Rheological Behavior under Hot Compression and the Constitutive Model of 35CrMo Steel

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***Abstract* — In order to achieve digitization and simulation of hot forging and optimize the hot compression process parameters with 35CrMo steel, we performed experiments at temperatures from 850 to 1150 and strain rates from 0.01 to 50 s^{-1} on a Glebe−3810 thermo-simulation machine during a series of isothermal compression tests. The results indicate that the true stresses were influenced by the deformation temperature and strain rate. For fixed strain rate, stresses increased with the increasing of strain rates, while for a constant strain rate, the true stress decreased with the raising of temperature. A constitutive equation was obtained by linear regression from the flow stresses obtained from the compression tests for the studied 35CrMo steel. The constitutive equation proposed was coded into a finite element simulation software Deform-3D, and simulations indicated exact match between experimental results and simulated data. Finally, microstructures after deformation is discussed.**

Keywords - 35CrMo steel; hot compression; constitutive equation; flow stress

I. INTRODUCTION

Rheological behavior of metals and alloys is important of hot metal-forming progress for designers. During this progress, flow behavior and microstructures evolution are complex, and they are a combined effect of work hardening, dynamic recovery (DRV), and dynamic recrystallization (DRX) and so on [1, 2]. The constitutive relation during hot deformation is one of the most vital factors for the study of this progress, it can be used as the indicators of microstructure transformations to predicate the final condition of the part forged. Also, true stress-strain curve described by constitutive equation is a most important gradient in performing the finite element simulation, which has attracted a lot of researcher's attention [3, 4].

Stress-strain curve received from a series of tests is the reflection of the microstructure change during deformation, from which, dynamic model of DRX and corresponding constitutive equations can be constructed to predicate the evolution of DRX and resistance stress. Those models and equations can be coded into the software to predicate the final situation of the component deformed, which is helpful in industry. In order to construct a precise constitutive equation, softening effect caused by DRV, DRX and work hardening must take inconsideration, and critical variables should introduce into the equations. On the basis of the analysis of the dislocation density, Laasraoui and Jonas established a constitutive equation in the form of the piecewise function by thermodynamic simulation, indicating the rheological properties of the materials under high temperature can be described accurately by including the deformation temperature, true strain, deformation rate and other parameters, and fitting well with experiment results[5]. In order to predict a lot of metallic constitutive behaviors, it puts forward with all kinds of constitutive models. The exponential model proposed by Sellars and McTegart, and adapted for different temperature ranges by Rokni and Zarei-Hanzaki is one of the most-widely used models of constitutive equations under hot working conditions[6-10]. This model describes the flow stress of the material as a hyperbolic sine-type Arrhenius-type equation. According to the results of hot compression tests, Ebrahimi etc. established the hot deformation constitutive equation of for Ti-IF steel, explaining the work hardening and dynamic softening, quite well[11].

35CrMo is one of the representative mdium carbon alloy steel with high intensity, strong tenacity, and good machining ability, it has been widely used for the manufacture of important parts like rolling mill herringbone gear, engine transmission parts etc [12].Considerable attentions have been for used on the corrosion properties, heat treatment and other issues for 35CrMo steel. For example, Bin Zhang et al. have studied DRX behavior of 35CrMo structural steel; LI Hui and his co-workers have studied the effects of the process of heat treating on the corrosion resistance of 35CrMo.

In recent years, different kinds of constitutive equation have been put forward for metals and alloys to describe the hot deformation behavior. However, to the best of our knowledge, there is little information about the hot compression rheological stress behavior of 35CrMo steel, which require be further studied to accomplish digital forged simulation, and to make the related parameters better during thermoforming progress.

II. EXPERIMENTS

35CrMo high-strength steel as electromagnetic cast was used for the present investigation, chemical compositions are as follow (wt%): 0.36% C- 0.26% Si- 0.18% Mn - 0.01% S- 0.007% P-0.95% Cr- 0.18% Mo-0.07% Ni- -0.06% Cu-(bal.)Fe. Cylindrical specimens were machined with a diameter of 10 mm and a height of 12 mm. A series of experiments data were showed on a Glebe 3810 thermo-simulation machine in temperatures which selected from 850 to 1150℃ at an interval of 100 ℃ and from 0.01 to 50 s^{-1} with strain rates.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. *True Stress and Strian Curves*

