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Effect of Two Steps Overaging on Mechanical Properties of Tailor Rolled Blank of Dual Phase Steel

Xianlei Hu 1,2,*, Diwen Ke 1,*, Ying Zhi 1 and Xianghua Liu 3

1 State Key Laboratory of Rolling and Automation, Northeastern University, NO. 3-11, Wenhua Road, Heping District, Shenyang 110819, China; zhijing@ral.neu.edu.cn
2 Suzhou Dongbuxing Metal Material Science and Technology Company Limited, 24 Building, Yuqiao Village, Jinfeng Town, Zhangjiagang, Suzhou 215624, China
3 Research Academy, Northeastern University, NO. 3-11, Wenhua Road, Heping District, Shenyang 110819, China; liuxh@mail.neu.edu.cn
* Correspondence: hu_xianlei@263.net (X.H.); 1410193@stu.neu.edu.cn (D.K.)

Abstract: Herein, a new kind of overaging strategy: two steps of overaging for tailor rolled blank of dual phase steel (DP-TRB) was investigated. The results indicate that two steps of the overaging process is a useful way to control the mechanical properties of DP-TRB. In the premise of satisfying the requirement for the strength of DP590 grade, the total elongation can be significantly increased (3~7% in most cases). Due to the different degrees of ferrite recrystallization (differences of densities of dislocation) among the thicknesses, the obvious changes of mechanical properties among thicknesses are found. The thicknesses zones of 1.0~1.4 mm show lower strength, while the zones of 1.6~1.8 mm present higher strength. Otherwise, the high density of dislocations in samples of 1.6~1.8 mm provide more locations for Cottrell atmospheres, yield plateau occur easier. The zones with different thicknesses for one DP-TRB show two kinds of yield behaviors (continuous yield and non-continuous yield) simultaneously. The subtle C diffusion control by two step overaging leads to the quite different pinning effect of Cottrell atmospheres. Thus, the pinning effect occurs in a gradual way, and a transition state of yield behavior, which combines the characteristic of smooth curve in continuous yield and the plateau in non-continuous yield, is found.

Keywords: dual phase steel; tailor rolled blank; overaging process; mechanical properties

1. Introduction

Tailor rolled blank of dual phase steel (DP-TRB) combines the advantages of the lightweight of dual phase steel [1–3] and tailor rolled blank [4–6]. The key factor for the annealing of dual phase steel is the intercritical annealing process, which has been studied by many researchers [7–12]. The influence of intercritical temperature on DP-TRB had been investigated in previous work [13]. Besides, overaging process is also a key factor during the annealing of dual phase steel. The purpose of overaging is to adjust the state of martensite and avoid aging problem. The quenched martensite as metastable phase would decompose after a period of time, and the mechanical property alters obviously. This phenomenon is called aging, and it’s an undesired thing in steel products. Otherwise, the state of martensite plays an important role in controlling the mechanical properties of DP steel.

However, the studies of overaging process is much less than that of the intercritical annealing process. Most studies of the overaging process focus on one step overaging, where the temperature is stationary during the entire process [14–18]. This one step overaging is similar to the one step partitioning in quenching and partition (Q&P) steel [19]. According to the researches, overaging process had less influence on the mechanical properties of dual phase steel when the overaging temperature is below 300 °C. On the other hand, overaging process made great changes in mechanical properties when the
temperature is above 300 °C. However, the obvious influence in mechanical properties is always accompanied with yield plateau. The yield plateau is undesired yield behavior for followed forming. So a subtle overaging process is needed. Otherwise, the microstructure, which is made of ferrite, bainite, and martensite, gained much more elongation at expense of slight reduction in strength, result in great combination of ductility and strength, and get the attention of some researchers [20–23]. One more step of overaging, which temperature is above Ms, could form bainite in conventional dual phase (martensite and ferrite) steel, and would also show great combination of ductility and strength. Two or more steps overaging procedures were less studied, and could provide subtler control in mechanical properties. Li et.al studied the two steps overaging with a lower quenching temperature followed by a higher overaging temperature which is similar to the two-steps Q&P process [24]. It was found that two steps overaging can adjust the tensile strength with fewer effects on yield strength, and provide a more flexible strategy in controlling combination of strength and plasticity. However, two steps overaging proposed by Li includes a reheating course which is not well suitable for the normal continuous annealing furnace.

