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Strain Hardening Behavior Characterization of Dual Phase Steels

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ABSTRACT

The requirements for higher passenger safety, improved fuel economy and weight reduction in automobile industry necessitates the usage of advanced high strength steel (AHSS) grades. Dual phase (DP) steels are the most widely used one among AHSS. DP steels become increasingly popular, since they provide a combination of sufficient formability at room temperature and tensile strength over 1000 MPa. The current standards for DP steels only specifies yield and tensile strength. Steels from various producers have considerably different composition and microstructure; however they still have the same grade name. Combined with the inherited heterogeneous microstructure, those steels exhibit different strain hardening behavior. The aim of this study is to evaluate the strain hardening behavior of DP800 steels, obtained from different vendors and thus having different compositions and microstructures. The strain hardening behavior was characterized with tensile tests performed along rolling and transverse directions. The microstructure has been characterized with optical and scanning electron microscopes. The martensite fraction, grain size of ferrite and chemical composition has been correlated to the strain hardening behavior. The results show that the steel with more micro-alloying addition has finer ferritic grain size, which cause higher initial strain hardening rate. The steel with higher Mn and Cr has higher martensite fraction, which cause strain hardening rate to be higher at higher strain levels.

Keywords:
Dual phase steels, hardening behavior, alloying design

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INTRODUCTION

Dual phase (DP) steels have been continuously used in automotive industry for decades. Due to the necessity of light-weighting, DP steels have been served as a good solution for the automotive industry and more specifically for the body design engineering. The production of A-pillar, B-pillar, and bumper like automotive components are generally made up of DP steels. DP steels typically have high ultimate tensile strength (590-1400 MPa) due to the presence of martensite; combined with low initial yield strength (enabled by ferritic matrix), high early-stage strain hardening, and macroscopically homogeneous plastic flow (due to the absence of Luder's bands). These features render DP steels ideal alloy systems for automotive-related sheet forming operations [1, 2].

DP steels are basically composed of a ferritic-martensitic microstructure as seen in Fig. 1, usually involving some alloying elements as well. Although the term dual phase refers to the predominance of two phases, ferrite and martensite, small amounts of other phases, such as bainite, pearlite, or retained austenite, may also be present [3]. Thus, the parameters such as the fraction of two basic phases, alloying design, average grain size, distribution of the phases and etc. directly influence the overall mechanical behavior. In other words, different grades of DP steels can be obtained by altering these parameters with a high precision control. The mechanical properties of DP steels can be enhanced by changing the amount of martensite in the structure, by carrying out inter-critical annealing followed by water quenching. The amount of martensite in DP-steel depends on the inter-critical annealing temperature in the ferrite plus austenite region. Different amounts of martensite in a dual phase steel, which determines the mechanical properties, can be produced by inter-critically annealing in the range of 760°C - 840°C for different holding times of 2 to 6 minutes, followed by water quenching [4].

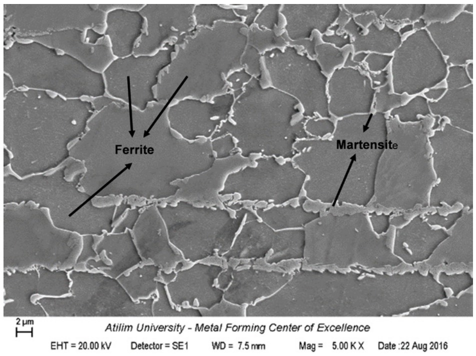

Figure 1. A representative microstructure of a DP steel, obtained by scanning electron microscope (SEM)

As a result of this remarkably sophisticated thermo-metallurgical process including specific rolling constraints, steelmakers have various individual solutions. Furthermore, steelmaker could employ different production strategies and methods to obtain dual phase microstructure either. In general, there exists three commercial production methods of dual-phase steels. These are (a) the hot-rolled approach, where the dual phase microstructure is developed during the conventional hot-rolling cycle by careful control of chemistry and processing conditions., (b) the continuous annealing approach, where hot or cold rolled strip is uncoiled and annealed intercritically to produce the desired microstructure and (c) the batch annealing where the hot or cold rolled material is annealed in the coiled condition [5]. It is the fact that this variety of production methods in general combined with the lack of a detailed standard for DP steels. The consequence is the existence of different microstructure and strain hardening behavior under the same grade name. Even some steelmakers have some DP grades with "Low Yield Strength" and "High Yield Strength" options [6]. Therefore, in this contribution the different hardening behaviors of two specific DP steel is investigated aiming to correlate this behavior with both specific micro-structures. Such correlations between macro-mechanical properties with microstructural characteristics like phase composition, texture and etc. would definitely contribute to define a reference volume element (RVE) for any finite element modeling. For instance, Darabi et al showed the effects of martensite phase distributions on the mechanical properties of DP800 and DP980 steels by 2D and 3D micro-mechanical modeling. The micro-mechanical models resulted in successful predictions of the flow curve and even the initial yielding of the ferrite phase compared to experimental studies [7]. Huang et al, also studied on the RVE modeling of DP 800 steel by means of point interpolation method. The proposed model is capable of predicting the effects of grain sizes of ferrite and martensite phases on the hardening behavior [8]. As aforementioned, the authors would like to discuss the fundamental correlations between the hardening and the microstructural properties in this study. The detailed RVE modeling of DP steels with mesoscopic micromechanical modeling approach is intended to be treated as a future work.

