Research Article

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Hot deformation behaviors and microstructure characteristics of Cr–Mo–Ni–V steel with a banded structure

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Abstract: On a Gleeble-3800 thermal simulator, the hot deformation behavior of Cr–Mo–Ni–V steel was studied, with the designed deformation temperature varying from 900 to 1,200°C and the strain rate in the range of 0.01–10 s⁻¹. It was observed that as the strain rate was increased and the hot working temperature was reduced, the flow stress of the experimental steel increased. The study also evaluated the safe parameters for deformation of the Cr–Mo–Ni–V steel in the hot working process, based on the established processing maps. It was found that the deformation temperature window varying from 1,050 to 1,150°C and the reasonable strain rate in the range of 0.01–1 s⁻¹ are beneficial to the hot deformation of the steel. In this research, the effect of processing parameters of the hot working process on the microstructure evolution of the banded structure was also investigated. According to the research result, the banded structure in the steel remained visible under the conditions of a strain rate of 10 s⁻¹ and the hot working temperature in the range of 900–1,200°C. However, it should be noted that the banded structure in the steel then gradually disappeared when the hot working temperature was increased to 1,200°C.

Keywords: hot deformation behavior, Cr–Mo–Ni–V steel, banded structure, processing map

1 Introduction

Considering the excellent hardenability, high strength, and favorable toughness, Cr–Mo–Ni–V steel has usually been used as a structural component for gun barrels and ultra-high-pressure vessels. Mechanical properties and hardenability of the steel could be enhanced by adding a small amount of alloying elements. However, segregation of these alloying elements during smelting and forging could induce the banded structure formation in such steels [1–5]. According to Du et al., the segregated Cr, Ni, V, and Mo alloying elements in the microstructure were identified as the primary cause for the generation of the banded structure in Cr–Mo–Ni–V steel [6].

Previously reported research works on Cr–Mo–Ni–V steel have generally focused on their precipitation behavior and the relationship between microstructure characteristics and mechanical properties, while the interactions between the banded structure and hot deformation behavior have attracted much less attention [6–10]. In addition, the hot working process is particularly important to obtain excellent mechanical performance of the steel. Song et al. studied the effect of phase transformation in 2205 duplex stainless steel on the strain rate by the hot working process [11]. Pu et al. studied the processing maps for S32654 super-austenitic stainless steel to improve its hot deformation characteristic [12]. Thus, it is meaningful to explore the hot deformation behaviors in Cr–Mo–Ni–V steel with a banded structure to achieve better microstructural control by optimizing the hot working process [13,14].

In this study, we aimed to evaluate the hot deformation behaviors of the Cr–Mo–Ni–V steel. The compressive true strain–true stress curves of the steel were obtained by a hot working process, and the processing maps were also

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established. Microstructure characteristics of deformed steels as well as microstructure evolution were explored in detail with various hot working parameters.

2 Materials and methods

The material applied in the present research is Cr–Mo–Ni–V steel, with an actual chemical composition of 0.36C–0.27Si–0.33Mn–3.19Ni–1.2Cr–0.2V–0.4Mo–0.005P–0.12Cu–Fe (in mass percentage). The testing sections were taken from an electro-slag refined steel forged with high purity. Hot deformation tests were performed on a Gleebel-3800 testing machine with various strain rates of 0.01, 0.1, 1, and 10 s⁻¹ at temperatures ranging from 900 to 1,200°C with intervals of 100°C. The engineering strain of the steel was set to 60% in this research. Cylindrical samples were cut from the experimental cast ingot by a wire cutting machine. Prior to the deformation, all samples were heated to 1,200°C in the muffle furnace and maintained under this condition for 180 s, cooled to the designed temperature, and then kept for 30 s at this specific temperature. Once the hot deformation was finished, the specimen was instantly cooled in water to retain the deformation microstructure of the steels. Figure 1a shows the hot compression process of the studied steel schematically. The examining direction of samples for microstructure characterization was perpendicular to the forging direction (Figure 1b), and the observed surface of the specimen after compression is presented in Figure 1c. Microstructures after hot deformation were examined by optical microscopy (Zeiss Axio Imager-A2m), and the samples were prepared by metallographic techniques. A saturated aqueous picric acid solution was applied as the corrosive to reveal the boundaries of prior austenite grain, and metallographic samples were soaked in this solution at a temperature of 60°C for a time of 3 min.