In this paper, a new two steps procedure with overaging firstly at a higher temperature then followed by a lower temperature is proposed to apply to the annealing of DP-TRB. This two steps overaging matches the continuous annealing furnace better and can provide a better-controlled method on mechanical properties of DP-TRB.

2. Materials and Methods

The raw material is a commercial dual phase steel DP590 and its chemical composition (wt%) is 0.1 C, 0.41 Si, 1.76 Mn, 0.016 P, 0.005 S, 0.04 Al and bal. Fe. The thickness of the raw material is 2 mm and the microstructure is made up of ferrite and martensite, the microstructure and mechanical properties are shown in Figure 1. The TRBs with different thickness zones were obtained by variable gauge cold rolling (single pass). Figure 2 shows the schematic process of rolling of DP-TRB. After rolling, the experimental tailor rolled blanks with different thickness zones were put into the muffle furnace (furnace had reached the setting temperature) with intercrirical temperature 800 °C and hold for 660 s. Then heated blanks were immediately quenched at 300 °C, 350 °C, 400 °C and 450 °C for 30 s, 60 s and 120 s in the salt-bath furnace (composition of salt: 50% KNO3 + 50% KNO2, and temperature of salt had reached the setting temperature), named as the step 1. When step 1 finished, the DP-TRBs were subsequently put into another salt-bath furnace with overaging temperature of 300 °C, and ensuring the total time of step 1 and step 2 is 300 s. In order to express easily, the two steps overaging process is represented by step 1 process. One step overaging which is holding temperature at 300 °C for 300 s was set as a comparison. Conclusively, all overaging processes are shown in Figure 3.

![Figure 1](image-url)

**Figure 1.** The microstructure and tensile curve of raw material: (a) microstructure, (b) tensile curve.
The steel specimens of dimension 12 mm × 10 mm (transverse direction (TD) and rolling direction (RD)) with different thicknesses were prepared from every equal thickness zone. Subsequently, the specimens were mechanically polished and chemically etched with 4% Nital. Microstructure observations by SEM (FEI QUANTA 600, FEI, Hillsboro, OR, USA) and samples of EBSD were performed on the TD-ND plane. For microstructure investigation by EBSD, the samples were further electropolished at room temperature for 25 s at 20 V using an electrolyte consisting of 400 mL ethanol and 64 mL perchloric acid. EBSD measurements were carried out using a ZEISS ULTRA 55 field-emission scanning electron microscope (FESEM) (Carl Zeiss AG, Jena, Germany) equipped with an Oxford Instruments EBSD camera and the raw data were dealt with Channel 5 software (5.0.9.0, HKL Technology Inc., Danbury, CT, USA) and the step size of EBSD is 0.1 μm. For the nanoindentation test, the test plane was also TD-ND plane, specimens were first electropolished at room temperature for 15 s at 20 V with the same polishing solution as used in the specimens of EBSD, and then followed by chemically etched with 4% Nital with 2 s. Nanoindentation tests were carried out by HYSITRON TRIBOINDENTER (Hysitron, Minneapolis, MN, USA) with max force of 2 mN. A point array of 5 rows and 5 columns whose array pitch is 5 μm was used in a specimen. Tension test specimens that were cut from equal thickness zones (TD) with a gauge length of 50 mm and gage width of 25 mm were machined. And the parallel length of specimens is 80 mm. The tensile tests were carried out at room temperature and a rate of 1 mm/min (strain rate: 0.00033 s⁻¹) with a SANS CMT5105 universal testing machine of 100 kN capacity.
3. Results
3.1. Microstructure

The microstructure of the specimens among different thicknesses overaging at 400 °C for 60 s (named as step 1) shows a great similarity as shown in Figure 4. All the specimens of this process consist of equiaxial ferrite matrix and island-like martensite (located at the ferrite boundary). Besides, some martensite islands are located inside the ferrite. The volume fraction of martensite is same for all thicknesses when considering the measuring error, and it was measured to be 30.5% ± 1.5% by Image J. The shape of martensite and the distribution of martensite are also similar for all thickness zones. This characteristic of similarity of martensite can be found among all processes. Thus the martensite volume fraction of all samples with different thicknesses and different overaging process is all around 30.5% with a similar shape and distribution.

