International Journal of ISSI, Vol.11 (2014), No.1, pp . 31-34

Microstructural Evolution of X45CrNiW189 Valve Steel During Hot Deformation

A.H. Meysami[1] , R. Amini Najafabadi[2]*
Metallurgy & Material Dept., Golpayegan University of Technology,
P.B.: 87717-65651, Golpayegan, Iran.

Abstract

The hot compression tests were carried on X45CrNiW189 valve steel (X45) in the temperature range of 1000– 1200 °C and the strain rate range of 0.004 – 0.5 s^{-1} in order to study the high temperature softening behavior of this steel. For the exact prediction of flow stress, the effective stress-effective strain curves were obtained from experiments under various conditions. On the basis of experimental results, the dynamic recrystallization fraction (DRX), austenite grain size (AGS), hot deformation and activation energy behavior were investigated. It was found that the calculated results were in a good agreement with the experimental flow stress and the microstructure of the steel for different conditions of hot deformation.

Keywords: X45CrNiW189, Valve, Compression, Recrystallization, Deformation.

1. Introduction

The X45CrNiW189 (X45) is a high-alloy austenitic valve steel. Usually, it is used in medium stressed outlet valve. Sodium cooling highly stressed outlet valve is used in all aspects of aviation, aerospace, shipbuilding, petromechemical, medical instruments, etc. up to 730 °C operating temperature. These products are made by hot forging processes in the temperature range of 1000-1200 °C.

In order to design and develop the required products and also, to predict the microstructure and the properties of the component, the mathematical model of hot forming processes has been applied increasingly such that it has become a very important tool[1-9)].

Accurate prediction of the grain size due to microstructure evolution will be helpful in the improvement of steel products after hot forming[5,6)]. However, a model describing the dynamic recrystallization and austenite grain size (AGS) for carbon and alloyed steels has not been developed yet, but process simulation can be used to optimize the process parameters. Physical Simulation of materials processing involves the exact reproduction of the thermal and mechanical processes in the laboratory such that the material can be subjected to actual fabrication or end use and mathematical simulations can provide the further development of new products with controlled microstructures. In terms of physical simulation, hot torsion and /or compression tests are normally used to acquire the steel flow behavior and these data are further employed to model the hot rolling of strip, plate, bar and rod [6,7)]. Since the microstructural evolution model is the function of a large number of parameters, the complete models will take the form expressed as a function of temperature, strain, strain rate, inter pass time, restoration process, pre-test thermal history and the potential for precipitation.

The relation between the austenite grain size and deformation conditions becomes complicated when the influence of restoration process is considered. The contribution of dynamic recrystallization (DRX) to austenite grain size (AGS) modeling is very important; many researchers have considered that 100% dynamic recrystallization occurs if the applied strain exceeds a critical strain (ε_c) [4-6,8)]. However, the decrease of flow stress and AGS after peak strain (ε_p) with increasing strain means that the softening process by dynamic recrystallization is still in progress. Therefore, for a more precise calculation of DRX, it has been considered that as a function of strain rate, a combination of Zener-/Hollomon parameter needs to be incorporated into the model [6-10)].The Zener–Hollomon parameter is used to help describe the high temperature strain of a material such as steel. The working temperature and strain rate are combined and expressed by the Zener–Holloman parameter, $Z=\varepsilon^{\circ}\exp(\frac{Q}{RT})$, where ε° is the strain rate, R is the gas constant, T is the temperature, and Q is the related activation energy[10)]. This parameter appears to be useful in predicting the resulting grain size and controlling the hot working parameters.

In this work, a procedure has been proposed and applied to investigate the hot deformation of X45CrNiW189 steel by analyzing flow stress curves of the material.

**Corresponding Author*
Email: amirhossein.meysami@gmail.com
Address: Metallurgy & Material Dept., Golpayegan University of Technology,
P.B.: 87717-65651, Golpayegan, Iran.
1. Assistant Professor
2. Assistant Professor

DRX, which affects the flow stress and AGS, is expressed by modified Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation. The JMAK equation describes how solids are transformed from one phase to another at constant temperature. It can specifically describe the kinetics of crystallization and is, therefore, generally applicable to other changes of phase in materials, like chemical reaction rates. It can even be meaningful in the analyses of ecological systems 6). Modified JMAK's equation includes the strain at the maximum softening rate (ε^*) as well as the critical strain (ε_c) for DRX initiation. Predicted AGS was compared with the experimentally measured one.

