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Research Article

Work-Hardening and Deformation Mechanism of Cold Rolled Low Carbon Steel

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Abstract: The study reports the mechanical property and microstructure of cold rolled low carbon steel and its work-hardening behavior in the deformation process. The tensile test in room temperature of low carbon steel was implemented for the different cold rolling deformation, the stress-strain curve was draught according to the relationship between strength and deformation and fitted for the polynomial fitting, the strain hardening exponent (n) of test steel was calculated by the Hollomon method. In the whole cold deformation process, the work-hardening of cold rolled steel is significant, work-hardening rate has different degrees decreasewith the deformation increase. The strain hardening exponent is simple and dislocation strengthening is the major cause of hardening processing. The microstructure of test steel was observed after different deformation, the room temperature organization is the ferrite and few pearlite. The original grain is equiaxial and the average grain size is about 23.5 um, and pearlite distributes in ferrite grain boundaries. It was consequently established the cold deformation energy according to dislocation model, the cold deformation energy is main concerned on the plastic deformation to resistance and the initial stress**.**

Keywords: Cold deformation, deformation energy, hollomon method, low carbon steel, microstructure, work-hardening

INTRODUCTION

Cold rolled sheet belt and its extension product is the most widely used steel varieties which has beautiful surface, good processing performance, high size precision, widely used in vehicles, ships and household electrical appliances, (González *et al*., 2010; Liu *et al*., 2003). Especially used in automobile industry of cold-rolled drawingsheet and high-tensile steel, accounts for above 50% of the car body steel (Fu, 2005; Li *et al*., 2010). Cold rolling low carbon steel shows well mechanical properties and excellent forming performance, with the development of social and economic, more and higher performance is required to the cold-rolled of low carbon sheet.

In the condition of hot rolling products confirmed for the original cold rolling, the performance of cold rolling low carbon steel is determined by cold deformation and after heat treatment process conditions (Abou-Msallem *et al*., 2010; Kandavel *et al*., 2009). Material mechanical performance index in the cold rolling deformation is the basic premise and important bases of the rolling process decided and the production stably, material microstructure of deformation process is effect the evolution of organizational structure during annealing process and there is part of work inverting energy during cold deformation processing, but the rest of the energy stores in the deformation metal, that is the deformation energy of cold rolled, this energy effects the incubation period and particle nuclear and growing up in heating process. In this study, research on the cold deformation of low carbon steel using the rolling-stretching method, analyzes its performance and microstructure with different deformation, put forward the Hollomon method to treating strain-hardening and the deformation mechanism hardening of cold rolling low carbon steel, the model of relationship between deformation energy and flow stress is built. The research results is important for cold rolling deformation mechanism of cold rolling understanding deeply and heat treatment process of low carbon steel establishing precisely and also important theoretical and directing significance for good performance of cold-rolled steel sheet product.

EXPERIMENTAL DETAILS

Material: The experimental material is the common quality grade of steel plate hot rolling produced by CSP

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process, the thickness is 3.5 mm and chemical constitution (mass %) 0.04 C, 0.03 Si, 0.30 Mn, 0.015 P, 0.015 S, 0.025 Al, 0.003 N.

Test methods: The experimental plate was cut to same standard ten pieces that size is 200×40×3.5 mm by steel shear, the pieces were rolled different deformation by the two-roller mill in laboratory and the deformation was progressive 0, 18.57, 28.56, 39.23, 43.71, 57.14, 64.26, 70.38, 75.42 and 84.57%, respectively. Based on GB/T288-2002, the tensile sample was gained along rolling direction by linear cutting machine and tensile test was implemented by universal material testing machine. Making metallographic specimen each piece after rolling, the microstructure of specimen was observed in Axiovert-200 MAT Metalloscope (OM) and KYKY-2800 Scanning Electronic Microscope (SEM) and JEM-2010 Transmission Electron Microscope (TEM), respectively.

RESULTS AND DISCUSSION

Mechanical property: Figure 1a shows the tensile test results of test steel in different deformation in the room temperature, the yield and tensile strength are gradually raise with the increase of the deformation and generate evident work-hardening (M'Guil *et al*., 2011). At the beginning of deformation work-hardening is more serious, this hardening is becoming slowly when cold deformation about 50%, but the strength of steel value is increased above 80%.