The microstructure of DP-TRB after different annealing processes is shown in Figure 5. The classical microstructure for one step overaging is shown in Figure 5a. And Figure 5b,c,e, which step 1 time of the specimens are all 30 s, show a similar microstructure. The difference in step 1 temperature doesn’t make an obvious difference in the microstructure, the microstructure of samples look like the one step overaging in Figure 5a. As shown in Figure 5d,f, retained austenite or partial martensite decomposes when the step 1 time getting longer. Figure 5d shows some incompletely decomposed structure, and the precipitation of carbide appears. In Figure 5f, some completely decomposed structure which is from retained austenite is shown, and the original shape of island is disappeared. Thus the temperature has more influence on microstructure than time, as specimens that hold temperature at 450 °C for 60 s have a greater degree of decomposition than specimens that hold at 400 °C for 120 s. The Ms calculated by Jmatpro is 350 °C, the C concentration used in calculation is the austenite equilibrium concentration at 800 °C, this temperature is
same as the temperature of intercritical annealing. And other component content used in calculation is same as raw material. The step 1 temperature of 450 °C, 400 °C and 350 °C is above or near Ms, and located at the temperature range of bainite transformation. In this condition, some bainite generates in step 1, besides, some retained austenite at step 1 would decompose. The bainite transformation is a kind of semi-diffusion phase transformation, and the generated bainite plays a similar role as the decomposed martensite in C partition, and the decomposed austenite also shows the same characteristic. It means that the carbon will diffuse from bainite, martensite, and decomposed austenite into the ferrite. Besides, it’s difficult to distinguish bainite from martensite without an obvious substructure. In this paper, the bainite, martensite, and decomposed austenite play a similar role in microstructure and mechanical properties. Thus, they are all called the second phase.

![Figure 5. Microstructure of 1.0 mm specimens for different step 1 overaging process: (a) 300 °C for 300 s, (b) 350 °C for 30 s, (c) 400 °C for 30 s, (d) 400 °C for 120 s, (e) 450 °C for 30 s, (f) 450 °C for 60 s.](image)

3.2. Mechanical Properties

Figure 6 shows the mechanical properties of specimens which step 1 temperature is 400 °C. It’s obvious that the yield strength (YS) is different with the thicknesses. For the nearby thicknesses of 1.4 mm and 1.6 mm, the difference of yield stress is as large as~90 MPa. And the yield strength is improved as the time of step 1 increases. While the ultimate tensile strength (UTS) shows an opposed phenomenon. The total elongation (TE) shows little difference between the different time of step 1. The main factor for the difference of TE is thicknesses. The 1.2 mm specimen has the maximum TE and the 1.6 mm specimen has the minimum TE, while the specimens of 1.4 mm and 1.6 mm show minimum strength and greatest strength.
Figure 6. Mechanical properties of specimens with step 1 temperature of 400 °C with different overaging time: (a) yield stress, (b) ultimate tensile stress, (c) total elongation. The 400-30 means the process in which step 1 is holding at 400 °C for 30 s and 400-60 and 400-120 have the same meaning.

The mechanical properties of specimens with step 1 temperature of 450 °C are shown in Figures 7 and 8 respectively. And the same change tendency of strength and plasticity as Figure 6 is observed when comparing between 30 s and 60 s. And the difference of mechanical properties between step 1 time at step 1 temperature of 450 °C is not as large as of that step 1 temperature of 400 °C. The specimens with the thickness of 1.0 mm, 1.2 mm and 1.4 mm show little difference of strength between step 1 time of 30 s and 60 s. The obvious differences of strength among the two processes are found on specimens with thicknesses of 1.6 mm and 1.8 mm. And specimens with thicknesses of 1.6 mm and 1.8 mm in the two steps overaging process (step 1 is holding at 450 °C for 60 s) have the yield plateau as can be seen in Figure 8d. Whereas the specimens of 1.0 mm–1.4 mm still show the continuous yield behavior.
Figure 7. The mechanical properties of DP-TRB for different step 1 temperature: (a) yield stress, (b) ultimate tensile stress, (c) total elongation.