EXPERIMENTAL STUDIES

Within the scope of this project two commercially available hot rolled DP steels of 2 mm thickness (DP-800) were compared regarding their strain hardening behavior. It should be noted that those DP steels have indentical strength levels. The efforts focused on mechanical comparison performed by means of tensile testing which is being assisted by the detailed microstructural analysis. In order to determine the representative volume element (phase composition, average grain size and etc.) SEM and quantitative metallographic techniques were employed. As an another comparison criteria the chemical compositions of two different DP800 steels were determined by optical emission spectroscopy. Since the alloying solutions for DP steels may alter among steelmakers, the strain hardening behavior may also be influenced by the weight fraction of the specific alloying elements.

CHEMICAL COMPOSITION

Chemical compositions of the samples were determined via Bruker Tasman Q4 optical emission spectrometer (OES). The RD-TD surfaces of the samples were carefully ground with 120 grit (ANSI) emery papers using a belt grinder, before the OES measurements. The chemical compositions of the samples are given in Tables 1 and 2.

The chemical composition of the Sample-2 is relatively richer in C, Mn, Cr compared to Sample-1. Those ele-

Table 1. Chemical composition of sample-1 (in weight percent)

C	Si	Mn	Cr	Mo	Al	Nb	V	Co	P	S	Ca
0.12	0.194	1.549	0.035	0.0091	0.032	0.016	0.015	0.013	0.0073	0.0026	0.0034

Table 2. Chemical Composition of Sample-2 (in weight percent)

C	Si	Mn	Cr	Mo	Al	Nb	V	Co	P	S	Ca
0.145	0.208	1.986	0.258	0.015	<0.001	0.006	0.0051	0.0052	0.018	<0.0003	0.00013

ments retard diffusional transformations, and hence make martensite transformation easier. On the other hand, the amounts of Nb and V (i.e. micro-alloying), as well as Co are higher in Sample-1.

TENSILE TESTS

Tensile tests were performed on Zwick/Roell Z300 Machine (load cell capacity 300 kN) using standard tensile test specimens conformed to ISO 6892-1. The elongations were recorded by extensometer which was attached to the Zwick machine. The extensometer used was class 0.5 type. By means of the extensometer the elongations of the specimens could have been recorded with a 100 Hz frequency. After performing the tensile tests, data processing studies have been completed, for this purpose specific MatLab scripts were created. The flow curves were obtained by plotting true plastic strain versus true stress curves, as seen in Figs. 2 and 3. Furthermore, in order to observe the strain hardening behavior, (which can be totally linear or not) logarithm of true stress versus logarithm of true strain values were also plotted, as seen in Figs. 4 and 5. Due to the fact that martensite and ferrite have to yield at different stress states, normally there should exist a non-linearity in the strain hardening exponent "n". The data observed within this study correspond with the data in the literature. A small amount of non-linearity could be more easily seen in Figs. 4 and 5.

As it could be observed in Figs. 4 and 5, the here investigated two DP800 steels have different strain hardening behavior. Sample 1 shows non-linearity at higher strain levels, whereas sample 2 at lower strain levels. This trend is same among the tests performed among the transverse direction. The non-linearity in Figs. 4 and 5 indicate that the flow curve is deviating from the Hollomon Law (power law). Discontinuous yielding, changes in stress and strain partitioning can cause this non-linearity. In other words, "n" (strain hardening exponent) exhibits specific variation with increasing strains for two DP steels. For further investigation of the strain hardening behavior, Kocks-Mecking plots are created. Kocks and Mecking presented a novel way of depicting the stress-strain curves namely, by plotting the work hardening rate (θ) against stress (σ); where the work hardening coefficient is given as