Dislocation density is sharp augment during the metal cold deformation lead to above changing phenomenon. The sliding deformation is the main mode of texturing for face-centered cubic metal in room temperature cold-forming, it is essential that large number of dislocation is movement along the gliding plane lead to dislocation multiplication. The dislocation multiplication makes more and more dislocation density and more reciprocal delivery chance of dislocation; it also makes bigger resistance of metal atom, so the resistance to deformation of test steel is followed augment. In reverse, augmentation of resistance to deformation is indicated that resistance of dislocation movement is increased and easily amassed in crystalloid, so dislocation density is augment more quickly. The both factors reciprocity leaded to the strength increase and plastic decrease.

In order to get more details work-hardening of cold rolling low carbon steel, according to the principles of constant volume, $\sigma = s(1+e)$ $\varepsilon = \ln(1+e)$ (where the s is engineering stress, e is engineering strain, σ is true stress and ε is true strain). The engineering stress and strain of different deformation was converted to true stress and strain. Figure 1b shows the true stress-strain curve of low carbon steel and its polynomial fitting curve (Chen and Deng, 2011; Zhang *et al*., 2012). The stress continuously increases with the

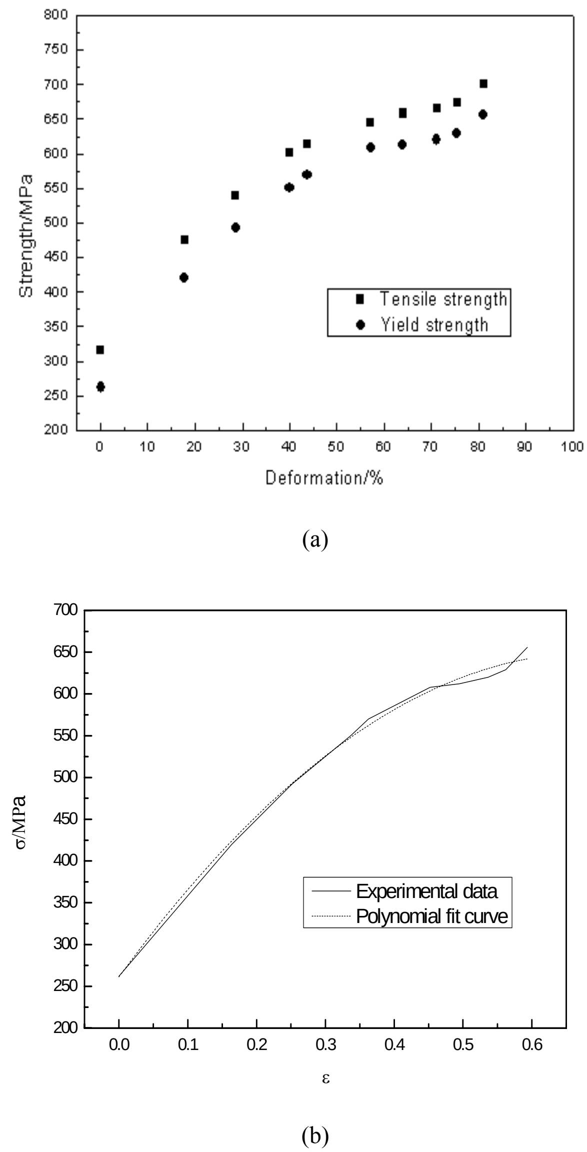
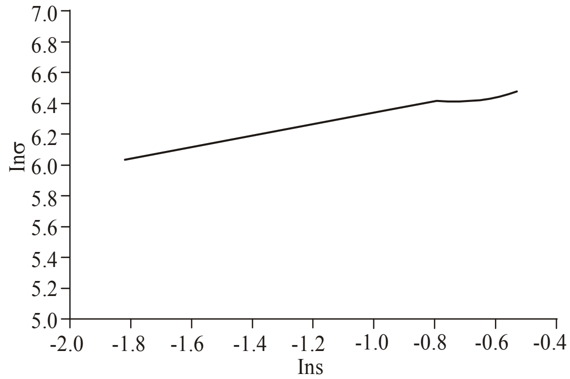