3 Results and discussion

3.1 Compressive strain–stress behavior

Figure 2 displays the true strain–true stress characteristics of Cr–Mo–Ni–V steel under various deformation conditions.

Figure 1: Schematic images showing the (a) multi-step heat deformation process, (b) sample direction, and (c) observed surface after compression.
In general, the flow stress of the steel shows significant dependency on temperatures and strain rates in the hot working process. In particular, as strain rates decrease and hot deformation temperatures increase, the flow stress would increase. At the early stage of hot deformation, the stress instantly goes up with the increase of strain, which can be regarded as the result of enhanced generation and interaction of dislocations. With the increase of hot compression degree, the flow stress of the steel exhibits two different characteristics. For high deformation temperatures with low strain rates, the flow stress would increase to one peak value after the initial rapid increase, followed by a small downward tendency, until a steady state is reached, as shown in Figure 2a and b. The decreasing work-hardening rate indicates the occurrence of dynamic softening. For Cr–Mo–Ni–V steel, the dominant softening mechanisms include dislocation recovery and grain recrystallization. The final steady state is achieved as a result of the competing balance between the dynamic softening mechanism and the work hardening behavior of the steel. With respect to strain rates above 1 s\(^{-1}\), after the initial fast increment, the stress continues to increase with increasing strain rate (Figure 2c and d). The slower increasing trend indicates that, with the increase of the strain rate, the process for nucleation and growth of recrystallized grains upon dynamic recrystallization is shortened, which means that the time for grain nucleation and growth is not enough. Then, the dynamic softening caused by DRX is not able to offset work hardening, and the stress continues to increase again. It should be noted that the mechanical behaviors of the studied steel at high temperatures are affected by the competition of these contradictory processes.

In addition, the flow stress of the steel decreases with increasing hot-deformation temperature at a specific strain rate. According to the result shown in Figure 2c, when the strain rate of the steel reaches 1 s\(^{-1}\), the maximum stress of the steel is ~168 MPa under the condition of a hot working processing temperature of 900°C, while the maximum stress value decreases to ~63 MPa with the hot working processing
temperature increasing to 1,200°C. This is mainly due to the fact that as the hot working temperature is increased, the thermal activation energy effect is enhanced and the atomic activity ability is improved, which lead to the improvement in the rate of nucleation and growth of dynamic recrystallization of the steel. As a result, the softening effect upon the hot working process is enhanced, which in turn results in a decrease in the flow stress.

### 3.2 Compressive stress–strain behavior

Aimed at describing the flow behaviors of the studied steel quantitively, the Arrhenius equation, one of the most widely used constitutive equations, is applied to represent the relationships between processing parameters and flow stress during the hot compression process [15,16].

\[
\dot{\epsilon} = A_1 \sigma^n \exp\left(-\frac{Q}{RT}\right), \quad \sigma < 0.8, \quad (1)
\]

\[
\dot{\epsilon} = A_2 \exp(\beta \sigma) \exp\left(-\frac{Q}{RT}\right), \quad \sigma > 1.2, \quad (2)
\]

\[
\dot{\epsilon} = A [\sinh(a \sigma)]^n \exp\left(-\frac{Q}{RT}\right). \quad (3)
\]