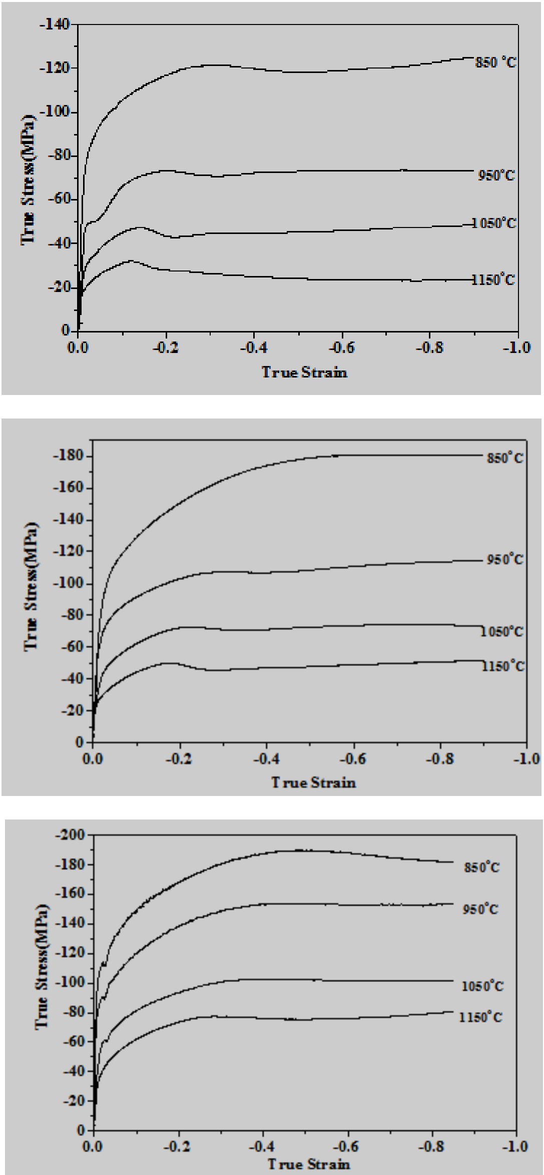


Figure 1. True stress− strain curves for 35CrMo steel at different temperatures with strain rates: 0.01s^{-1}, 0.1s^{-1}, and 1s^{-1}

True stress- strain curves of 35CrMo steel under different strain rates and deformation temperatures are shown in Fig. 1.

As we can seen from the Fig 1, in the primary phase of deformation, a sharp rise in the rate of work hardening caused by a slight increase of strain; Softening mechanism during deformation mechanism is weak, makes small contribution to the decrease of work hardening, the stress value reaches a peak afterwards. The peak stress increases with decreasing deformation temperature and increasing strain rate. When the flow stress reaches a peak, it decreases continuously with the increase of flow strain. It can be give more time to collect more energe and higher mobility with small strain rates and higher temperatures. Then benefits to growth dynamically recrystallized grains and finally decrease the flow stress level.

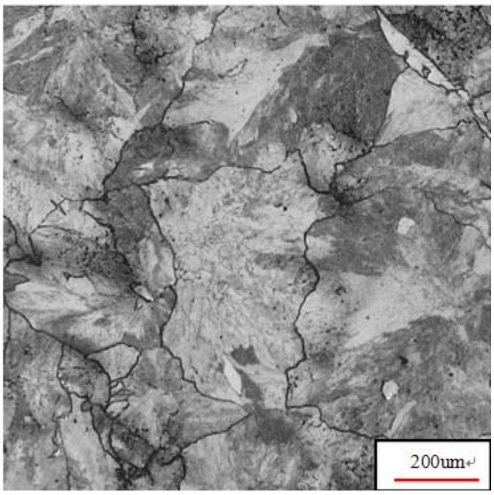
One obvious tendency is that the stress increases rapidly with increasing true strain, then declines after the peak stress, basically remains unchanged when it reached a certain true strain. The higher the setting temperature is, the lower the corresponding stress is under the condition that those stress states are similar. With decreasing deformation temperature, the peak stress moves towards to the direction of the increasing strain. At a certain deformation temperature, flow stress increases with increasing strain rate.

In the hot deformation process, alloys will occur two typical softening mechanisms of dynamic recovery (DRV) and dynamic recrystallization (DRX) .While DRV process occurs in the course of the thermal deformation behavior, the hardening rate and DRV reach dynamic equilibrium, and the flow stress will gradually rise to a steady state with increasing strain. While DRX process occurs in the course of the thermal deformation behavior , the flow stress quickly reach peak stress with small strain, then, flow stress gradually stabilized with a gradually decreasing the flow stress.

The true stress curve end up with experiment generally fall into three stages according to check up data. This is a combination effect of work hardening and thermally activated softening. In the initial stage of the deformation, stage I (work hardening stage), hardening rate is higher than the softening rate and flow stress exhibits a rapid increase to a critical value. The competition between the work hardening and the softening phenomenon induced by DRV, as well as the DRX, takes place. What’s more, the flow stress increases but the increase rate continuously decreases. In stage II (softening stage): the dislocations are annihilated in large numbers through the migration of a high angle boundary and the stress drops steeply, which is related with DRX, dynamic precipitation, etc. the thermal softening due to DRX and DRV becomes more and more predominant, then it exceeds WH. Finally, stage III (steady stage): the stress becomes steady when a new balance between softening and hardening is obtained. At the third stage, three types of curve variation tendency can be generalized as following: decreasing gradually to a steady state with DRX softening 850-1150 ℃ and 0.01 s^{-1}, 950-1150 ℃ and 0.1 s^{-1}, 1050-1150℃ and 1

s^{-1}), maintaining higher stress level without significant softening and work-hardening (850-950 ℃ and 1 s^{-1}), and increasing continuously with significant work hardening (850 ℃ and 0.1 s^{-1}).

