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Effects of Pre-strain and Temperature on Bake Hardening of TWIP900CR Steel

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Abstract: The effects of pre-strain and baking temperature on bake hardening behaviour of TWIP900CR steel were investigated. The results reveal that the bake hardening process contributes to an increase in yield strength up to 65 MPa at the baking temperature of 200 ℃. The difference in yield strength between baking temperatures of 170 and 200 ℃ is almost insignificant. It is clearly observed that baking at a high temperature does not result in a significant increase in yield strength. For a reasonable bake hardening, a good combination of pre-strain and baking temperature is necessary. Besides, the toughness of the material is found to decrease with increasing pre-strain.

Key words: twinning-induced plasticity steel; TWIP; bake hardening; strain hardening; toughness

High oil prices, environmental regulations, and light weight design demands result in more application of advanced high strength steels (AHSS) in structural components of automotive. These steels have high strength, improved formability and crash worthiness. Normally, high strength is accomplished with the expense of ductility. While the strength is increased, the ductility is usually decreased, and vice versa. In recent years, high manganese austenitic twinning-induced plasticity (TWIP) steel has been developed in order to improve strength and ductility together. The TWIP steels contain high manganese in the austenite phase[1]. Unlike other high-strength steels, TWIP steels contain slip dislocation and twinning deformation mechanisms[2,3]. The TWIP steels which have high strength above 800 MPa are accomplished by the twinning mechanism. In this type of steel, a higher strain-hardening coefficient delays necking. Therefore, a high amount of elongation (more than 40%) is achieved. Although the TWIP steel has very attractive strength and ductility combination, springback of the steel is quite high, compared with other advanced high strength steels[4].

Automotive industry has interested in using this type of steel on the body of the car in order to reduce its weight. Bumper beam, crash box or similar components for its high energy absorption and elongation ratio material can be given as current applications in automotive industry. Basically, less amount of sheet materials are used due to high strength to weight ratio of the steel. In sheet metal part production, sheet metals are stamped first and then painting process including coatings is performed. Baking process is done following the painting process at 170 ℃[5]. During this operation, carbon and nitrogen atoms dissolved in the ferrite structure and diffused to dislocations. Following the diffusion process, Cottrell atmosphere occurred in the microstructure and this leads to an increase in the yield strength[6]. This process is called bake hardening. A bake hardening process provides a significant increase in strength through the combination of work hardening during stamping and strain aging during paint baking process.

Bake hardening is considered as the process of increasing yield strength. First, the process was developed for the low carbon steels. Several researches have been conducted regarding effects of pre-strains, temperature, and temperature exposure time on the performance of bake hardening process for AHSS.

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Timokhina et al.[7] studied 5% pre-strained dual phase (DP) and transformation-induced plasticity (TRIP) steels in order to see the increase in yield strength when holding the steels at 175 ℃ for 30 min. Their results showed that the increases of work hardening and bake hardening were about 80 MPa for DP and 60 MPa for TRIP steels, respectively. The bake hardening behaviour of TRIP steel with and without Nb and Mo with 4% pre-strain was investigated by Pereloma et al.[8]. A 90 MPa increase was measured after adding Nb and Mo and a 70 MPa increase was seen for TRIP steel without Nb and Mo. Dehghani et al.[9] evaluated the bake hardening of 3%−9% pre-strained Al7075 material held at 115−285 ℃ for 11−35 min. They obtained the best results after pre-straining of 6% and holding at 200 ℃ for 23 min using optimization techniques. In other studies, Dehghani[10] examined the effect of grain size on bake hardening. At the same time, the condition of best bake hardening using artificial neural network (ANN) was predicted[11]. Durrenberger et al.[12] investigated the effect of pre-strain and bake hardening on the collision properties. They exposed TRIP780 steel to bake hardening process at 170 ℃ for 20 min and demonstrated that tensile strength increases with increasing pre-strain and yield strength increases and then starts decreasing after a certain rate. Kvackaj and Mamuzic[13] exposed BH220 steel to bake hardening process at 170 ℃ for 20 min and they showed that there is an increase in the range of 73 to 82 MPa with work hardening. Momeni et al.[14] conducted the research on bake hardening of St14 steel with 4%, 6%, and 8% pre-strain for 20 min at 150, 180, and 210 ℃. Results reveal that strength increases with increasing baking temperature and pre-strain. Similar research was performed by Wang et al.[15] in 2%, 6%, and 8% pre-strain conditions for low carbon steel held at 170 ℃ for 20 min. In another study, effects of bake hardening and work hardening were examined for TRIP, DP, and HSLA (high strength low alloy) steels. In the study[16], the samples were held at 2% pre-strain and 170 ℃ for 30 min. The results reveal that the bake hardening property of TRIP steels is better than that of DP and HSLA steels.