Figure 7 shows the mechanical properties of the different step 1 temperatures with the same time of 30 s. The YS is shown in Figure 7a, and the yield stress of different step 1 temperatures is disordered in specimens of 1.0 mm, 1.2 mm and 1.8 mm. For the specimens of 1.4 mm and 1.6 mm, the overaging processes can be divided into two groups according the mechanical properties. One group is one step overaging process at 300 °C, and another group is two steps overaging processes with different step 1 temperatures. The same classifies are also obvious in UTS and TE, which is shown in Figure 7b,c. For samples with step 1 time of 30 s, the properties of UTS and TE match the microstructure (Figure 5b,c,e) well. Less difference can be found in UTS and TE, and less difference can be seen in the microstructure.
The mechanical properties for special processes: (a) yield stress, (b) ultimate tensile stress, (c) total elongation, (d) engineering stress-strain curve for 1.6 mm with different processes.

Figure 8. The mechanical properties for special processes: (a) yield stress, (b) ultimate tensile stress, (c) total elongation, (d) engineering stress-strain curve for 1.6 mm with different processes.

A comparison of mechanical properties between the one step overaging process and the two overaging processes (partial second phase is clearly decomposed) is shown in Figure 8. The change tendency among thickness of mechanical properties is similar to that in Figure 6. A huge gap in UTS: 70 MPa~120 MPa between the one step overaging process and the two steps overaging process with step 1 of 400 °C for 60 s is found, but the YS between these two processes is very close. According to Figure 6, it’s easy to find that the YS is greater and the UTS is lower as the decomposition becomes more obvious. But the regularity is opposite between two steps overaging processes in Figure 8. The martensite in specimens which step 1 is holding at 450 °C for 60 s decomposed more obviously than that of specimens of step 1 temperature of 400 °C, but the specimens of step 1 that hold at 450 °C for 60 s also have the lower YS and greater UTS.

4. Discussion

4.1. Similarity in Microstructure

The volume fraction of the second phase and the shape of the second phase are found similar for all processes and all thicknesses. It is known that the second phase comes from the austenite at the intercritical temperature. The composition of different thicknesses of TRB is same, and the same ratio of equilibrium phase should be taken into count for different thicknesses and different processes, because of the same intercritical temperature. In addition, the time of intercritical annealing is enough to reach the equilibrium phase ratio. Based on above two reasons, the same volume of second phase for all thickness and all processes is achieved. The similar morphology of microstructure for specimens with different thicknesses is due to enough annealing time. The dual phase structure of raw material forms the high C concentration areas (martensite) and low C concentration
areas (ferrite). The high C concentration areas, exhibiting banding structure because of rolling, are the preferential nucleation and growing locations for austenite transformation. Thus, these areas control the distribution of martensite after annealing [8,10]. On the other hand, austenite grows faster in high C concentration areas with a higher driving force. Therefore, the austenite inherits the shape of high C concentration areas: the band structure during the early stage of transformation. This phenomenon has been described by Cellular Automation simulation and verified by experiments [25]. When the annealing time increases, the main factor of austenite transformation is grain boundary energy. The sphericity has a lower grain boundary energy than the band shape. Enough annealing time gives a chance for austenite to spheroidize completely. Thus the rolling influence on the shape of martensite is eliminated, and a similar shape of second phase is found.

Another similarity is between samples of step 1 time: 30 s with different step 1 temperatures as shown in Figure 5b,c,e. The martensite in dual phase steel mostly shows the island shape, and it’s hard to find the substructure such as laths shape in such smaller island structure (1 µm~3 µm). The annealing of dual phase steel usually includes the overaging process. In this process, martensite would self-temper, and reduce the discrimination of substructure. Thus the substructure in the complicated condition is not easy to observed, even by TEM [26]. Without obvious difference in the morphology of substructure, a mixed microstructure, which contains martensite and decomposed austenite even bainite, increase the difficulty to distinguish each other. It is difficult to find the difference in microstructure though the phases. On the other hand, the step 1 overaging temperature is between Bs and Mf. The generation of bainite or the decomposition of retained austenite needs a certain time as an incubation period. Thus, only little austenite would decompose or little bainite forms in such process with short overaging time. 30 s is not enough to cause obvious differences in microstructure at different step 1 temperatures.

