doi:10.11835/j.issn.1671-8224.2018.02.03

To cite this article: ZHANG Suo-quan, JIAO Si-hai, DING Jian-hua, WANG Quan-sheng. Effect of carbon, silicon, and manganese content on mean flow stress at elevated temperature [J]. J Chongqing Univ Eng Ed [ISSN 1671-8224], 2018, 17(2): 55-60.

Effect of carbon, silicon, and manganese content on mean flow stress at elevated temperature *

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Received 13 January 2018; received in revised form 27 March 2018

Abstract: Ten studied steels including different carbon content, silicon content, and manganese content were deformed in compression over a temperature range of 600 °C to 1 000 °C at the strain rate of 1 s^{-1}. The curves of the mean flow stress-deformation temperature were drawn up. The mean flow stresses of higher carbon content steels decreased continuously as the applied deformation temperature increased in the whole temperature range, while the mean flow stress of lowest carbon steel displayed an abrupt drop near the two phases region. The reason for the abrupt drop phenomena was explained as the result of phase transformation. The mean flow stresses of steels with high silicon content and low manganese content also have this phenomena.

Keywords: carbon content; silicon content; manganese content; high temperature deformation; mean flow stress

CLC number: TF761 Document code: A

1 Introduction

It is well known that the mean flow stress (MFS) is determined by the chemical element content, deformation temperature, strain and strain rate, while it is not easy to calculate the mean flow stress accurately. Over the past several decades, several researchers had systematically investigated the factors that influence the mean flow stress. The previous work [1-14] on mean flow stress has indicate that there is a the abrupt change and minimum of stress on the mean flow stress-deformation temperature curves. There have been a few studies highlighting the solid solution hardening of silicon and manganese. Great progress has been made in this field, it is generally accepted that the flow stress-temperature curves will have an abrupt drop near Ar3 temperature for low carbon steels with lower strain rate. The drop will move the position with different carbon content, as shown in Fig. 1. The aim of this study was to systematically study the effects of carbon, silicon, and manganese on the MFS at high temperature.

2 Experiment materials and method

The steels used in this study have 10 different chemical composition (Table 1). The ingots were cast

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* Funded by Shanghai Pujiang Program (No. 16PJ1430200).

in a vacuum induction furnace, then directly forged into cuboid samples, the hot rolling were conducted after forging, and finally cylindrical samples 8 mm in diameter and 12 mm in length were machined from hot rolled plates.

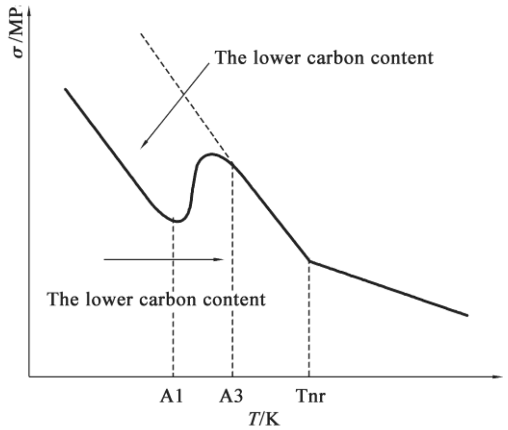

Fig. 1 Schematic diagram of the effect of carbon on the mean flow stress

To investigate the effect of carbon, silicon and manganese content on flow stress at elevated temperature, simulation experiments were conducted by using THERMOMASTER-Z thermo-mechanical simulator. As shown in Fig. 2, under the vacuum condition of less than 7 Pa pressure, these samples were heated to 1 050 °C at the heating rate of 20 °C/s from room temperature, and kept there for 300 s. Then these samples were cooled to the deformation temperature at a rate of 10 °C/s, held for 30 s before deformation, and then deformed isothermally to 60% strain at different deformation temperatures from 600 °C to 1 000 °C. The temperature interval is 40 °C, and the strain rate was $1s^{-1}$. After the deformation, these samples were quenched immediately to room temperature. The deformation temperatures, strain, and stress were recorded by means of the software program automatically.