Wagener[17] studied the strength increase after the painting process. The results indicate that the stamping and painting process of a car door increase yield strength of the material gradually.

In present research, the effects of pre-strain and baking temperature were studied for TWIP900CR and results were discussed in detail.

1 Experimental Procedure

In this study, a TWIP900CR steel of 1.3 mm in thickness was used in order to determine effects of pre-strain and baking temperature on material properties. The chemical composition of the material is given in Table 1.

Table 1 Chemical composition of TWIP900CR steel

mass%

C	Mn	Si	Cr	Al
0.37	20.96	0.17	0.46	4.80

Test samples shown in Fig. 1 were prepared according to ASTM E8 standard by water jet cutting along rolling direction. The as-received and pre-strained samples were used. The pre-strains of 2%, 4%, and 6% were applied by Shimadzu Autograph 100 kN testing machine. The samples were put in furnace for bake hardening process. Firstly, the furnace was stabilized for 4 h at 170 and 200 ℃. Then, the samples were put inside the furnace and exposed for 20 min. Then samples were put outside the furnace and cooled down to room temperature (RT). Finally, tensile test was conducted at a speed of 25 mm/min. Deformation was measured with a video type extensometer measurement system. Mechanical properties such as yield and tensile strengths, strain hardening and strength coefficients, uniform and total elongations, and toughness were determined.

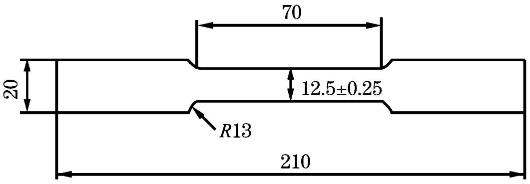

Fig. 1 Tensile test specimen dimensions (Unit: mm)

2 Results and Discussion

A flow curve shows the relationship of true strain (ε), strain rate ($\dot{\varepsilon}$) and temperature (T in K). This function can be expressed in a general form in Eq. (1).

$$\sigma=f(\varepsilon,\dot{\varepsilon},T) \tag{1}$$

Several empirical models were proposed in literatures. The most widely used models are Hollomon, Swift (Krupskowsky), and Ludwig equation (Power law) models. The Hollomon equation is given in Eq. (2). This equation depends on two parameters:

strength coefficient (K) and strain hardening exponent or coefficient (n).

$$\sigma=K\varepsilon^{n} \tag{2}$$

The other model is the Swift model (also called Swift-Krupkowsky law) given in Eq. (3). In this model, K, n and the initial strain (ε_0) should be defined.

$$\sigma=K(\varepsilon_0+\varepsilon)^{n} \tag{3}$$

The other most widely used model is the Ludwig equation (Power law) that is given in Eq. (4). The model consists of three parameters: K, n, and the material yield strength (σ_0).

$$\sigma=\sigma_0+K\varepsilon^{n} \tag{4}$$

The strain hardening coefficient of the material is defined as stress-carrying ability of the material as seen in Eq. (5). The high n value indicates high formability of materials.

$$n=\frac{\mathrm{d}(\log\sigma)}{\mathrm{d}(\log\varepsilon)}=\frac{\mathrm{d}(\ln\sigma)}{\mathrm{d}(\ln\varepsilon)}=\frac{\varepsilon}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} \tag{5}$$

The hardening rate ($\mathrm{d}\sigma/\mathrm{d}\varepsilon$) is an important parameter to determine strengthening of the material as shown in Eq. (6). This is not identical to strain hardening exponent, given in Eq. (5).