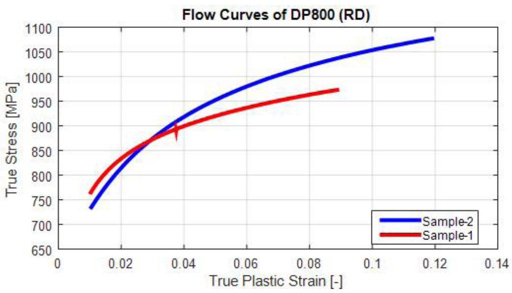

Figure 2. Flow curves in rolling directions

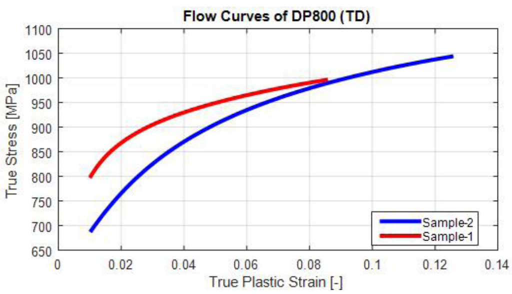

Figure 3. Flow curves in transverse directions

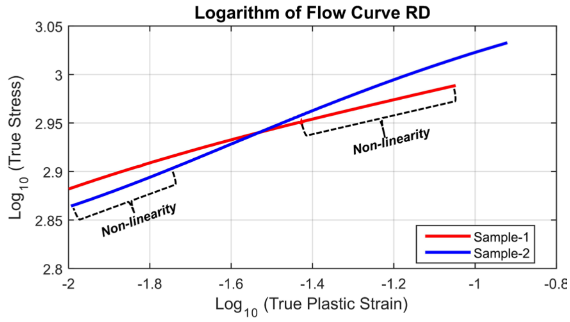

Figure 4. Logarithm of flow curves in rolling direction

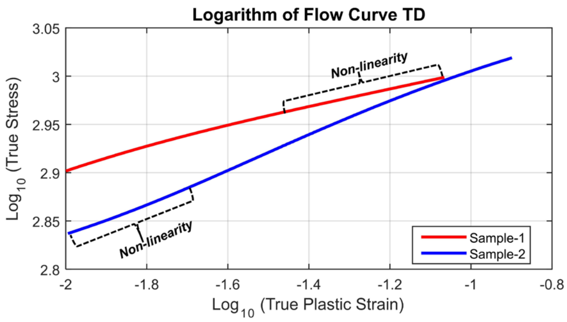

Figure 5. Logarithm of flow curves in transverse direction

$$\theta = \left.\frac{\partial \sigma}{\partial \varepsilon}\right|_{\dot{\varepsilon},T} \qquad \text{(A1)}$$

This plot is very commonly referred to as the "Kocks-Mecking" plot [9].

In order to plot Kocks-Mecking curves, differentiation on the flow curve is necessary. This task is accomplished by taking the numerical derivative via "diff" command of MatLab software. As it is a well-known fact that numerical derivative approach is fairly sensitive to the noise level in experimental data. To overcome this problem before taking numerical derivative, data filtering is engaged. The possible data filtering algorithms were all performed to make a meaningful comparison among them. By means of this comparison, "moving average filtering" is found to be the most proper one as can be seen in Fig. 6. After applying the moving average filtering of the raw data, the Kocks-Mecking curves of the present DP800 steels were determined for tests

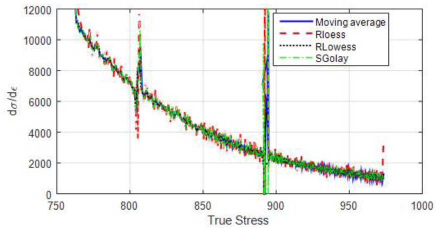

Figure 6. Comparison for different filtering algorithms

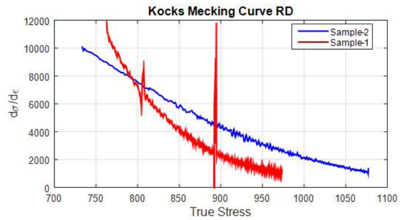

Figure 7. Kocks Mecking curves for tests along rolling direction

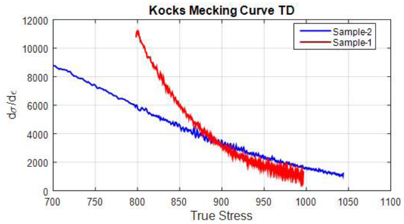

Figure 8. Kocks Mecking curves for tests along transverse direction

among rolling and transverse directions, and shown in Figs. 7 and 8. The Kocks-Mecking curves of both directions exhibit the same trend; sample 1 shows higher initial strain hardening but it decays faster. It should also be noted that the strain hardening rates along rolling and transverse directions are almost the same, the differences in those values are less than 10%.