3 Result and discussion

For 110 deformation of samples, the flow stress-deformation temperature curves were obtained from above experiments automatically by software program. The MFS for all samples were calculated by using the equation in Fig. 3. The calculated strain φ1 in equation was 0, and φ2 was 0.8.

Table 1 Chemical composition of the studied carbon steels in terms of weight fraction %

	C	Si	Mn	P	S
BA	0.164	0.255	0.523	0.006 52	0.002 10
A1	0.057	0.263	0.511	0.005 40	0.002 28
A2	0.464	0.266	0.499	0.005 76	0.000 26
A3	0.794	0.273	0.487	0.005 50	0.000 01
B1	0.153	0.035	0.550	0.006 88	0.005 00
B2	0.148	0.634	0.540	0.006 69	0.002 16
B3	0.153	1.457	0.527	0.006 95	0.001 06
C1	0.161	0.238	0.245	0.006 64	0.003 90
C2	0.148	0.272	0.980	0.007 10	0.002 59
C3	0.155	0.261	1.454	0.007 02	0.003 00

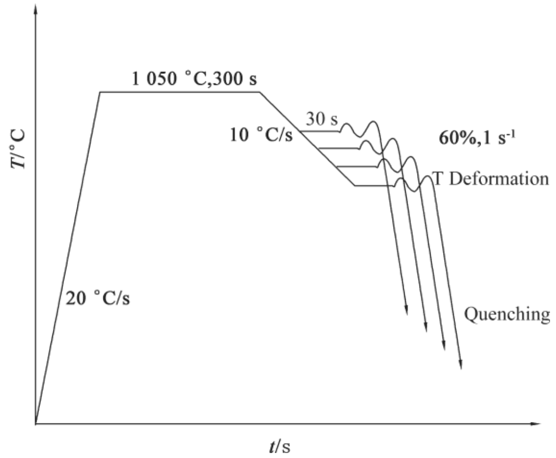

Fig. 2 Schematic draw of the experiment

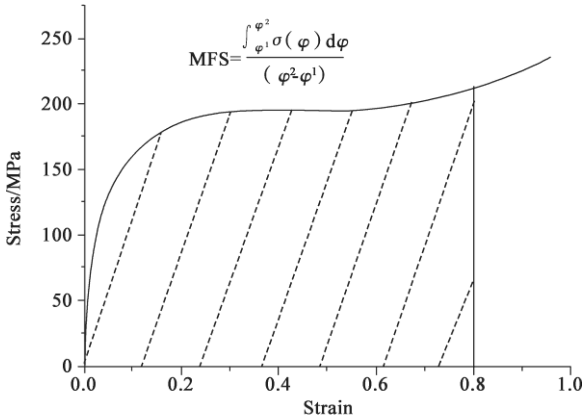

Fig. 3 Schematic diagram of calculating the mean flow stress (MFS)

3.1 Effect of carbon content on the MFS

Fig. 4 shows that the MFS at a high temperature (austenite region) has no significant difference for 4 studied steels at the same deformation temperature. At low strain rate, there is a transition zone between solid solution hardening and solid solution softening, so the carbon content has no significant effect on the MFS here [3]. The MFS at lower deformation temperature increases sharply with increasing carbon content at a certain deformation temperature. It should be the result of more cementite and lower ferrite fraction for higher carbon content, and the precipitation strengthening of carbide is the main strengthening mechanism here.

It is important to note that the MFS for A2 and A3 increase continuously with the decreasing deformation temperature. However, an abrupt change and minimum of flow stress were found for A1 in the γ+α region. The MFS of BA sample also has the similar phenomena but no minimum take place. This conclusion is the same as the results of previous studies.