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon}=n\frac{\sigma}{\varepsilon} \tag{6}$$

True stress *vs*. true strain curve for as-received TWIP900CR steel was plotted and mechanical properties were determined as shown in Fig. 2. Curve fitting analysis was performed for several well-known models such as Hollomon, Swift (Krupskowsky), and Ludwig (Power law) as described previously. Even though all the models have reasonable predictions, the Ludwig model has the best prediction capability of the flow curve for TWIP900CR steel. The material models are practically used in finite element (FE) software. Therefore, the Ludwig model should be considered in the FE analysis.

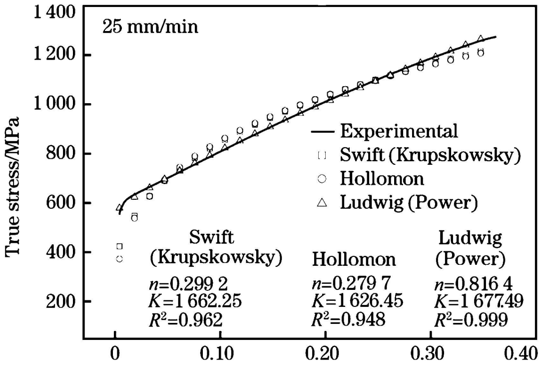

Fig. 2 True stress *vs*. true strain curves of different material models for TWIP900CR steel

The variation of strain hardening exponent *vs*. true strain is drawn as shown in Fig. 3 using the described models. The results reveal that a conformable tendency is obtained using the Ludwig model. As it is quite known that the strain hardening exponent is increased with increasing strength and strain.

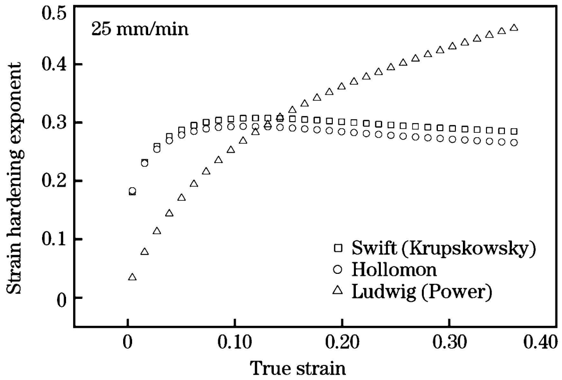

Fig. 3 Variation of strain hardening exponent *vs*. true strain

Similarly, the work hardening rate was also studied using the previously described models. The results are illustrated in Fig. 4. It indicates that the necking starts at the intersection of the true stress *vs*. true strain curve and the work hardening curve. The Ludwig curve shows that necking will take place at the later stage.

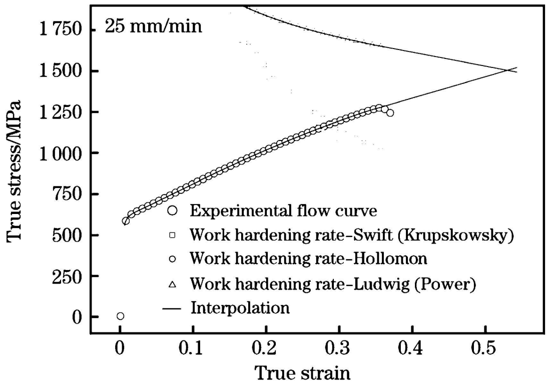

Fig. 4 Effect of work hardening rate *vs*. true strain

Fig. 5 summarizes the variation of the strength coefficients and the strain hardening exponent with respect to several pre-strained values. It is indicated that similar results were observed at different furnace temperatures. The strength coefficient starts increasing at the beginning and then starts decreasing at 4% pre-strain. However, the strain hardening exponent increases with increasing pre-straining values for both temperatures. The higher temperature (200 ℃) heating does not contribute to strain har-

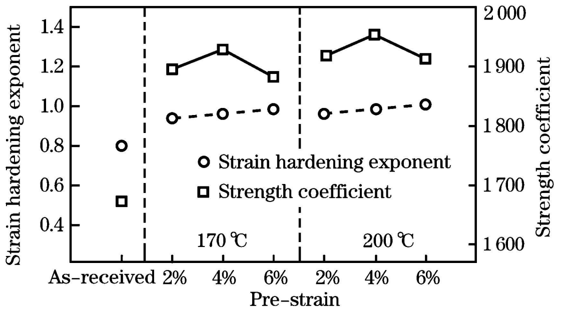

Fig. 5 Variation of strain hardening exponent and strength coefficient *vs*. baking temperature