Optical microstructural analysis results of the samples are shown in Fig. 2, it is apparent that the microstructures of the deformed samples are characterized by approximately equated and fine grains under the two tested forming temperatures, which indicates DRX occurs. Furthermore, it is noted that as the forming temperature increased, the grain size coarsens and the dynamic recrystallized grains are finer than the original ones (Fig. 2(a)). Fig. 2(d) shows the microstructure of the studied 35CrMo steel at the temperature of 850 ℃ and the strain rate of 0.1 s^{-1} after hot deformation. A paradox is discovered between the stress-strain curve of Fig. 1(b) and the microstructure of Fig. 2(d). The phenomenon is DRX has taken place rather than DRV process by the optical microscope. It is unreasonable to judge from the strain-stress curve whether or not DRX occurred alone.



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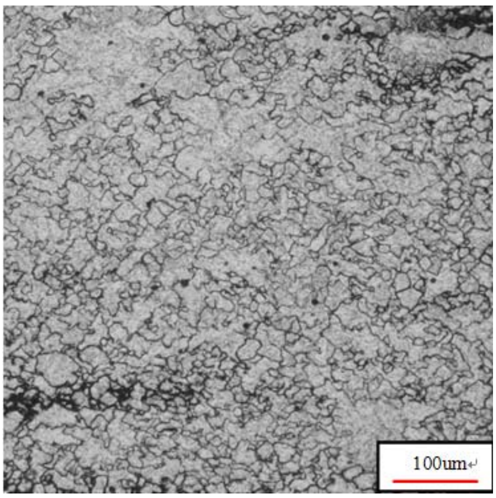

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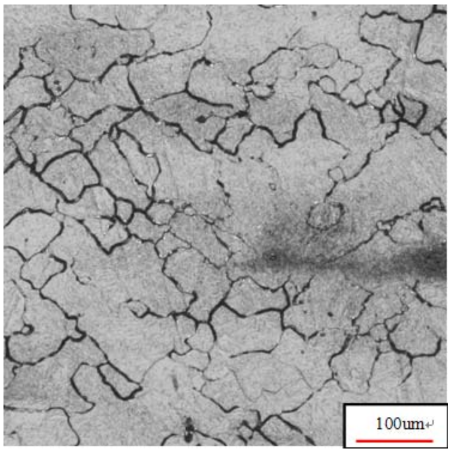

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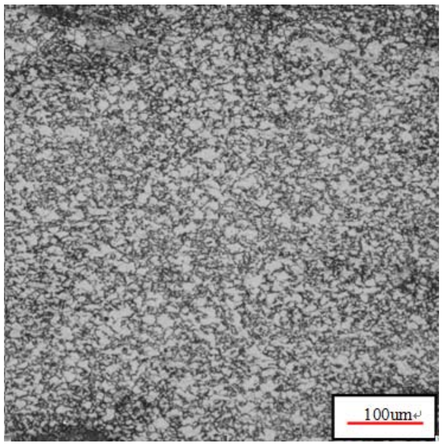

d.

Figure 2. Microstructures under the different conditions of:
(a) original; (b) strain rate of 0.01 s-1 and temperature of 850 oC; (c) strain rate of 0.01 s-1 and temperature of 1050 oC; (d) strain rate of 0.1 s-1 and temperature of 850 oC.

B. Deformation constitutive equations of true stress

Stress values (peak stress) of 35CrMo steel are obtained by compression tests at different temperatures and strains.

Several constitutive equations have been applied for description of the deformation process in hot working. It is based on the Arrhenius equation about Eq. (1) which can be expressed the relationship of the strain rate and flow stress, in addition to the temperature especially at high temperature. According to Eq. (1), the peak stress can be calculated at a given strain rate and temperature. Material constants like a , n , A and activation energy Q in the equation are the unkown parameters, which must be carried out. The effects of the strain rate and temperature on the deformation behavior can be represented by Zener-Hollomon parameter in an exponent-type equation. For $F(\sigma)$ in Eq. (1), the power law and the exponent-type equation apply to low stress and high stress respectively. The hyperbolic law gives a superior approximation between the Zener-Hollomon parameter and the flow stress.