The ferrite transformation at higher temperature is the reason for significant drop on the MFS-deformation temperature curve. Based on the JMatPro calculation result, the calculated A3 temperature of A1steel is 883.1 °C. Actually the sample cooled to 800 °C at the cool rate of 10 °C/s and held 30 s will start ferrite transformation. At this temperature, the MFS of austenite is much higher than that of ferrite, so there is a significant drop on the stress-deformation temperature curves. While the calculated A3 temperature of A2 steel is 775.2 °C, which is relative lower than A1 steel. Meanwhile, the higher carbon content move the C curve of ferrite right, which also retard the transformation, which start at 720 °C. At this time, the difference of MFS between austenite and ferrite is relative small, there are no abrupt change and minimum of flow stress for A2 and A3 [15].

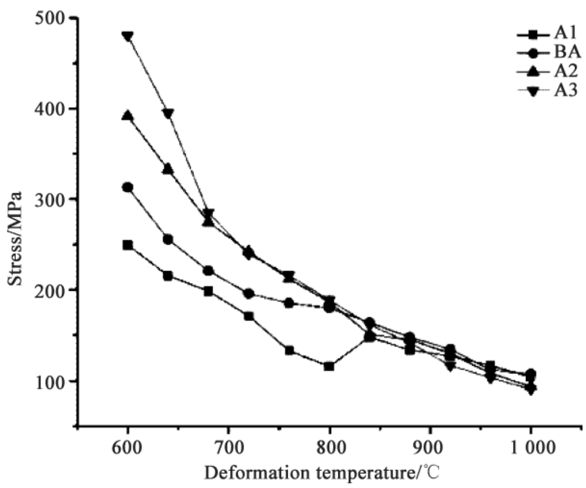

Fig. 4 Mean flow stress- deformation temperature curves with different carbon content

3.2 Effect of silicon content on the MFS

As shown in Fig. 5, in both austenite and ferrite regions, the MFS increases with the increase of silicon content. The solid solution strengthening of silicon is the main reason for the increase of MFS. The solid solution of the alloy elements leads to the distortion of the matrix lattice, which increases the resistance of dislocation motion and increases the strength. The difference between the size of the substitution atom and the size of the iron atom affects the effect of solid solution strengthening, the silicon atom is 8.5% smaller than the iron atom. Each increase of 1% silicon atoms can increase the high temperature strength of 8.3% at 1 000 °C.

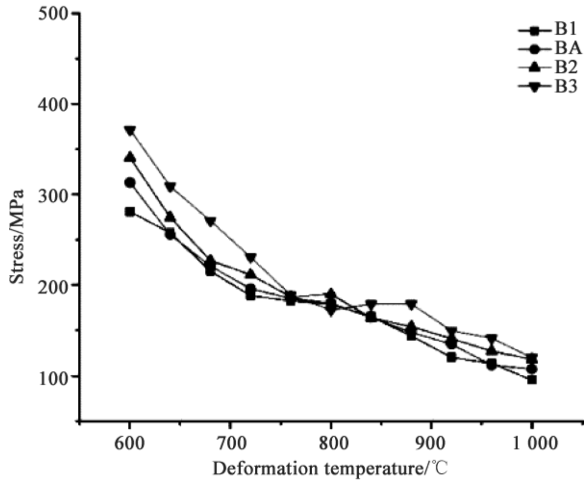

Fig. 5 Mean flow stress-deformation temperature curves with different silicon content

At the same time, the MFS for B1 and BA increase continuously with the decreasing deformation temperature, while B2 and B3 have minimum of flow stress at 760 °C and 800 °C, respectively. The ferrite transformation at higher temperature is the reason for significant drop on the MFS-deformation temperature curve. Studied steel B3 has higher ferrite start temperature due to higher silicon content than B2.

3.3 Effect of manganese content on the MFS

Compared with silicon, the solid solution strengthening effect of manganese is slightly smaller because of the smaller size difference between manganese and iron atoms. The diameter of the manganese atom is 4.7% larger than that of the iron. It is reported that the increase of 1% of manganese results in an increase of high temperature intensity by 4% at 1 000 °C [17], while the increase in austenite area is not significant in this study.