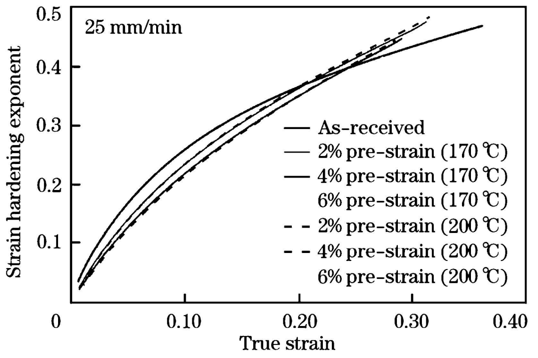

Fig. 6 Strain hardening exponent *vs*. true strain

dening coefficients. It seems that 170 ℃ is an ideal temperature for bake hardening process of this material.

The strain hardening coefficient *vs*. true strain is plotted using the Ludwig model (Fig. 6). Results indicate that higher temperature does not produce higher value. The highest values were obtained at pre-strain of 2% and baking temperature of 170 ℃.

True stress *vs*. true strain curves were plotted as shown in Fig. 7(a) for various pre-strains and two baking temperatures of 170 and 200 ℃, respectively. The graph was zoomed in Fig. 7(b).

The results indicate that the higher baking temperature does not contribute to strength increase significantly. It means that higher baking temperature is not necessary. As expected, the higher curve was observed at 6% pre-strain.

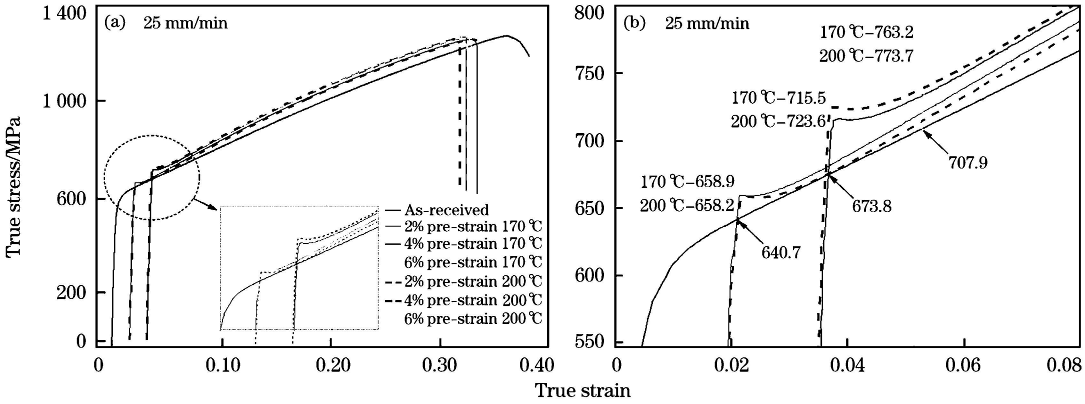

Fig. 7 True stress *vs*. true strain curves for various pre-strains and baking temperatures

The variation in yield strength is illustrated as graphical bars in Fig. 8. It shows that higher increase was determined as 65.8 MPa at 6% pre-strain and 200 ℃. The value was 55.3 MPa for 170 ℃. A 30 ℃ temperature difference made a 10.5 MPa difference in strength values.