In the high-temperature plastic deformation, the relationships among flow stress, strain rate and temperature can be used by hyperbolic sine form model propossed by W.J.M. Tegart and C.M.Sellars , which contains deformation activeation energy (Q) and temperature (T). These equations are confirmed precision by previous studies into the prediction of flow stress. They are frequently given by:

$$\dot{\varepsilon} = AF(\sigma)\exp[-Q/(RT)] \quad (1)$$

$$F(\sigma) = \sigma^n, \quad (\alpha\sigma < 0.8) \quad (2)$$

$$F(\sigma) = \exp(\beta\sigma), \ (\alpha\sigma > 1.2) \quad (3)$$

$$F(\sigma) = [\sinh(\alpha\sigma)]^n, \text{For all } \sigma \quad (4)$$

in which, α=β/n; n , α , β, and A are the material costants, Q is the activation energy of hot forming (K*J*mol-1); R is the universal gas constant and equal to 8.3145 J*mol-1*K-1; ε̇ is the strain rate(s-1); T is the absolute temperture(K); σ is the peak stress(MPa). The constant n is the stress exponent and the stress multiplier α is an adjustable constant which brings ασ into the correct range to make constant T curves linear and parallel. According to the study of C.Zener and H.Hollo-mon, the relationship of strain rate and temperature can be used by Z parameter:

$$Z = \dot{\varepsilon}\exp[Q/(RT)] = A[\sinh(\alpha\sigma)]^n \quad (5)$$

Physical meaning of the Z parameters is the temperature-compensated strain rate. Under the high stress and low stress, substituting the power law and the exponential law of F(σ) into Eq. (1), respectively, expressed as:

$$\dot{\varepsilon} = A_1\sigma^n \quad (6)$$

$$\dot{\varepsilon} = A_2\exp(\beta\sigma) \quad (7)$$

In which, A1 andA2 are the constants that are unrelated to the temperature. Taking the natural logarithm of both sides of Eqs. and , respectively, can be written as:

$$\ln(\dot{\varepsilon}) = \ln(A_1) + n\ln(\sigma) \quad (8)$$

$$\ln\dot{\varepsilon} = \ln(A_2) + \beta\sigma \quad (9)$$

They give the relationship between the flow stress and strain rate with Eqs. It is quite clear that the flow stresses obtained from the compressed tests can be approximated by a group of parallel and straight lines in the hot deformation conditions as shown in Figs. 2 and 3.

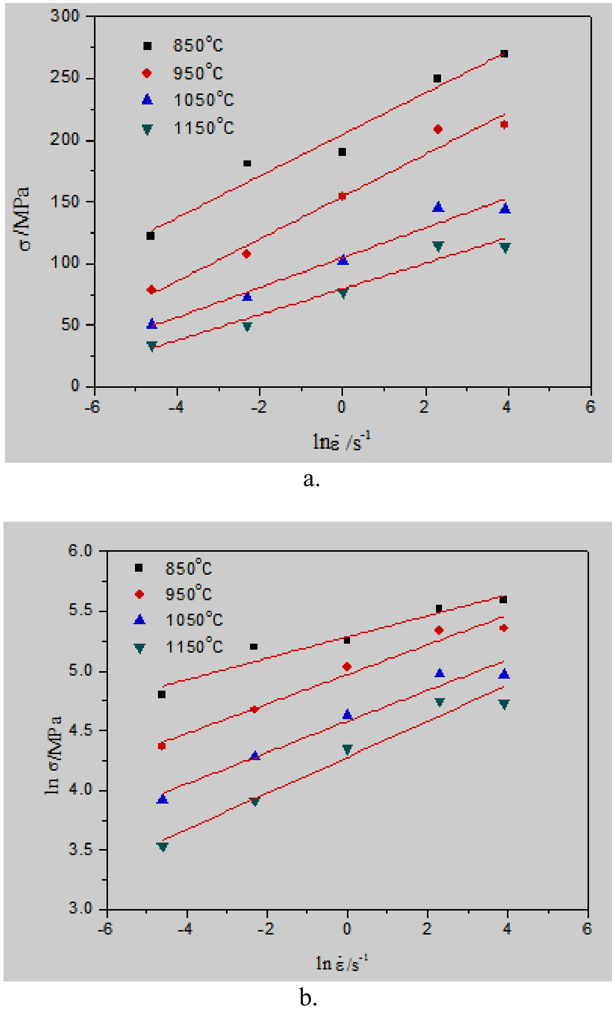

Figure 3. Relationships of $\ln\dot{\varepsilon}$ to σ (a) and lnσ (b) at different temperatures

By substituting the experimental data, namely true stress, true strain and the corresponding strain rates into Eqs and, the function relationships and curves of $\sigma - \ln\dot{\varepsilon}$ and $\ln\sigma - \ln\dot{\varepsilon}$ can be deduced. As shown in Fig. 3, obviously, the peak stress can be approximated by the group of parallel and straight line, also, the slope of those lines are approximately same .They are all linear relationships. It can be calculated line slope by taking the least squares linear regression, and figured the derivative and average of the slope out.