4.2. The Different Mechanical Properties among Thicknesses

A greater gap in mechanical properties between different thicknesses is found in all overaging processes. In order to know the reason for this phenomenon, the EBSD test is used to find inner factor. Figure 9 shows the Kernel Average Misorientation (KAM) maps of different thickness zones. The color from blue to yellow means the strain become more intense. The blue means the strain is nearly zero. Because martensite and ferrite are both the bcc structure, it’s difficult to distinguish the two phases by EBSD. According to the microstructure in Figures 4 and 5, the size of martensite and ferrite has a obvious difference, where the ferrite grain size is large but the martensite grain size is small. Thus, the grains which diameter is above 5 µm are considered as ferrite, the grains which diameter is less than 3 µm are considered as martensite. In Figure 9d, the ferrite is almost blue in 1.0 mm specimen, and the green areas at the inner ferrite represent the second phase when comparing the Band Contrast (BC) + Euler map in Figure 9a. Thus, the ferrite recrystallization occurs completely in 1.0 mm specimen and eliminates the strain resulted from rolling deformation. But in 1.6 mm and 1.8 mm specimens, green and yellow areas are obviously observed in ferrite, especially in the inner of ferrite, and the 1.8 mm specimen shows less strain than that of 1.6 mm specimen. The martensite phase transformation occurs with volume expansion, therefore the strain on the ferrite area which is near ferrite/martensite boundary is natural [27]. But the strain on the inner of ferrite grain is the key factor for distinguishing recrystallization and non-recrystallization. Many grains of ferrite of 1.6 mm and 1.8 mm specimens have the inner strain, and these strains are not caused by second phase after comparing the BC+Eular map. This strain which comes from rolling deformation retained in the specimens after annealing, so the recrystallization did not happen in these grains. The non-recrystallized ferrite has higher strength but poorer plasticity. Thus, 1.6 mm and 1.8 mm specimens have higher strength and lower elongation than that of 1.0 mm~1.4 mm specimens, and the obvious difference between different thicknesses can be seen in Figures 6–8.
temperature of 400 °C. In this condition, martensite softening is also an influencing factor of YS \[28,29\], which plays an important role on samples with step 1 temperature of 450 °C. Due to the high overaging temperature in step 1, decomposition becomes faster and obvious. The decomposed behavior is a process of C redistribution, which C escapes from the second phase and comes into ferrite. As it is known, the more C concentration is, the harder the second phase is. The C concentration of the second phase decreases while the time of step 1 increases, so the hardness and strength of the second phase decrease. The UTS of dual phase steel is mainly controlled by the C concentration of the second phase and the volume fraction of second phase \[7,12,14\]. The volume fraction of the second phase is same for all samples, so the C concentration becomes the key factor to determine UTS. Thus the UTS decreases while increasing the time of step 1. On the other hand, the C concentration of ferrite increases when the time of step 1 increases. The C element in ferrite plays the role of solution strengthening. Otherwise, Li et.al found that the C concentration exceeding the solid solubility limit would form the nanoparticle cementite \[11\]. These cementite particles are also key factor for ferrite strengthening. The difference in yield strength between ferrite and martensite is huge, the ferrite yield far earlier than martensite. So the yield behavior is mainly controlled by ferrite. Thus the yield strength was increased by increasing the C concentration of ferrite, as the time of step 1 increases.