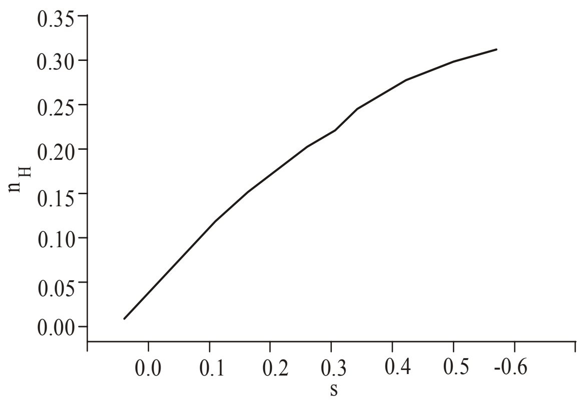
Fig. 1: Mechanical properties of test steel during cold deformation, (a) relationship between tensile and yield strength with deformation, (b) true stress-strain curve and its polynomial fit curve of low-carbon cold rolling

Table 1: The fitting result of stress-strain

Appellation	Polynomial model information		
Fitting coefficient	a	b	c
Value of coefficient	261.213	1127.018	-816.806
Standard error	5.965	14.038	8.984
R^2	0.9953	-	-
Residual sum of squares	912.393	-	-



(a)



(b)

Fig. 2: Mechanical properties of test steel during cold deformation, (a) relationship between tensile and yield strength with deformation, (b) true stress-strain curve and its polynomial fit curve of low-carbon cold rolling

strain increasing and the work-hardening rate ($\theta = d\sigma/d\varepsilon$) is decrease gradually, but work-hardening rate shows a increase tendency when true strain is 0.58 or engineering strain more than 80%. The polynomial fitting result was shown the Table 1.

Characteristics of strain hardening: Work-hardening is a mechanical behavior in the process of metal plastic deformation, its production is due to the amount of flaw interaction inner metal crystals (Deva *et al*., 2011), blocking the dislocation movement and inhibiting the proceeding of plastic deformation, so, it leads to the true stress augment with the strain increasing. The Fig. 2a shows the curve of double-log true stress-strain, the curve is near to linear, according to Hollomon equation $\sigma = K\varepsilon^{n_H}$ (where, K is coefficient of deformation strengthening, n_H is index of strain hardening) suitable to describe bi-logarithm coordinates to linear work-hardening curve that the log-log coordinate is linear (Wank *et al*., 2006; Wu *et al*., 2009), logarithm of Hollomon equation is counted as:

$$\ln \sigma = \ln K + n_H \ln \varepsilon \tag{1}$$

Then:

$$n_H = \frac{d \ln \sigma}{d \ln \varepsilon} = \frac{\varepsilon d\sigma}{\sigma d\varepsilon} \tag{2}$$

Figure 2b is the relationship between index (n_H) of strain-hardening and true strain, the index of strain-hardening increases with the true strain increasing. The effect of hardening is become slowly, but the total cumulative strain-hardening is increased, the capacity of the material's resistance to continue plastic deformation is increased too, the resistance to deformation is augment.

Deformation mechanism of work-hardening: The metallographic microstructure pictures of Fig. 3 shows that the microstructure of deformation fore and after of cold rolled low carbon steel is ferrite and few pearlite, the few pearlite distributes in the grain boundaries of ferrite and no other second-phase separate inner the ferrite grain, the scanning electron micrographs photos also shows this point in the Fig. 3d. The original grain is equiaxial before deformation and the average grain size is 23.5 um, as shown in the Fig. 3a. With the deformation increase, grain size decreases and grain is elongated and bruised gradually along the rolling direction. While deformation amount to 75.42%, it can't see grain boundaries in the crystals, a large number of ferrite grain is distorted and refined and produced fibrous structure for clear preferred orientation. In the Fig. 3e and f shows that internal twin phenomenon has not happened inner metal, produced large amount of dislocation for cold deformation (Niang *et al*., 2012; Yang *et al*., 2009; Xiang *et al*., 2011), plastic deformation is blocked by dislocation jog and climbing and entwist, it leads the work-hardening, dislocation strengthening mechanism is the main cause of hardening.

