approach using Johnson-Cook model on dual phase steel. *Comput. Mater. Sci.* **54(1)** : 48-55.

3. Vajragupta, N., Uthaisangsuk, V., Schmaling, B., Munstermann, S., Hartmaier, A. and Bleck, W. (2012). A micromechanical damage simulation of dual phase steels using XFEM. *Comput. Mater. Sci.* **54** : 271-279.

4. Uthaisangsuk, V., Prahl, U. and Bleck, W. (2009). Characterisation of formability behaviour of multiphase steels by micromechanical modeling. *Int. J. Fracture.* **157(1-2)** : 55-69.

5. Ramazani, A., Mukherjee, K., Quade, H., Prahl, U. and Bleck, W. (2013). Correlation between 2D and 3D flow curve modelling of DP steels using a microstructure-based RVE approach. *Mater. Sci. Eng., A.* **560(1)** : 129-139.

6. Ramazani, A., Mukherjee, K., Schwedt, A., Goravanchi, P., Prahl, U. and Bleck, W. (2012). Quantification of the effect of transformation-induced geometrically necessary dislocations on the flow-curve modelling of dual-phase steels. *Int. J. Plasticity.* **43** : 128-152.

7. Bag, A., Ray, K.K. and Dwarakadasa, E.S. (1999). Influence of martensite content and morphology on tensile and impact properties of high-martensite dual-phase steels. *Metall. Mater. Trans. A.* **30A(5)** : 1193-1202.

8. Anazadeh, S.A. and Kheriandish, S.H. (2012). Affect of the tempering temperature on the microstructure and mechanical properties of dual phase steels. *Mater. Sci. Eng.* **532(1)** : 21-25.

9. Gündüz, S. (2009). Effect of chemical composition, martensite volume fraction and tempering on tensile behaviour of dual phase steels. Mater. Lett. 63(27) : 2381-2383.

10. Kamp A., Celotto S., Hanlon D.N., 2012. Effects of tempering on the mechanical properties of high strength dual-phase steels. *Mater. Sci. Eng., A.* **538(1)** : 35-41.

11. Rèche, D., Besson, J., Sturel, T., Lemoine, X., Gourgues-Lorenzon, A.F. (2012). Analysis of the air-bending test using finite-element simulation : Application to steel sheets. *Int. J. Mech. Sci.* **57(1)** : 43-53.

12. Kaupper, M. and Merklein, M. (2013). Bendability of advanced high strength steels - A new evaluation procedure. *CIRP Ann.- Manuf. Techn.* **62(1)** : 247-250.

13. Zadpoor, A.A., Campoli, G., Sinke, J. and Benedictus, R. (2011). Fracture in bending - The straining limits of monolithic sheets and machined tailor-made blanks. *Mater. Des.* **32(3)** : 1229-1241.

14. Dünckelmeyer , M., Karelová, A., Krempaszky, C. and Werner, E. (2009). Instrument hole expansion test. *Proceedings of International Doctoral Seminar*. Slovakia : Smolenice Castle.

15. Sartkulvanich, P., Kroenauer, B., Golle, R., Konieczny, A. and Altan, T. (2010). Finite element analysis of the effect of blanked edge quality upon stretch flanging of AHSS. *CIRP Ann.- Manuf. Techn.* **59** : 279-282.

16. Chung, K., Ma, N., Park, T., Kim, D., Yoo, D. and Kim, C. (2011). A modified damaged model for advanced high strength steel sheets. *Int. J. Plast.* **27(10)** : 1485-1511.

17. Sodjit, S. and Uthaisangsuk, V. (2012). Microstructure based prediction of strain hardening behaviour of dual phase steels. *Mater. Des.* 41(1) : 370-379.

18. Ramazani, A., Schwedt, A., Aretz, A., Prahl, U. and Bleck, W. (2013). Characterization and modelling of failure initiation in DP steel. *Comp. Mater. Sci.* **75** : 35-44.