As shown in Fig. 1, the functional relation of flow stress, strain rate and thermoforming temperatures can be painted in accordance with experimental results. They satisfy the linear relationship among double logarithmic of steady flow stress and strain rate, hyperbolic sine logarithm of flow stress and the derivative with respect to temperature. It can be considered that the relationship between flow stress and strain rate in high temperature compression meets hyperbolic sine form, flow stress and deformation temperature satisfies

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Arrhenius relationship for 35CrMo steel. That is, it can be described rheological behavior during the high temperature deformation using Z parameter obtaining Arrhenius item.

For all stress level, Eq. can be given as:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp[-Q/(RT)] \quad (10)$$

There is an assumption that the thermal activation energy is unrelated to the temperature, taking the natural logarithm of both sides of Eq., gives:

$$\ln\dot{\varepsilon} = \ln A - Q/(RT) + n\ln[\sinh(\alpha\sigma)] \quad (11)$$

Data relationships of ln$\dot{\varepsilon}$-lnsinh(ασ) are fitted by using origin data processing software, and is analyzed with linear regression equation. Under the Corresponding deflection Temperature, linear correlation coefficient results of the four straight lines satisfy linearity requirements. So, it is can be shown that stress - strain relationship is reasonable by using hyperbolic sine function in the high temperature deformation. The average slope of the fitted straight line is 5.7803, namely n=5.7803. Results are shown in Fig. 4.

$$\ln[\sinh(\alpha\sigma)] = \ln\dot{\varepsilon}/n + Q/(nRT) - \ln A/n \quad (12)$$

Line chart described the relationship between lnsinh(ασ) and 1000/T in the origin software. The linear correlation coefficient results of the five straight lines satisfy linearity requirements. The curve of lnsinh(ασ) and 1000/T can be shown in the Fig. 4 under different strain rates. The value of Q can be calculated from Eq. 12 and Fig. 5. According to taking in the values of n and R, it can be easily evaluated the value of activated energy (Q) as 372.355 kJ/mol by averaging the values of Q under different strain rates.

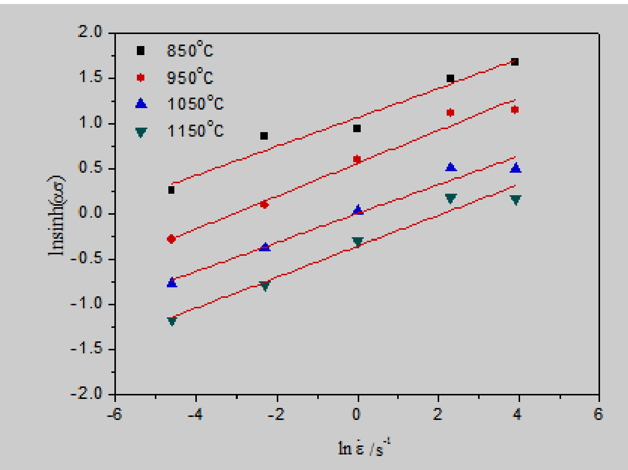


Figure 4. Relationships between lnsinh(ασ) and ln$\dot{\varepsilon}$ at different temperatures

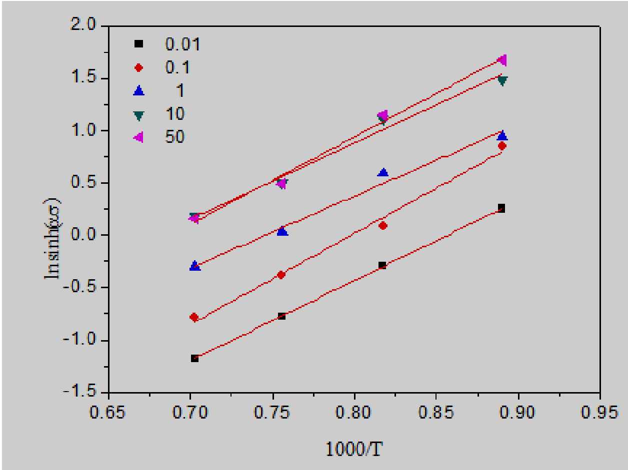


Figure 5. Relationship between lnsinh(ασ) and temperature at different strain rates.

By substituting the values of the strain rate and flow stress for all the tested temperatures into Eq., the relationship of lnsinh(ασ)-ln$\dot{\varepsilon}$ can be obtained as shown in Fig. 4. The value of the material constant A can be calculated by the intercepts of the straight lines with the longitudinal axis in Fig. 4 under each deformation temperature. That is A= 2.895 $\times 10^{14}$s^{-1}

According to the definition of the hyperbolic sine function and Eq., the flow stress coded into computer in the essay can be gotten. It can be shown as:

$$\sigma = \frac{1}{\alpha}\ln\{(\frac{Z}{A})^{\frac{1}{n}} + [(\frac{Z}{A})^{\frac{2}{n}} + 1]^{\frac{1}{2}}\} \quad (13)$$

Putting Qand deformation conditions into Eq(13)., Z can be calculated. The curve of $\ln Z - \ln[\sinh(\alpha\sigma)]$ can be drew and is analyzed with linear regression in Fig. 6.

