Effects of DP steel microstructure on the disappearance of discontinuous yielding

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Abstract. Although in terms of quality is not as high as TRIP steel, DP steel has been developed as an option to meet the minimum standard industrial requirement for automotive. Steel development for automotive material leads to possess high strength without suffering its ductility and weld ability, in addition there is no appearance of discontinuous yielding that cause stretcher strain marking. The change of micro structure as a result of the intercritical annealing process not only increases the strength of Dual Phase Steel, but also eliminates the discontinuous yielding. The phenomenon of discontinuous yielding is no longer appear in Dual Phase Steel which heating time on intercritical annealing process more than 1 minute, the minimum time is equal to the disappearance of discontinuous yielding. The phenomenon of upper yield point and discontinuous yielding on carbon steel is strongly influenced by the magnitude of the stress acting on the Ferrite phase to move the dislocation of the pinned state by the interstitial atom. From the recent works gives the result that the disappearance of discontinuous yielding in Dual Phase Steel resulting from the intercritical annealing process makes Dual Phase Steel very suitable as an automotive material.

1 Introduction

Currently, the development of automotive steel with high strength, weldable and formable is answered by the development of TRIP (Transformation Induced Plasticity) Steel. Unfortunately on the commercial aspect, the TRIP production process will still facing with two major obstacles includes red scale and complicated micro-structure which are not easily resolved. Although in terms of quality is not as high as TRIP steel, DP steel has been developed as an option to meet the minimum standard industrial requirement. The above obstacles has not occurred on DP steel production process. The main concern of DP steel comparing with TRIP steel is the total elongation, while the uniform elongation is not significantly different. Considering the automotive industry requirement, the uniform elongation is more important factor in forming processes.

Steel development for automotive material leads to development “Formable-Weldable High Strength Steel” possessing high strength without suffering its ductility and weld ability. In addition there is no appearance of discontinuous yielding that cause stretcher

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strain marking, the unwanted metallurgical phenomenon during metal forming process upon automotive body production. The phenomenon of discontinuous yielding is also known as Luder's band which resulted defects in the forming process as slip bands on the surface of the plate, and it is known as stretcher strain marking. Intercritical annealing process was chosen to modify microstructure of an ordinary commercial C-Mn Steel. On her research works, Pritadewi Basoeki (2017) found that intercritical annealing process is the simplest and best compared to cyclic heat treatment and interrupted cooling in transforming C-Mn Steel into Dual Phase Steel for automotive material [1,2]. Disappearance of discontinuous yielding, having high strength and high impact strength and isotropic as well make the Dual Phase Steel meet for the automotive material. The microstructure of Dual Phase Steel in the form of Ferrite surrounded by Martensite is obtained by heating C-Mn Steel until it reaches the Ferrite and Austenite regions in the Fe-Fe₃C phase diagram, held for in certain time at that temperature and then cooled by a rapid cooling.

2 Literature Review

Dual Phase Steel is a group of high strength steel (HSLA) with carbon content between 0.05-0.2%; which generally contain Mn and Si in amounts between 1-1.5% and other micro-alloyings. Tensile strength of Dual Phase Steel can reach 1 GPa in laboratory scale. In addition to having high strength, Dual Phase Steel with low carbon content has unique characteristics in the presence of discontinuous yielding phenomenon. The addition of Mn in a sufficiently large amount of between 1-1.5% is required for the formation of 20% Martensite after rapid cooling, in addition to maintain its welding ability.

At the beginning of plastic deformation certain types of steel will have the phenomenon of discontinuous yielding which is the beginning of another phenomenon called Luder's band. In the automotive industry, the formation of Luder's band should be avoided as much as possible because it will result a surface defect on the plate, as shown in Figure 1. If the defect occurs it will be very difficult or even impossible to remove, more worse again this defect will still appear even though the plate has been painted. This phenomenon is studied in this works because as the initial material of C-Mn Steel shows the occurrence of stretcher strain marking. Anticipation needs to be done to prevent the occurrence of it in Dual Phase Steel.