The studied steel C1 has a minimum of MFS at 760 °C (Fig. 6), while the MFS of other studied steels increase with the decreasing deformation temperature. The ferrite transformation at 760 °C is also the reason for abrupt drop on the MFS-deformation temperature curves.

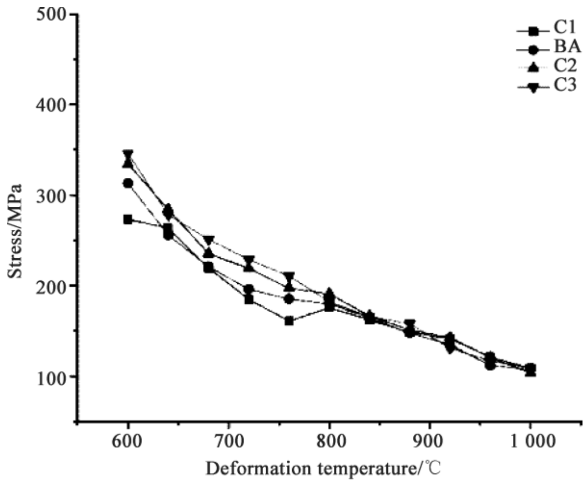

Fig. 6 Mean flow stress-deformation temperature curves with different manganese content

3.4 Strengthening effect of carbon, silicon, and manganese

Fig. 7 shows the strengthening effect of carbon, silicon, and manganese on the high temperature strength of steel.

The carbon and manganese content has little effect on the flow stress in the austenite region. The increase of silicon content increases the flow stress in the austenite region. The increase of the content of carbon, silicon and manganese has an obvious increase in the flow stress in the ferrite region, the most significant influence is carbon content, followed by silicon and manganese. The difference of the strengthening mechanism is the main reason, and the difference in size of these atoms and iron atoms is also an important reason.

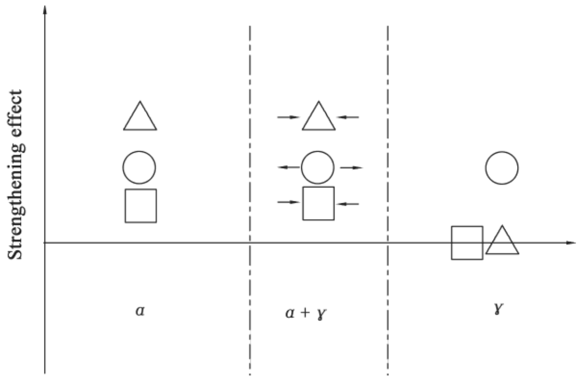

Fig. 7 Schematic diagram of strengthening effect of C, Si, Mn where Δ, ○ and □ represent the strengthening effect of C, Si and Mn on the flow stress at high temperature

At the same time, the increase of the silicon content enlarges the two-phase region and increases the temperature of Ar3, and then the minimum of the flow stress in the two phase region takes place. The increase of carbon and manganese content reduces the Ar3 temperature, and the minimum of flow stress in the two-phase region disappears.

4 Conclusion

From the discussion above, the following conclusions could be drawn:

1) At the studied deformation rate, the carbon content has no significant influence on the MFS of austenite region. The low carbon steel has an abrupt drop on the MFS-deformation temperature curve, while the higher carbon steels does not have this phenomena. In the low temperature ferrite region, the increasing carbon content significantly increases the MFS.

2) The solid solution strengthening of silicon results in an increasing of MFS. Steel with higher silicon has higher ferrite transformation start temperature in this study, which results in an abrupt drop on the MFS-deformation temperature curve.

3) In the austenite region, the effect of solid solution strengthening of manganese is not significant. With the increase of manganese content, the MFS-deformation temperature curve has no an inflection point any more.

Acknowledgments

The authors would like to express their sincere appreciation to ZHANG Ge and JIN De-long for their support in experiment.

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