2. Materials and Methods

The chemical composition of X45CrNiW189 steel is given in Table 1. This grade of steel was produced by continuous casting process at Iran alloy steel Co. Hot compression tests were performed to investigate the hot deformation behavior of the material. The high temperatures of material were acquired by enclosing the specimen in an electrical furnace. The specimens with a gauge length of 15 mm and the diameter of 10 mm were carefully machined and pre-heated up to 1250 °C in the furnace holding for 3 minutes to obtain a uniform temperature. It should be noted that prior to hot compression test, the AGS of annealed samples at 1250 ºC was measured for 5 minutes according to ASTM standard E112 before deformation was measured to be 120 µm. The samples were further placed into hot compression test chamber immediately for testing. To investigate the effects of deformation temperature and strain rate on the microstructure and flow stress, continuous compression tests were conducted in the temperature range of 1000-1200 ºC and the strain rate range of 0.004 – 0.5 s^{-1}. As the X45CrNiW189 steel is a high strength alloy steel, the hot compression instrument used was 200 tons INSTRON. The preliminary experiment showed that this tonnage was adequate for tests. In order to reduce the friction effect between the specimen and the jaw, mica sheets were used.

The water quenched specimens, after compression tests, were polished in horizontal and vertical sections and then etched with a solution including $CuCl_2$-HCl solutions in water. The grain size was determined on immediately quenched specimens after deformation to evaluate the DRX model.

Table 1. Chemical composition of X45CrNiW189 steel used in this work

Sn	Mo	P	S	Cu	W	Co	Mn	Si	Ni	Cr	C	Element
0.1	0.01	0.02	0.03	0.05	0.8	0.1	1.2	2.5	9	18	0.43	wt%

3. Results and Discussion

3.1. High temperature stress-strain curves

Figs. 1 shows the stress-/strain curves for the X45CrNiW189 steel obtained at various temperatures and strain rates. The flow curves exhibited the peak and softening to an extensive steady state, thereby indicating DRX behavior. As shown in Figs. 1, at lower strain rate, the flow stress and peak stress were decreased and the steady state region was more extensive. Each curve primarily consisted of four distinct segments. First, the work hardening rate was increased linearly with the flow stress over the stress-/strain curve from σ=0 to the stress in which the onset of sub-grain formation could not be observed from curves (σ_c). Second, the σ-ε curve was gradually changed into a lower slope linear segment. Third, the curve was dropped towards $d\sigma/d\varepsilon$=/0 at peak stress, σ_p, indicating that DRX became effective6.10). One of the objectives was to identify the strains σ_c, σ_p, ε_c and ε_p. The critical point for the initiation of DRX was determined using the method of Polliak and Jonas as modified by Najafizadeh and Jonas11).

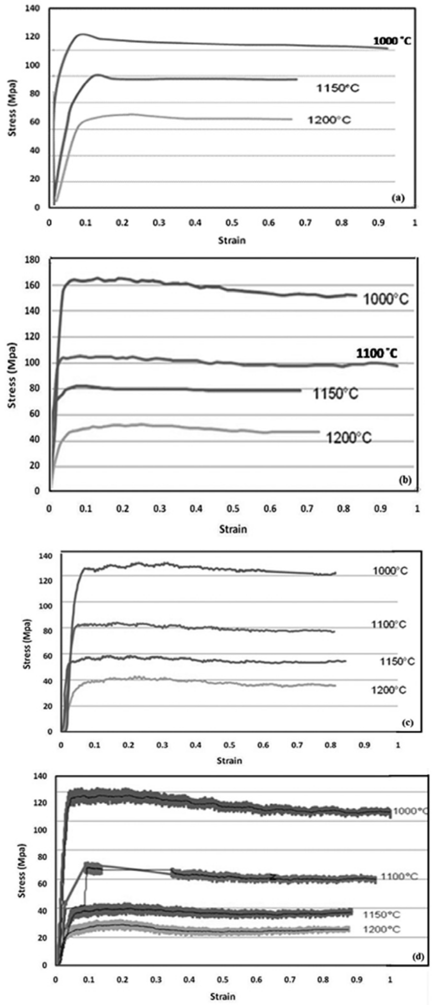

Fig. 1. Stress-Strain curves in the hot compression of X45CrNiW189 steel at various strain rates:
(a): 0.5 s^{-1}, (b):0.1 s^{-1}, (c): 0.02 s^{-1} and (d): 0.004 s^{-1}.

Fig. 2 presents the variations of pick stress temperature at different strain rates. From this figure, the pick stress and strain (σ_c and ε_c as identified above) for the onset of DRX at various temperatures were obtained.

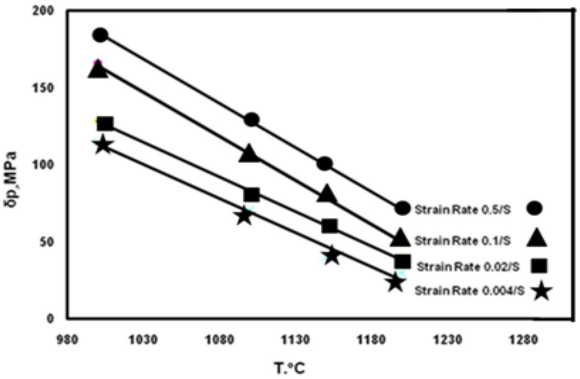

Fig. 2. Variations of pick stress temperature at different strain rate

Table 2 shows the values of σc and εc for the hot compression test of the steel as extracted from Fig. 1.