![Fig. 1. Stretcher Strain Marking on Low Carbon Steel Plate [3].](image)

In the continuous yielding phenomenon, the increase in stress (load) occurs immediately after the deformation enters the plastic region. But not so in the discontinuous yielding, the
plastic deformation region begins with a drastic and sudden drop of stress (load). This discontinuity creates a clear boundary between the elastic and plastic regions. The boundary point is indicated by UYP (upper yield point). After a sudden drop in stress (load), then plastic deformation occurs at a relatively constant load called the LYP (lower yield point). At a constant load the plastic deformation that occurs is called the yield point elongation, YPE. At the same time Luder's band is formed and grows.

According to D. Hull (1975), the stress drop after UYP will occur when the following three conditions occur:

1. The initial dislocation density is small,
2. The increase in working stress is not followed by an increase in high dislocation movement,
3. Multiplication of dislocations happens rapidly.

The phenomenon of discontinuous yielding is the result of the interaction of dislocations with the interstitial (carbon or nitrogen) atoms that are contained in the Ferrite phase. When the carbon atoms in the Ferrite phase get a chance to diffuse it will move toward the position shown in Figure 2. Positive side dislocations will result in a compressive stress field on the upper part of the AB line and the tensile stress below it. Since interstitial atoms also cause a compressive stress field, the most stable place for interstitial atoms is just below the CD line (extra half plane). The interaction that resulted in a dislocation locked by a carbon atom, this is called interstitial pinned dislocation. To move a dislocation unlocked by an interstitial atom requires a smaller (force) stress than when the dislocation is locked. The amount of additional stress (force) to move the dislocation from its locked position can be approached the interaction energy between the interstitial atoms and the dislocations as followed:

\[ U = \frac{A \sin \theta}{r} = -\frac{Ar_o}{r^2} = \frac{Ar_o}{x^2 + r_o^2} \]  

(1)

with A constant of about 1.84x10^{-29} Nm².

![Fig. 2. Carbon Atom Intersitial in Positive Edge Dislocation [4].](image)

In carbon steel, the multiplication of dislocations or the creation of new dislocations in the Ferrite phase occurs rapidly due to Ferrite having been in high stress of UYP. This condition is the beginning of the formation of Luder's band. The propagation of Luder's band at the grain is in fact a dislocation multiplied or created by UYP which moving in its sliding plan to the grain boundary and creating a new dislocation on its adjacent grain. The
dislocations created on the adjacent grains will also move to other grain boundaries. This condition repeats and spreads throughout the grains and will appear as Luder's band across the surface of the tensile test specimen, in this strain stress curve the phenomenon is measured as yield point elongation. Residual stress and the dislocation density in the Ferrite is thought to cause the disappearance of discontinuous yielding in Dual Phase Steel.

3 Methodology

On this work, the Dual Phase Steels were the result of the intercritical annealing process of C-Mn Steel having a relatively low carbon and manganese content of 0.179% C and 1.199% Mn. The intercritical annealing process is intended to produce a Ferrite phase surrounded by Martensite. The intercritical annealing process is performed by heating the specimen in the intercritical region of the two Ferrite and Austenite phases at a temperature of 740ºC, maintained for a moment at that temperature and then followed by rapid cooling. Heating rate takes place at 0.5ºC/sec, while the soaking time is varied, 1 second to 15 minutes, with the aim of understanding the mechanism/kinetics of Pearlite transform into Austenite. Target to be addressed in this work is Dual Phase Steel with strength of 1000 MPa or 1 GPa and ductility 0.2. Referring to the chemical composition of C-Mn steels and from the Fe-C-1.5Mn phase diagram, it can be predicted that at 740ºC temperatures Austenite is formed around 40%. Unintentional discontinuous yielding did not appear. Characterization with an optical/electron microscope (LOM/SEM) and X-Ray Diffraction (XRD) were performed on the Dual Phase Steel generated to obtain an overview of structural changes that occurred during the intercritical annealing process related to disappearance of discontinuous yielding.

4 Results and Discussion

As previously described, the phenomenon of discontinuous yielding can be fatal to the steel plate because of the stretcher strain marking. In contrast to other types of steel, in this works obtained results indicating that Dual Phase Steel does not indicate the presence of upper yield point and discontinuous yielding.