MICROSTRUCTURAL ANALYSIS

The microstructural analysis of the samples were performed along the RD-ND section, using optical and scanning electron microscopes. In order to obtain relief-free,

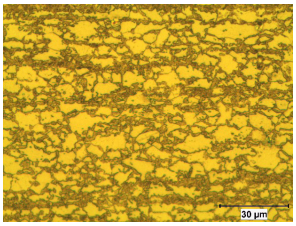

Figure 9. Optical micrograph of Sample-1

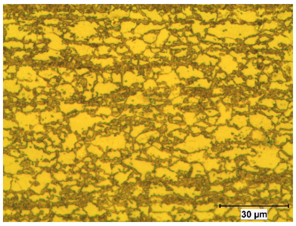

Figure 10. Optical micrograph of Sample-2

artifact-free surfaces samples were ground mechanically by 320 and 500 grit (ANSI) SiC grinding papers and then polished mechanically by conventional 9 µm, 3 µm, 1 µm diamond pastes and finally with 0.05 µm-diameter colloidal silica particles. Afterwards, the samples were etched with 2% Nital solution as well as with the method of LaPera [10]. The optical micrographs of Sample-1 and 2, taken under bright field illumination, are shown in Figs. 9 and 10, respectively. In both samples the martensite islands decorate the grain boundaries of ferrite; moreover, martensite is present in the form of bands, elongated along the rolling direction (RD). This second morphological form is more predominant in Sample-2. Using the optical micrographs, the volume fraction of martensite as well as the average grain size of ferrite were determined, and shown in Fig. 11. For each sample, the quantitative metallographic analysis were performed on randomly selected 3 different fields. For grain size determination, at each field 5 horizontal (RD) and 5 vertical (ND) lines were used to determine the grain size values. In both samples, since ferrite grains are elongated along rolling direction (RD),

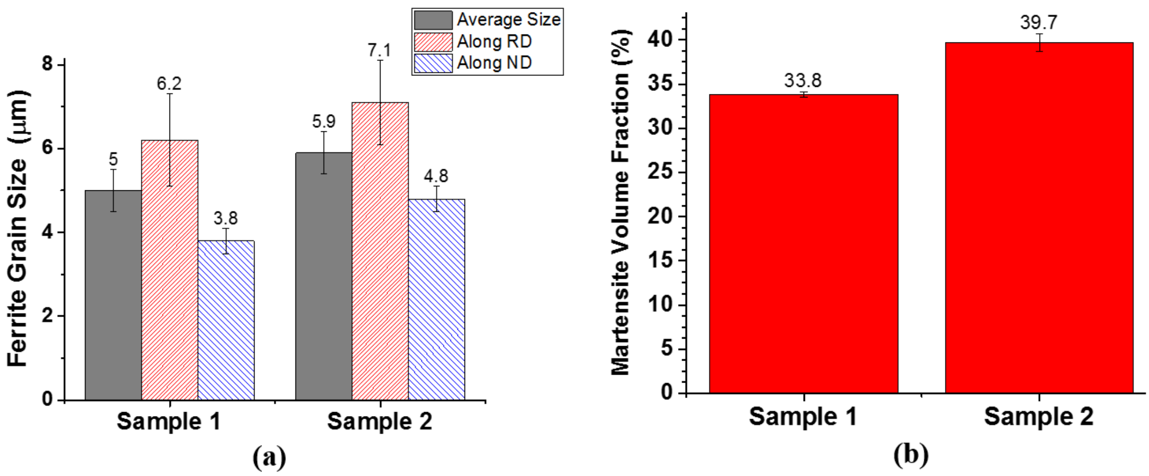

Figure 11. Results of quantitative metallographic analysis showing (a) average grain size of ferrite, and (b) volume fraction of martensite

K. Davut et al. / Hittite J Sci Eng, 2018, 5 (4) 301–306

their intercept lengths are higher along this direction. The standard deviations in both phase fraction and average grain size values are quite low, indicating the selection of correct magnification and representative field-size for the quantitative metallographic analysis.

RESULTS AND DISCUSSION

Conducted tests clearly reveal that DP-800 steels from different manufacturers have significant differences in microstructure and mechanical properties; as well as in alloying concepts. This clearly indicates the importance of processing route in production of DP steels.

The most obvious observations that can be made from the flow curves is that those steels have significantly different yield stresses and ductility, especially in the transverse direction. Because of that, significant differences are also expected in planar and normal anisotropy values.