Table 2. Values of σ_c, σ_p, ε_c and ε_c for hot compression tests.

Temperature ° C (strain rate s^{-1})	σ_c (MPa)	σ_p(MPa)	ε_c	ε_p
1000 (0.5)	84.4	130	0.0098	0.18
1000(0.1)	140	160	0.0192	0.2
1000 (0.02)	95	122	0.0393	0.22
1000 (0.04)	83	114	0.0002	0.16
1150 (0.5)	80	100	0.01	0.16
1150(0.1)	60	80	0.015	0.11
1150 (0.02)	4.45	33.41	0.01	0.34
1150 (0.04)	40	55	0.04	0.13
1200(0.5)	35	63	0.012	0.2
1200 (0.1)	20	45	0.05	0.17
1200 (0.02)	20	40	0.05	0.1
1200 (0.04)	25	30	0.07	0.18

Fig. 3 illustrates a plot of ln ε^{o} versus ln(sinh(α σ_p) at various temperatures. The slope of these lines represents the value of n´ in Eq. (1)[12]:

$$Z = A(\sinh \alpha\sigma_p)^{n'} \tag{1}$$

Z is Zener-Hollomon parameter, which is represented by Eq. (2) [11]:

$$Z = \varepsilon^{\circ} \exp(\frac{Q}{RT}) \tag{2}$$

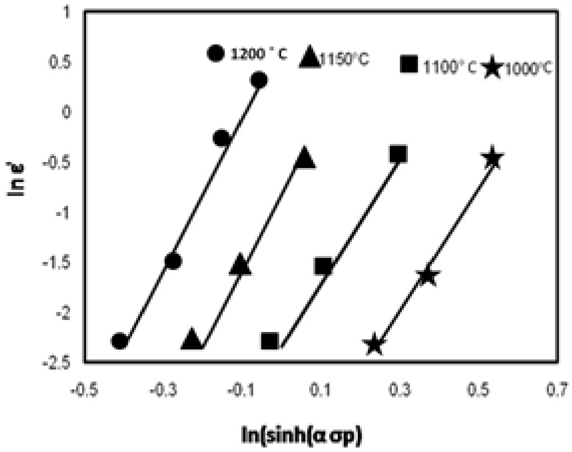

Fig. 3. Plot of ln ε versus ln(sinh(α σp) at various temperatures.

In Equations (1) & (2), A, n´ and α are material constants, and R and Q are the gas constant and activation energy, respectively. A and n´ can be determined from the relationship between stress and strain rate. Therefore, it can be seen that n´ in Eq. (2) for 1000- 1200 ºC is about 4.15. The activation energy of deformation, Q, can then be calculated from the relationship between stress and the reciprocal of the absolute temperature (1/T).

Fig. 4 illustrates the values of n´ln(sinh(α σ_p) versus 1/T at various strain rates. By using the slope of the lines (Fig. 3), the activation energy of deformation could be calculated. Therefore, the average of hot deformation activation energy for strain rates 0.004 -0.1 s^{-1} was 398 kJ/mol.

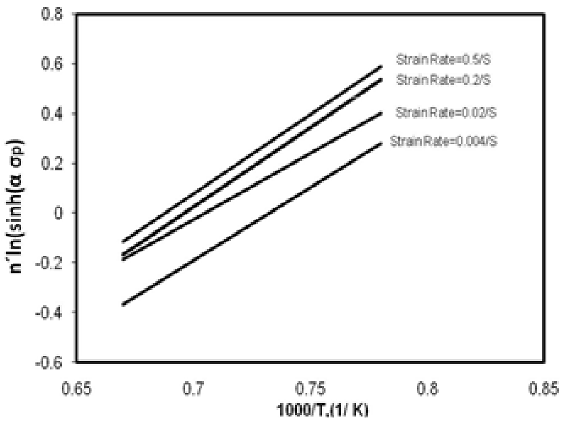

Fig. 4 Values of n´ln(sinh(α σp) versus 1000/T at various strain rates.

Since the DRX is a continuous process of deformation (with the nucleation of grains and the migration of grain boundaries), XDRX was increased with increasing the strain. Dynamic recrystallization produced new austenite grains and these grains could dynamically grow during hot deformation. It has been proposed that dynamic recrystallized (DRX) austenite grain size (AGS) during deformation can be formulated as follows[11]:

$$D_{DRX} = BZ^r \tag{3}$$

where B and r are 1.8×10^3 and -0.15, respectively.