The change of micro structure as a result of the intercritical annealing process not only increases the strength of Dual Phase Steel, but also eliminates the discontinuous yielding. Viewed from the standpoint of the steel industry this is certainly very profitable. Further metallurgical discussions of the disappearance of discontinuous yielding phenomenon in Dual Phase Steels will be discussed in more detail, due to the lack of research in this field. The possibility of reappearance of discontinuous yielding phenomenon due to strain aging will also be discussed to provide a metallurgical aspect for quality assurance of Dual Phase Steel.

The influence of the soaking time period on the intercritical annealing process on the yield phenomenon of the Dual Phase Steel is depicted in Figure 3. The phenomenon of upper yield point and discontinuous yielding is clearly appear in C-Mn Steel, whereas in Dual Phase Steel both phenomenon is still appear at soaking time of 15 seconds but with smaller yield point elongation. The phenomenon of discontinuous yielding is no longer appear in Dual Phase Steel which heating time on intercritical annealing process more than 1 minute. This finding can immediately be attributed to the perfection of Austenite formation at the intercritical annealing temperature. The process of intercritical annealing with a minimum of 1 minute soaking time has been able to produce Martensite volume fraction of 40%. The minimum time is equal to the disappearance of discontinuous yielding. The phenomenon of upper yield point and discontinuous yielding on carbon steel
is strongly influenced by the magnitude of the stress acting on the Ferrite phase to move the dislocation of the pinned state by the interstitial atom. The phenomenon also requires a very low initial dislocation density in the Ferrite phase. D. Hull, (1975) states that the phenomenon of upper yield point and discontinuous yielding will be disappeared if the following conditions are met [5]:
1. Carbon atoms are not allowed to dissolve interstitially in the Ferrite but are bond as carbides such as TiC or NbC as carried out on Interstitial Free (IF) steel.
2. Increases the amount of initial dislocation density in the Ferrite phase. This is commonly done by temper rolling.
3. Creates a compressive residual stress on the Ferrite phase so that plastic deformation or dislocation starts moving at higher stress, compare to the stress required to move dislocation from its pinned position.

In Dual Phase Steel, the first condition can not be fulfilled because steel does not contain Ti or Nb. However, the second and third conditions, increasing the dislocation density and the compressive residual stress on the Ferrite phase can easily be fulfilled. This happens by itself at the stage of the rapid cooling process from intercritical annealing temperature to room temperature. Schematically the creation of a new dislocation and residual stress on the Ferrite is indicated on Figure 4.

According to V. Bata, and E. Pereloma, (2005), Austenit transformation into Martensite with volume addition will create a strain of \( e^* = 0.0058 + 0.0045 C_\text{c} \), with \( C_\text{c} \) is the carbon content in Austenite, then the compressive stress (hydrostatic) Ferrite expressed in the equation below [6]:

\[
\sigma = \frac{2}{3} Y_0 + 2 H_0 e^* + \frac{2}{3} Y_0 \ln\left\{ \frac{E e^*}{(1-\nu)Y_0} \right\}
\]

(2)

**Fig. 3.** The Stress-Strain Curve Expresses the Effect of Soaking Time on the Intercritical Annealing Process on the Yield Phenomenon.
For Ferrite:

\[
\begin{align*}
Y_0 & = 400 \text{ (yield strength)} \\
H_0 & = 1000 \text{ (stain hardening rate)} \\
\nu & = 0.28 \text{ (Poisson ratio)}
\end{align*}
\]

When the carbon content in the Austenite ranges from 0.3 to 0.4% wt then the Ferrite will have a compressive stress of between 710 to 730 MPa. The yield strength of the Ferrite without the effect of Austenite transformation into Ferrite can be estimated from the yield strength of C-Mn Steel which is 405 MPa. The compressive stress on each Ferrite and each location on a single grain of Ferrite is certainly not guaranteed the same. It is heavily influenced by carbon content, shape and size of artensite as the second phase. Consequently the three-dimensional stress on Ferrite is not the same on the three axes, in other words the compressive stress of the ferrite is not all hydrostatic components but still contains the deviatoric component. This deviatoric stress will cause the shear stress on the Ferrite, when the magnitude exceeds the shear yield stress, the plastic shear strain will occur and create a dislocation. While the hydrostatic component will cause the Ferrite get tensile residual stress.