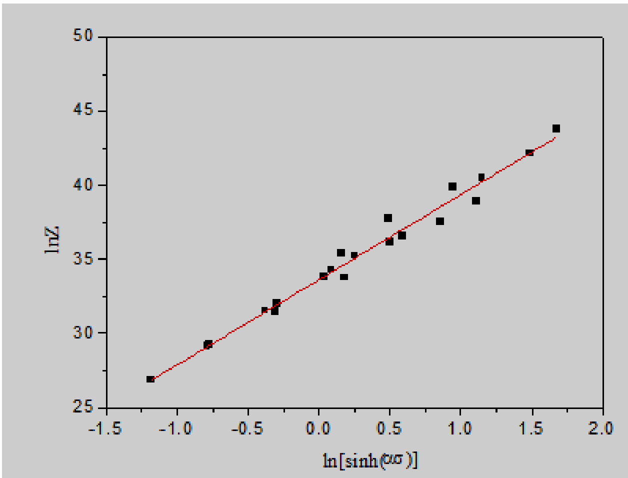


Figure 6. Relationship between ln sinh (ασ) and Z parameter.

The result satisfies linearity requirements in the range of strain rate and temperature, and further explained the relationships of temperature, flow stress and strain rate can be described by Eq. in pyroplastic deformation of 35CrMo.

Z parameter can be presented as:

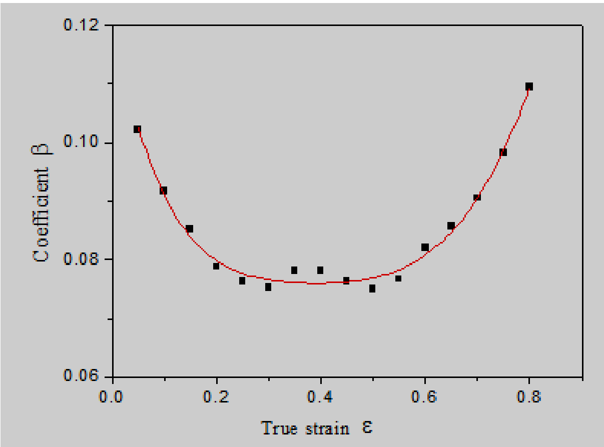
$$Z = \dot{\varepsilon}\exp[3.724\times10^5/(RT)]^n = 2.895\times10^{14}[\sinh(8.8\times10^{-3}\sigma)]^{5.7803}$$

Then flow stress can be written as:

$$\sigma = \frac{1}{0.0088}\ln\{(\frac{Z}{2.895\times10^{14}})^{\frac{1}{5.7803}} + [(\frac{Z}{2.895\times10^{14}})^{\frac{2}{5.7803}} + 1]^{\frac{1}{2}}\}$$

The values of material constants (Q, A, β, n and α) of the constitutive equations were computed under different deformation strains within the range of 0.05–0.8 with the interval of 0.05. The relationships between Q, lnA, β, n and α and true strain for 35CrMo steel (Fig. 7) can be polynomial fitted by the compensation of strain, as shown in Eq..

$$\begin{aligned}
\frac{Q}{1000} &= q_0 + q_1\varepsilon + q_2\varepsilon^2 + q_3\varepsilon^3 + q_4\varepsilon^4 + q_5\varepsilon^5 \\
\ln A &= A_0 + A_1\varepsilon + A_2\varepsilon^2 + A_3\varepsilon^3 + A_4\varepsilon^4 + A_5\varepsilon^5 \\
\beta &= \beta_0 + \beta_1\varepsilon + \beta_2\varepsilon^2 + \beta_3\varepsilon^3 + \beta_4\varepsilon^4 + \beta_5\varepsilon^5 \\
\alpha &= \alpha_0 + \alpha_1\varepsilon + \alpha_2\varepsilon^2 + \alpha_3\varepsilon^3 + \alpha_4\varepsilon^4 + \alpha_5\varepsilon^5 \\
n &= n_0 + n_1\varepsilon + n_2\varepsilon^2 + n_3\varepsilon^3 + n_4\varepsilon^4 + n_5\varepsilon^5
\end{aligned} \tag{14}$$