The work-hardening rate depends on the dislocation multiplication and its interaction multiplication and its interaction. At the beginning of deformation, plastic deformation caused by applied stress prompts out pouring dislocation movement along gliding plane and lead to the dislocation multiplication. It further makes the dislocation density bigger and bigger, the main and second slip system of the parallel dislocation interaction blocks the dislocation further moving (Xue *et al*., 2010), so it produces remarkable work-hardening. Meanwhile, dislocation density increasing causes unlike dislocation meeting and vanishing and lead the harden ability slowing, but the total work-hardening is still increase with the

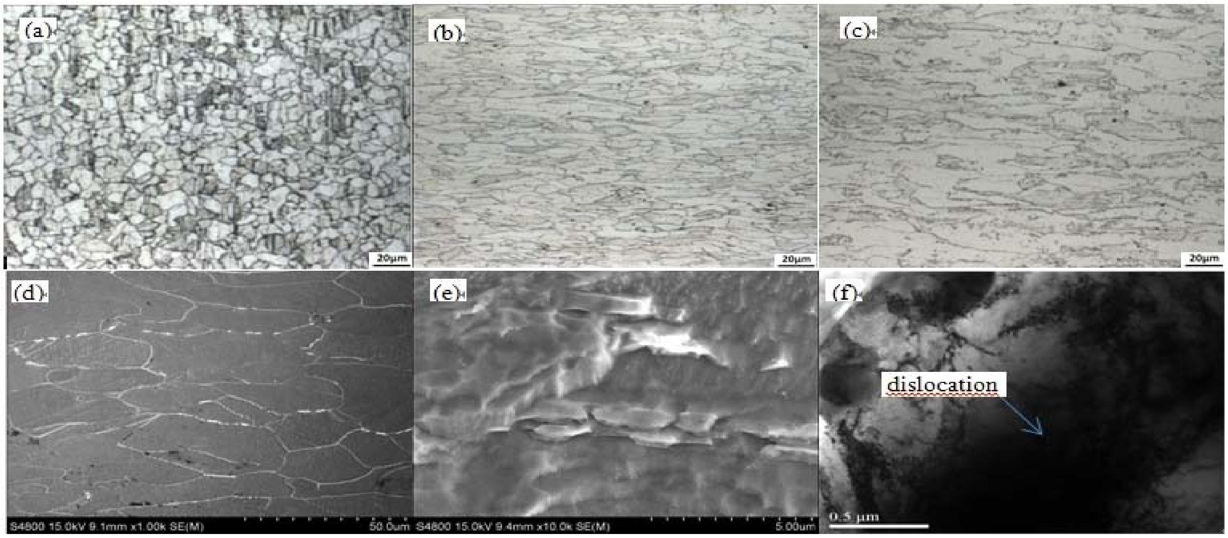


Fig. 3: Microstructure of cold low carbon steel in different deformation, Metallograph: (a) initial microstructure, (b) e = 39.27%, (c) e = 75.4%, Microstructure for SEM: (d) e = 28.56%, (e) e = 75.4%, Microstructure for TEM: (f) e = 75.4%

deformation increasing. When the deformation (e>80%) is very large, the delivery of mutual vertical screw dislocation forms the dislocation jog of edge dislocation as shown in Fig. 3e, the dislocation jog makes the further climbing, screw dislocation with dislocation jog is blocked severe continue movement and material strength increased sharply.

Deformation energy of cold rolled: The deformation energy of metal is decided to deformation parameters (deformation, deformation rate, deformation temperature) and soft action or others of energy expenditure in the process of deformation, it is very complex and difficult to measure and calculation accurately. Cold deformation energy was measured by the X-ray diffraction broadens determination and Electronic Backscatter Diffraction (EBSD) observation overseas (Humphreys, 2004; Ungar, 2004). The microstructure of cold rolled of low carbon is mainly ferrite room temperature, the mechanism of plastic deformation is mainly dislocation glide, deformation energy is the results of dislocation multiplication and cross slip combined action. Generally, deformation rate is often ignored in the cold deformation process, the main consideration deformation is the main influencing factor, so it is suitable to analysis the cold deformation energy according to the dislocation model in the of the theory.