The result of charaterization with XRD and micro hardness measurement of the Ferrite proves the truth of the effect of the volume expansion due to the transformation of Austenite into Martensite. Figure 5 depicted FWHM increase due to the increasing of heating time in the intercritical annealing process. The longer the heating time of intercritical annealing, the Austenite becomes more fully formed and no more cementite remains. As a second phase, Austenitic volume fraction measured from the transformation result into Martensite. In addition, the longer the time at 740 ° C the more the Ferrite grains will be directly adjacent to the Austenite. At room temperature it will be seen as a Ferrite surrounded by Martensite. Consequently the compressive stress of the ferrite (due to the transformation of Austenite into Martensite) are also greater so that the dislocation density measured by FWHM will also increase. The same analogy can also be used to explain the decrease in of Ferrite lattice parameters with increasing time of intercritical annealing. The decrease of the lattice parameter is an indication that the Ferrite crystal receives a compressive residual stress. The compressive residual stress of Ferrite influenced by the perfection of Austenite formation. Characterization with XRD (lattice parameters and
FWHM) is consistent with the results of the Ferrite micro-hardness measurements. The decrease in the hardness of the heated specimens for 8 minutes to 15 minutes was more affected by larger grain diameters on the specimens heated for 15 minutes.

The discontinuous yielding phenomenon as a cause of stretcher strain marking in practice is often avoided by conducting the temper rolling process. However, the process of temper rolling is still trouble to the return of the phenomenon discontinuous yielding. In Dual Phase Steels, the disappearance of discontinuous yielding is caused by two things: increasing dislocation density and residual stress both caused by Austenite transformation into Martensite. Thus the appearance of discontinuous yielding in Dual Phase Steel should involve three aspects as follows:

1. Shrinkage of martensite to lower the residual stress stress,
2. Decrease in dislocation density in Ferrite,
3. Carbon diffusion into its stable position (below dislocation).

The dislocation density decrease in the Ferrite due to heating has also been investigated by Ali Smith, dkk., (2004). In the study stated that the decrease of dislocation density occurs at temperatures between 150°C-300°C, by dislocation annihilation and rearrangement mechanism. Thus the tempering process of Dual Phase Steel will result in the transformation of Martensite into Tempered Martensite and Transition Carbide (η dan ε), as well as decreasing dislocation density and eliminated residual stress on Ferrite. Elimination of residual stress and decreasing dislocation density will reactivate the interaction between dislocations with carbon atoms, this is what causes reappearance of discontinuous yielding. Ali Smith, dkk., (2004), Waterschoot, dkk., (2006), states that discontinuous yielding will occur when Dual Phase Steel is heated at a temperature of 150°C for 1 day (86.400 detik) [7,8].

Industrial conditions in Indonesia that still often do the storage of raw materials in the warehouse can cause problems on the reappearance of discontinuous yielding, because of the tropical climate in Indonesia. Calculations for different temperatures and times can be approximated by formulas Johnson-Mehl-Avrami (JMA). When assumed storage temperature in the warehouse of 40°C, then using the JMA equation can be estimated when discontinuous yielding will appear [7,8]. The transformation fraction reaches one when the diffused carbon has been able to decrease the Martensite lattice parameter to \( c_m/a_m = 1 \),
which means that the Martensite originally had a BCT unit cell turned back into a BCC. From the graph on Figure 8, when the storage temperature is 40°C then the fraction of transformation equal to one will occur at the same time as $10^9$ seconds. Viewed from the very long discontinuous yielding time, $10^9$ seconds or around 31 years, and when associated with the automotive production process itself, the Dual Phase Steel resulting from the intercritical annealing process is safe from the phenomenon of strain aging.

![Graph of the Fraction of Transformation Over Heating Time at 740°C.](image)

**Fig. 6.** Graph of the Fraction of Transformation Over Heating Time at 740°C.

### 5 Conclusion

The analysis of the characterization result in this work gives some important points which become the note as follows:

1. The disappearance of discontinuous yielding in Dual Phase Steel resulting from the intercritical annealing process makes Dual Phase Steel very suitable as an automotive material.
2. The disappearance of discontinuous yielding is proven experimentally and can be explained metallurgically. The presence of residual stress and increased dislocation density are factors that play a role in the disappearance of discontinuous yielding.
3. Based on the time of reappearance of discontinuous yielding, 31 years, the Dual Phase Steel is safe from the phenomenon of strain aging.

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