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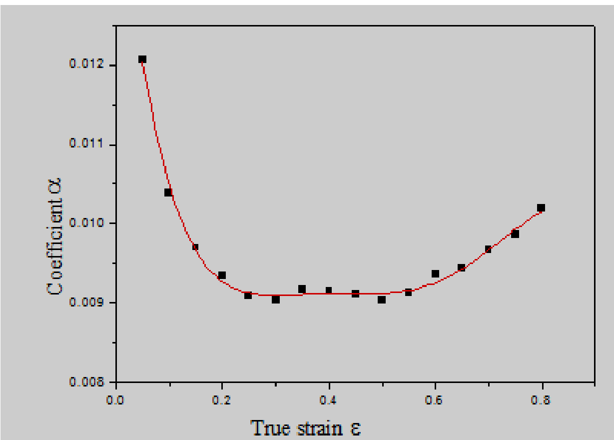

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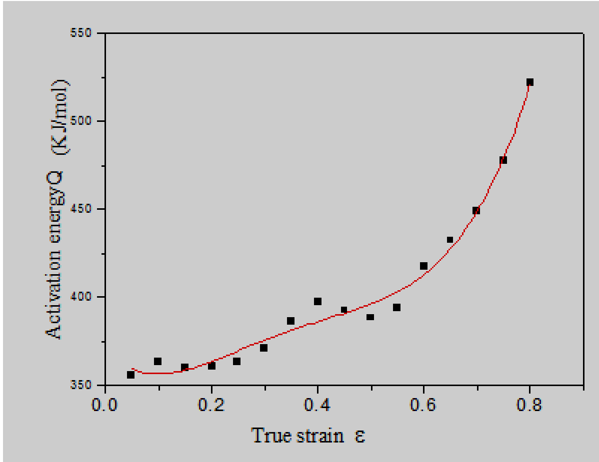

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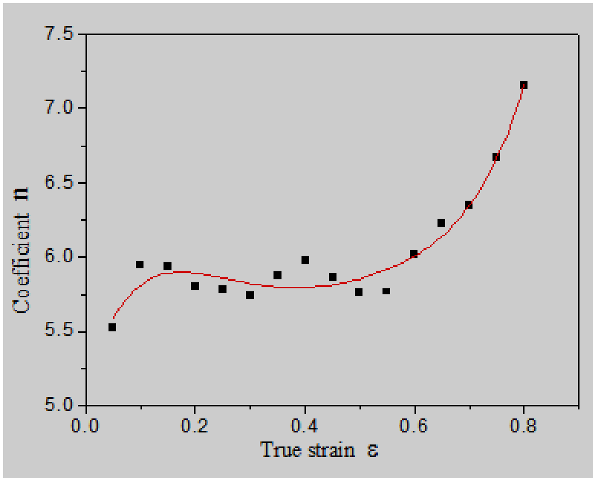

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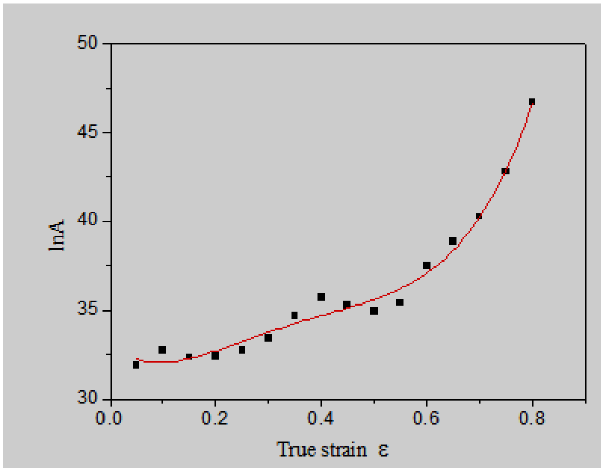

e.

Figure8. Relationship between (a) β ;(b) α ; (c) n ; (d) Q ; (e) $\ln A$ and true strain by polynomial fit of 35CrMo steel.

The polynomial fit results of Q, A, β, n and α of 35 CrMo steel are provided in Table 1.

TABLE I POLYNOMIAL FIT RESULTS OF Q，A，Β, N AND Α OF 35CRMO STEEL

Q		LnA		β	
q_0	369.31	A_0	32.971	$β_0$	0.121
q_1	-295.13	A_1	-22.78	$β_1$	-0.438
q_2	2129.8	A_2	170.10	$β_2$	1.736
q_3	-4783	A_3	-376.64	$β_3$	-3.433
q_4	4241.5	A_4	320.89	$β_4$	3.259
q_5	-803.12	A_5	-47.418	$β_5$	-1.067

Q		α		N	
q_0	369.31	$α_0$	0.015	n_0	5.126
q_1	-295.13	$α_1$	-0.065	n_1	12.335
q_2	2129.8	$α_2$	0.302	n_2	-70.487
q_3	-4783	$α_3$	-0.668	n_3	177.58
q_4	4241.5	$α_4$	0.707	n_4	209.09
q_5	-803.12	$α_5$	-0.283	n_5	97.683

B. Verification of the caculated constitutive equation

As depicted by L. Shi, H. Yang, a FEM model in Deform-3D was developed, and isothermal extrusion of the 6005A aluminum alloy was simulated under a series of simulation conditions, obtained the optimal solution.