As mentioned above, ferrite hardening is the key factor for increasing the YS. But the softening of martensite is also an influencing factor of YS \[28,29\], which plays an important role on samples with step 1 temperature of 450 °C at different time. Due to the higher step 1 temperature, the decomposition is faster. In terms of diffusion equation \[15\], the C diffusion coefficient at 450 °C in ferrite is \(3.013 \times 10^{-13}\) m\(^2\) s\(^{-1}\), much more than that at 400 °C \(6.828 \times 10^{-14}\) m\(^2\) s\(^{-1}\). It is known that diffusion is the key factor for decomposition. So the speed of decomposition is much faster at 450 °C while comparing with step 1 temperature of 400 °C. In this condition, martensite softening also becomes an important factor to determine YS. The softening effect of martensite and the hardening effect of ferrite reach the balance between 30 s and 60 s for specimens of 1.0 mm, 1.2 mm and 1.4 mm.
and little difference is shown in these thickness zones. As for specimens of 1.6 mm and 1.8 mm, the dislocations from rolling deformation play a key role in the difference of YS. First of all, the roots of dislocations have lattice distortion, and this distortion with pull stress is the gathering place for interstitial solid soluble atom C. The C which escapes from martensite assembles together in the area and forms the Cottrell atmosphere. Then the dislocations are pinned by atmospheres. The movements of dislocations are the reason for plastic deformation, so it needs larger force to move these pinned dislocations. The much more dislocations show stronger strengthening effect on ferrite than 1.0~1.4 mm specimens, and break the balance of ferrite strengthening and martensite softening in 1.0~1.4 mm specimens. Thus 1.6 mm and 1.8 mm specimens with many pinned dislocations show a larger YS when the step 1 time increases from 30 s to 60 s.

It’s found in Figures 5 and 7 that the 30 s of step 1 time is not enough to makes a difference between step 1 temperature of 350 °C~450 °C, but one more step make huge difference in mechanical properties between one step and two steps processes. Martensite of normal composition of dual phase has better stability at the overaging temperature below certain temperature [18], and the properties change is clear when temperature is above such temperature. In this paper, 350 °C is higher than the certain temperature, so an obvious difference is shown between two steps overaging and one step overaging.

In order to prove the C strengthening effect, nanoindentation test was done to evaluate ferrite hardness. The hardness of ferrite has a positive relationship with strength. The measured point was chosen far away from the second phase as much as possible and avoiding the influence from the second phase, as shown in Figure 10a. Figure 10b shows the load curves of selected points in Figure 10a. The result of nanoindentation tests are exhibited in Figure 10c. The hardness for a sample is the average value of 5 different locations which contain 3 or 4 measured points. The specimens of 1.0 mm and 1.6 mm represent the two kind of microstructure respectively: the recrystallization ferrite and non-recrystallization ferrite. It’s clear that the non-recrystallization ferrite is much harder than recrystallization ferrite, which matches the rule of yield stress. It confirms that the yield behavior has a close link with ferrite strength. It can be observed that process in which step 1 is holding at 400 °C for 120 s has a greater hardness than the process in which step 1 is holding at 400 °C for 30 s. The effect of solution strengthening of C element is proved by this phenomenon. The C from decomposed phases strengthen the ferrite strength. The hardness for step 1 time of 30 s is close between step 1 temperature of 350 °C and 400 °C, which corresponds well with the rule: temperature has nearly no influence on the microstructure and mechanical properties when the step 1 time is 30 s.

![Figure 10](image-url)

**Figure 10.** The hardness of different processes: (a) the schematic diagram of measured point; (b) the load curve of selected point in (a), (c) the average hardness of different processes.

It was reported that the suitable volume fraction of bainite instead of martensite show greater UTS in Q&P steel [30]. The C concentration in bainite or other second phase caused by decomposition is less than prior austenite after phase transformation. Some of the C atoms diffuse to ferrite and other C atoms diffuse to retained austenite. The C rich retained austenite transforms to high C martensite during step 2 of overaging. High C martensite has higher strength and shows greater effect in the second phase strengthening. So the
UTS of the specimens of the process which step 1 is holding at 450 °C for 60 s is larger than that of the process which step 1 is holding at 400 °C for 120 s. On the other hand, the yield behavior is the early stage of deformation (Rp0.2 is the strength with little plastic deformation), and the high C martensite has little influence on yield strength. Besides, more volume fraction of decomposed second phase with lower strength increases the harmony of deformation, so the yield behavior is easier to occur. Thus the opposite regularity in Figure 8 between the two overaging processes is shown.