Control of strain hardening is probably the key for development of high strength steels for metal forming application. Large strain hardening rates have an impeding effect on localization and associated damage processes. Most of the metals have a decaying hardening rate which limits the failure strain due to saturation of hardening. A strong and formable steel must have a high strain hardening together with a large saturation strain. Although both samples have approximately the same saturation strain according to Kocks-Mecking plot, the evolution of strain hardening is quite different. Sample-1 has a larger initial hardening rate which decays exponentially in a shorter strain range. In contrast, Sample-2 has a relatively smaller initial hardening rate with a smaller decay rate. Significantly higher uniform elongation in Sample-2 is probably associated with this contrast.

Aside from investigation of strain hardening behavior, Kocks-Mecking plots are also useful for selection of most appropriate hardening law for the simulation of metal forming processes. In this study, they indicate a power law hardening for Sample-1, while an exponential-saturation type hardening law seems to be more appropriate for Sample-2.

The microstructural differences of the samples correlate well with the mechanical properties. Both the martensite content and the UTS of Sample-2 is higher. This sample contains more C, Mn, Cr and Mo all of which retards bainite transformation and hence making the formation of martensite easier. On the other hand, the ferritic matrix of Sample-1 contains smaller grains. Moreover, this sample contains more micro-alloying elements than Sample-2. Due to those characteristics, the initial hardening rate of Sample-1 is higher; since the strain is predominantly partitioned into ferrite at earlier stages of deformation [11]. At later stages, localized strain fields in ferrite appear, and the fraction and strength of martensite, which is directly related to carbon content, influence the strain hardening behavior. Therefore, at second stage of deformation Sample-2 shows higher strain hardening.

CONCLUSION

The following conclusions can be derived from the presented results:

- DP-800 steels from different steel producers have significantly different mechanical and microstructural properties based on chemical composition. Additionally, it is thought that possibly different manufacturing routes have an effect on the aforementioned properties.
- Kocks-Mecking plots indicate the differences in the strain hardening behavior of the DP steel. The sample with a smaller hardening decay rate has a significantly large uniform elongation as suggested by the theory.
- The fraction of martensite, grain size of ferrite as well as the micro-alloying elements correlate well to the differences in the strain hardening behavior of the DP steels investigated.
- The sample with high initial-strain hardening has smaller ferrite grains as well as more micro-alloying elements. Moreover, this sample has slightly less martensite fraction, which may cause more strain to be partitioned into ferrite.

The here presented results agree well with the previous studies on identical steel grades. Further investigations are necessarily to clarify underlying microscopic mechanisms. More detailed mechanical characterization including determination of damage parameters, yield surface and its evolution is ongoing together with detailed microstructural characterization. This information will be coupled with mesoscopic computer simulations in the future.

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REFERENCES

1. Taşan, CC. et al. An Overview of Dual–Phase Steels: Advances in Microstructure–Oriented Processing and Micromechanically Guided Design. Annual Review on Material Research 45, pp. 19–40, 2005.
2. Billur E, et al. New Generation Advanced High Strength Steels: Developments, Trends and Constraints. International Journal of Scientific and Technological Research 2, pp.50–62, 2016.
3. Speich GR. Dual Phase Steels, ASM International, ABD,

1990.

4. Singh RR, et al. Comparison of Mechanical Properties of Medium Carbon Steel with Dual Phase Steel. International Journal of Mechanical Engineering 4, pp. 1–8, 2008.
5. Tsipouridis P. Mechanical Properties of Dual Phase Steels. Ph.D. Thesis, Technische Universitat München, Germany, 2006.
6. http://automotive.arcelormittal.com/repository2/About/Automotive/201404_datasheet-dualphase.pdf Date:01.03.2017
7. Darabi A Ch, et al. Micromechanical Analysis of Two Heat-Treated Dual Phase Steels: DP 800 and DP 980, Mechanics of Materials 110, pp. 68–83, 2017.
8. Huang TT, et al. Strain-hardening Behaviors of Dual Phase Steels with Microstructure Features, Material Science and Engineering A. 672, pp. 88–97 2016.
9. Parasad GVSS. An Improved Dislocation Density Based Work Hardening Model for Al-Alloys. Master Thesis, RWTH Germany, 2007.
10. LePera F. Improved Etching Technique for the Determination of Percent Martensite in High-Strength Dual-phase Steels, Metallography 12, pp. 263–268, 1979.
11. Taşan CC, et al. Integrated Experimental-simulation Analysis of Stress and Strain Partitioning in Multiphase Alloys. Acta Materiala 81, pp. 386–400, 2014.