By using the developed FEM model, isothermal extrusion of 35CrMo steel was simulated under the simulation conditions: initial height of the blank was 12 mm, diameter 10 mm, deformation temperature 850-1150 ºC and frictional factor 0.3. Pressing speed of die was determined by a constant strain rate of 0.1 s^{-1}. As is shown in Fig.8:

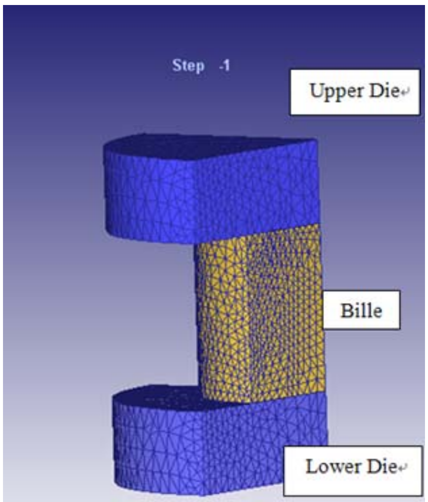

Figure 8. 3D cylindrical geometric model

The blank area can be easily computed the point no matter where in the operational process according to adopt the law of same volume .The finite element simulation was calculated, and the optimal process parameters can be gotten.

The true stress and true strain can be described as followed:

$$\sigma = \frac{F \cdot (h_0 - \int_0^t v_0 \cdot \exp(\dot{\varepsilon} \cdot t) dt)}{h_0 \cdot s_0} \quad (15)$$

$$\varepsilon = \ln \frac{h_n}{h_0} \quad (16)$$

Where F is the axial load of the die, h0 is primary height of the blank, vo is the primary velocity of the top die, $\dot{\varepsilon}$ is strain rate,t is the runtime of top die and hn is the height of the blank.

As shown in Fig. 9, compared with the simulated values, the experimental values show good accordance of the data sets, which indicated that the proposed constitutive model is reliable.

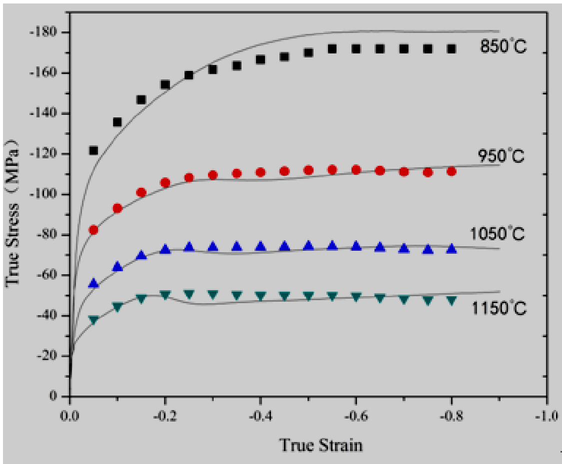

Figure 9 Comparison between the calculated and the experimental flow stress in the isothermal compression of 35CrMo steel at strain rate of 0.1s^{-1}.

IV. CONCLUSION

This paper is a one-hour lecture on the topic of fault current limiter presented to engineering students. The lecture has started with the causes and effects of fault on power systems. The traditional ways of fixing fault current have been described. The detailed analysis of two types of fault current limiters: based on magnetic materials and high temperature superconductor materials have been presented. With some modification (elimination of mathematical part) the lecture can be presented to general public.

In the present work, the flow behavior of 35CrMo steel carried out by the thermoforming experiments under the temperatures range of 850-1150 ℃ at an interval of 100℃

and at strain rates ranging from 0.01~50 s^{-1}. The following conclusions are drawn:

(1) The peak stress decreased with increasing deformation temperature and decreasing strain rate. It is based on the Arrhenius equation to indicate the effect of thermoforming behavior which can be expressed the relationship of the strain rate and temperature. That is, under constant deformation temperature, the flow stress increases with the increase of strain rate; under constant strain rate, the flow stress decreases with the increase of deformation temperature.

(2) The grain size coarsens as the forming temperature increased, and the dynamic recrystallized grains are finer than the original microstructure. It is unreasonable to judge from the strain-stress curve whether or not DRX occurred alone pursuant to comparison the calculated stress-strain curve of Fig. 1(b) and specific microstructure of Fig. 2(d).

(3) Deformation activation energy Q of 35CrMo steel increased as the rise of true strain, and flow stress deformation constitutive equation during hot compression can be described as:

$$\dot{\varepsilon} = 2.895\times10^{14}[\sinh(0.0088\sigma)]^{5.7803}\exp(\frac{-372.355\times10^{3}}{RT})$$

This obtained constitutive equation can be used to the veracious description with tested stress of the 35CrMo steel.

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