4.4. Yield Behavior

It’s interesting that the samples which step 1 are holding at 450 °C for 60 s show both two kinds of yielding behavior. The samples with the thickness of 1.0 mm, 1.2 mm and 1.4 mm exhibit continuous yielding behavior, while the 1.6 mm and 1.8 mm samples show the non-continuous yielding behavior. The density of dislocations is the reason for different yield behaviors. For the thin samples (1.0 mm, 1.2 mm, 1.4 mm), the densities of dislocations are very low due to the recrystallization of ferrite, which reduces the most of dislocations caused by rolling deformation, as shown in Figure 8d. However, for the thick samples (1.6 mm, 1.8 mm), the most dislocations keep remained during annealing, which acts as hyper-channel for C diffusion and provide the locations of Cottrell atmospheres. Besides, enough C element diffuse to ferrite from decomposed second phases. With enough C concentration in ferrite, the pinned effect caused by these dislocations results in the non-continuous yielding behavior which can be seen in samples of 1.6 mm and 1.8 mm. While this pinned effect is not significant in samples of 1.0 mm, 1.2 mm and 1.4 mm, no yield plateau was observed in them.

Figure 8d shows the transition of yield behavior changing from continuous yielding to non-continuous yielding in 1.6 mm samples with different step 1 temperatures and time. It is obvious that an intermediate state is shown in the transition of yield behavior. This state combines the characters of continuous and non-continuous behavior. A distinct plateau, which seems like the non-continuous yielding, is marked by the black dash line in Figure 8d, but the plateau is smooth during the whole yielding stage. The continuous yield behavior is caused by free mobile dislocations. The non-continuous yield is the result of cycles of pinning and unpinning with dislocations. Yield behavior is a macroscopic behavior caused by the moving of mass of dislocations. The decreasing of stress in non-continuous yield behavior should be the result of simultaneously unpinned behavior of mass of dislocations. These dislocations have the same critical stress for unpinned behavior. Thus the C atoms in Cottrell atmospheres for these dislocations are in a nearly saturated state. When the C atoms are not enough to reach the saturated state, the C atoms also assemble in the root of the blade dislocations. But the concentration of C atoms in these places are not same and they are influenced by the locations, stress and so on. Additionally, these atoms also provide impeded effect to glide of the dislocations. And the impeded effect is a positive correlation with the concentration of C atoms. The unpinned behaviors of dislocations occur gradually instead of the transient process in non-continuous yielding. During the unpinned behavior, the entanglements between dislocations act as work hardening, leading to the increasing of the strength continuously. As a result, the smooth yield plateau was formed by the above two factors: work hardening and slowly unpinned behavior. In addition, the non-continuous yielding is an undesired yield behavior in dual phase steel, this yield behavior would cause form problem in followed forming process such as ladders band. So the process, which the transition state of yield behavior is found, is an intercritical process for overaging processes, and it would guide the design of the annealing process of DP-TRB.

5. Conclusions

1. The two steps overaging is a useful way to control the mechanical properties of DP-TRB. In the premise of satisfying the requirement for the strength of DP590 grade, the
total elongation can be significantly increased (3~7% in most cases). The improvement of ductility is beneficial to the followed forming processes such as cold stamping.

2. The obvious changes of mechanical properties among thicknesses between 1.0~1.4 mm and 1.6~1.8 mm are found. The main reason for the changes is different degree of ferrite recrystallization. The thicknesses zones of 1.0~1.4 mm show lower strength with completely ferrite recrystallization, while the thicknesses zones of 1.6~1.8 mm present higher strength with incomplete recrystallization.

3. The zones with different thicknesses for one DP-TRB show two kinds of yield behaviors (continuous yield and non-continuous yield) simultaneously under some particular process (e.g., step 1 is holding at 450 °C for 60 s). This phenomenon is related to the difference in dislocation density. Much more dislocations in thicker zones provide more locations for Cottrell atmospheres. Thus the non-continuous yield behavior, which was caused by the pinned effect of Cottrell atmospheres, occurred in thicker zones while the thinner zones still showed continuous yield.

4. A transition state of yield behavior, which combines the characteristic of the smooth curve in continuous yield and the plateau in non-continuous yield, is found. The finer C diffusion control by two step overaging results in quite different pinning effect of Cottrell atmospheres. Thus, the transition state of yield behavior can be attributed to the occurring of the pinning effect of Cottrell atmospheres in a gradual way.

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