Fig. 5 shows the calculated and measured AGS variations versus strain rate at different temperatures by Eq. (3). Based on this plot, increasing the temperature and decreasing the strain rate made austenite grains grow. By decreasing the strain rate, there was more time for atoms diffusions; also with increasing the temperature, the activation energy for atoms diffusions was increased. Both decreasing strain rate and increasing temperature increased dynamic growth at high temperatures and low strain rates. There was also a good agreement between measured and calculated AGS by Eq. (3) model.

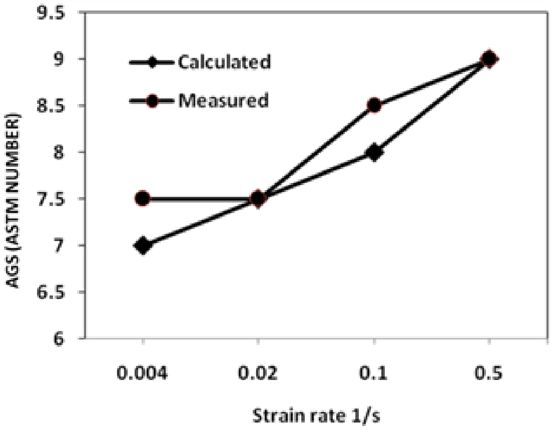

Fig. 5. Variations of austenite grain size versus strain rate at different temperatures.

Fig. 6 illustrates microstructures of hot deformation samples with the temperature of 1150 ºC and the strain rate of 0.05 s-1. The recrystallization grains and grain boundaries can be seen in these figures. Increasing temperature in a constant strain rate increased the AGS. This phenomenon is related to the increase of the atomic diffusion (as explained above).

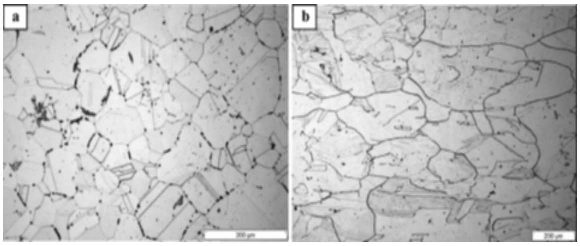

Fig. 6. Optical metalograph of hot deformation samples in the strain rates of 0.05s $^{-1}$: (a) 1200 ºC and (b)1000 ºC.

4.Conclusions

In this study, the modified JMAK model was developed to predict DRX, AGS and activation energy of hot deformation X45CrNiW189 high alloy carbon steel using hot compression test in the temperature range of 1000 -1200 ºC and the strain rate range of 0.004 -0.1. s^{-1} Based on the results obtained, the following conclusions can be drawn:

- The hot compression behavior of the X45CrNiW189 steel made the flow curves exhibit the peak and soften to an extensive steady state, thereby indicating DRX behavior in the mentioned temperature range.
- Activation energy for hot compression test of this steel at the strain range of 0.004 – 0.5 s^{-1} was found to be 398 kJ/mol.
- Both decreasing the strain rate and increasing the temperature in hot compression enhanced grains dynamic growth.
- There was a good agreement between measured AGS and AGS predicted by the modified JMAK model presented in this paper.

References

[1] A.H. Meysami, R. Ghasemzadeh, S.H. Seyedein, M.R. Aboutalebi, R. Ebrahimi, M. Javidani, J Iron Steel Res Int., 16(2009),47.

[2] M. Hajisafari, A.H. Meysami, EUR J SCI RES., 102(2013), 235.

[3] M. Hajisafari, A.H. Meysami, EUR J SCI RES., 107(2013), 7.

[4] H. Lee, H. Kwon, Y. Im, P.D Hodgson, J Mater Process Tech., 191(2007), 114.

[5] B. Smoljan, Mater Manuf Process., 24(2009), 786-790.

[6] D.N. Kamble, V. M. Nandedkar,. Mater Manuf Process., 26(2011), 677.

[7] S. B. M. Echrif, M. Hrairi, Mater Manuf Process., 26(2011), 1404.

[8] H. Faris, A.Sheta, Mater Manuf Process., 26(2013),762.

[9] S. Kim, Y. Yoo, Mater Sci Tech., 18(2002), 160.

[10] P. D. Hodgson, Mathematical modeling of recrystallization process during hot rolling of steels; Ph. D. thesis, University of Queensland, 1993.

[11] A. Najafizadeh, J.J. Jonas, G.R. Stewart, E.I. Pollak, Metall Mater Trans A, 37A(2006), 1899.

[12] P. D. Hodgson, R. K. Gibbs, ISIJ Int., 32(1992), 1329.