There is strain energy around distortion because of deformation, the strain energy is composed by center energy (E_1) and its outside energy (E_2) of dislocation stress field, because the value of E_1 is more smaller than E_2 and about tenth value of E_1, so dislocation energy is similar to value E_2. The screw dislocation has only one stress components in cylindrical coordinates, strain energy density is $\omega = \gamma_{z\vartheta}\tau_{z\vartheta}$, the strain energy per unit length for:

$$E_{2L} = 2\pi\int_{r_0}^{R}\omega r dr = 2\pi\int_{r_0}^{R}\gamma_{z\vartheta}\tau_{z\vartheta} r dr = \frac{Gb^2}{4\pi}\int_{r_0}^{R}\frac{dr}{r} = \frac{Gb^2}{4\pi}\ln\frac{R}{r_0} \tag{3}$$

The strain energy of edge dislocation is also obtained:

$$E_{2R} = \frac{Gb^2}{4\pi(1-\upsilon)}\ln\frac{R}{r_0} \tag{4}$$

According to the type (3) and (4), the strain energy of mixed dislocation is obtained as follow:

$$E_2 = \frac{Gb^2}{4\pi}\left(\frac{\sin^2\varphi}{1-\upsilon} + \cos^2\varphi\right)\ln\frac{R}{r_0} = \frac{Gb^2}{4\pi K}\ln\frac{R}{r_0} \tag{5}$$

where,

$$K = \frac{\sin^2\varphi}{1-\upsilon} + \cos^2\varphi, \quad \text{take } r_0 \approx b$$

(about 2.5×10^8 cm), R = 10^4. Then, the dislocation energy unit of length about (Yu, 2000):

$$E_{dis} = k_0 G b^2 \tag{6}$$

The dislocation energy unit volume:

$$E_s = k_0 G \rho b^2 \quad (7)$$

where,

- r_0 = Radius of dislocation stress field
- R = Outside center radius of dislocation stress field
- υ = Poisson's ratio
- φ = The angular between b and dislocation line of mixed dislocation
- G = Shear modulus of ferrite
- b = Value of Burgers vector module
- ρ = Dislocation density
- k_0 = Coefficient of dislocation energy, $k_0 = 0.5\sim1$

The mechanism of dislocation strengthening is the major cause for work-hardening of ferrite deformation in room temperature, the relationship between resistance to deformation and dislocation density accord with the model of Bailey-Hirsch (Mao, 2008):

$$\sigma = \sigma_0 + \alpha G b (\rho)^{\frac{1}{2}} \quad (8)$$

where, σ_0 is resisting force of dislocation motion except for the factor of dislocation, α is constant, α = -0.000628T+1.0693 (Luo *et al*., 2004).

Putting formula (8) in formula (7), the relationship is established between deformation energy and flow stress as follow:

$$E_S = \frac{k_0(\sigma - \sigma_0)^2}{G\alpha^2} \quad (9)$$

CONCLUSION

- The study-hardening phenomenon of low carbon steel is much more visible in the whole cold rolling process, cold rolling deformation leads to the strength of the low carbon steel improved greatly. The engineering stress and strain of low carbon steel is converted to true stress and strain in different deformation, drawing the true stress-strain curve is polynomial fitting and the fitting correlation coefficient R is above 0.99.
- The work-hardening mechanism of cold rolling low carbon steel mainly is dislocation strengthening. According to the dual logarithm true stress-strain curve tends to linear, it accords with the traditional Hollomon equation. Using the Hollomon method to analyze the strain hardening exponent n_H indices that it is a smooth curve along the true strain increasing and deformation is a single deformation mechanism-dislocation strengthening playing the leader role, this point is also certificated from transmission electron microscopy organization.
- The microstructure of cold rolling low carbon steel is ferrite and few pearlite in the room temperature and pearlite distributes in the grain boundaries ferrite. With the deformation increasing, the original equiaxial grain is gradually stretched and refined, grain is distorted and broken when the deformation reaches a certain extent and generated obvious preferred orientation.
- The relationship between deformation energy and deformation is established according to dislocation model in the theoretical, it has important theoretical significance for subsequent heat treatment to thermodynamics and kinetics calculation of phase change and technology determined.

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