Determining the yield strength, 0.2% offset rule was used. Yield strength increases with an increase of pre-strain ratio. When bake hardening with 2% pre-strain is applied to the as-received sample, approximately a 99.5 MPa increase in yield strength was observed. A 81.3 MPa part of this increase is caused by work hardening, and the other 18.2 MPa part of this increase is owing to bake hardening. The lowest value was determined at 2% pre-strain for both baking temperatures. Increasing pre-strains means additional dislocations. These results indicate that additional dislocations are needed for a suitable hard-

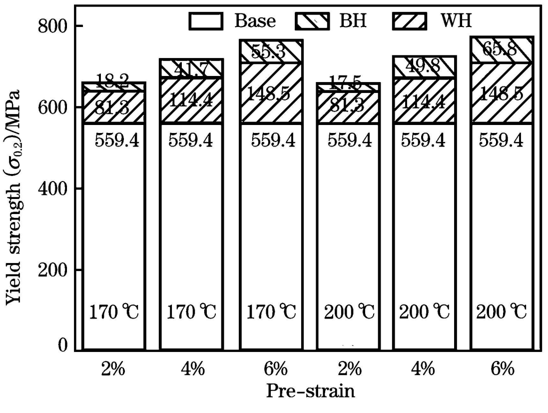

Fig. 8 Yield strength *vs*. pre-strains and baking temperatures

ening behavior.

The variation in tensile strength *vs*. pre-strain and baking temperature is given in Fig. 9. The results clearly showed that the combination of pre-strain and baking temperature has no positive effect on tensile strength.

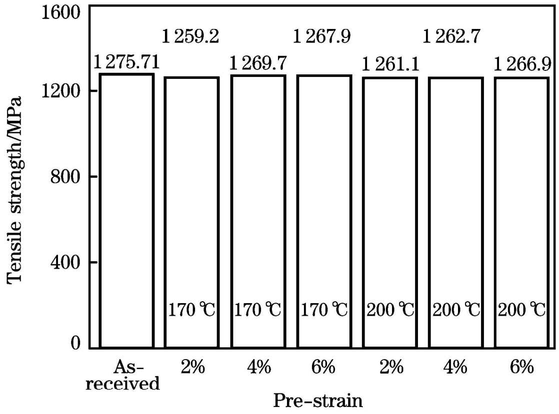

Fig. 9 Tensile strength *vs*. pre-strains and baking temperatures

As seen in Fig. 10, the total elongation was decreased with increasing pre-strain as expected. The similar behavior was observed at both baking temperatures.

The toughness of the material was also determined using the area under the true stress *vs*. true strain curve. This value indicates that the amount of energy is absorbed until the fracture. The results are summarized and displayed in Fig. 11. The results reveal that increasing pre-strain has a negative effect on the toughness. It is also obvious that increasing baking temperature has a negative effect in terms of toughness variation.

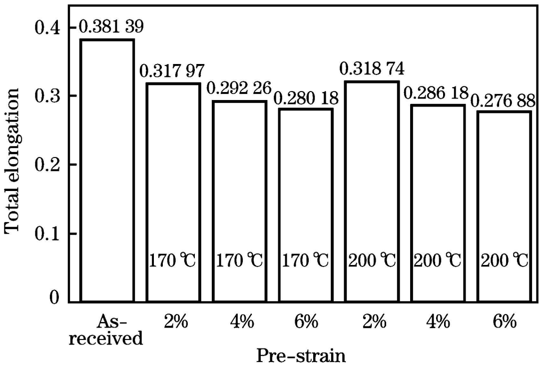

Fig. 10 Total elongation *vs*. pre-strains and baking temperatures

3 Conclusions

(1) The Ludwig model has better predictions than the Swift and the Hollomon models. Therefore, the Ludwig model should be considered in FE analysis.

(2) High baking temperature does not result in a significant increase in yield strength.

(3) High baking temperature has a negative effect on the material toughness.

(4) A good combination of pre-strain and baking temperature is necessary for a suitable bake hardening.

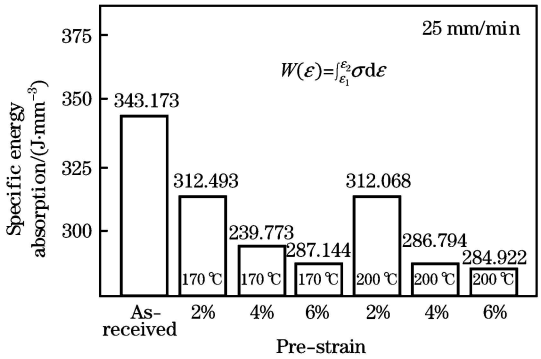

Fig. 11 Specific energy absorption *vs*. pre-strains and baking temperatures

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