The physical meaning of various parameters in the aforementioned equations is listed in Table 1. \(A_1, A_2, A, n, n_1, n, \beta, \) and \(a\) are temperature independent material constants which are generally determined experimentally. It should be noted that equations (1) and (2) are, respectively, valid at low and high levels of stress, and equation (3) could be applicable in broad ranges of strain rates and deformation temperatures of the steel. Based on the result of linear fitting of \(\ln \sigma - \ln \dot{\epsilon}\) and \(\sigma - \ln \dot{\epsilon}\), specific values of \(n_1\) and \(\beta\) can be determined (Figure 3a and b). Averaged values of \(n_1, \beta, \) and \(a\) are determined as \(n_1 = 5.749, \beta = 0.06554,\) and \(a = \beta/n_1 = 0.011401.\)

Relationships between the temperature of the hot working process and the strain rate could be evaluated as \(Z\), the Zener–Hollomon parameter, which is expressed by the following equation [15,16]:

\[
Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right) = A [\sinh(a \sigma)]^n. \quad (4)
\]

On both sides of equation (4), the logarithmic operation was applied simultaneously, so as to obtain:

\[
\ln Z = \ln A + n \ln [\sinh(a \sigma)]. \quad (5)
\]

According to equation (5), we can say that the intercept of linear function \(\ln [\sinh(a \sigma)] - \ln Z\) should be equal to just \(\ln A\), which could be applied to determine the value of parameter \(A\). The parameter \(\eta\), which denotes the power dissipation of steel, can be obtained according to the formula \(\eta = 2m/(m + 1)\), and the strain rate sensitivity is denoted by parameter \(m\). The value of \(m\) can be calculated by the strain rates and flow stress \((m = \ln \sigma/\ln \dot{\epsilon})\). The instability parameter \(\xi(\dot{\epsilon})\) is defined by equation (6), which is related to the value of parameters \(m\) and \(\dot{\epsilon}\):

\[
\xi(\dot{\epsilon}) = \frac{\partial \ln \left(\frac{m}{m + 1}\right)}{\partial \ln \dot{\epsilon}} + m \leq 0. \quad (6)
\]

As \(\xi(\dot{\epsilon})\) is smaller than zero, the flow instability of the steel occurs. Through the combination of the instability map with the efficiency of the power dissipation map, the processing map of the steel could be constructed finally. The processing maps of Cr–V–Ni–Mo steel at various strains are presented in Figure 4. The processing map is beneficial to determine the instability zone and the safety zone during the thermal deformation process, thereby optimizing the hot working process parameters [10,11]. In Figure 4, the points located on the contour curve represent the value of power dissipation \((\eta)\) of steel. The gray area indicates the unstable area, and the white part is the safe processing area. The distribution of unstable zones changes at different strains. Under the condition of low strain, the instability region mainly corresponds to the low deformation temperature and high strains. The power dissipation efficiency of the steel can be gradually improved by increasing the strain. The domain of the instability area progressively decreases, and at the same time, the instability region gradually shrinks toward the low-temperature parts. Upon the thermal deformation process, it is essential to avoid the occurrence of instability in the unstable region [14].

### 3.3 Microstructure characterization

Figure 5 shows the deformed microstructure of the studied steel at various hot deformation temperatures (900, 1,000, 1,100, and 1,200°C) at a strain rate of 0.01 s\(^{-1}\). From Figure 5a, it could be observed that some of the grains are elongated along the compression direction in the deformed microstructure at
900°C. A small amount of recrystallized grains is distributed around the elongated grains in a chain arrangement, and the occurrence of dynamic recrystallization under this condition is relatively low. In Figure 5b, with the increase of the hot deformation temperature to 1,000°C, obvious dynamic recrystallization can be observed in the microstructure and the recrystallized grains begin to grow. However, some elongated grains having not undergone dynamic recrystallization are...
unevenly distributed in the microstructure of the steel. With the increase of the hot working temperature to 1,100°C, the equiaxed grains after dynamic recrystallization continue to grow as the heat compression temperature increases, as shown in Figure 5c. It could be noted that the growth behavior of the grains after recrystallization is not consistent, which leads to significant differences in grain size. Under the condition of hot deformation temperature increasing to 1,200°C, the recrystallized grain size increases significantly, and the degree of variation in grain size is more pronounced than that in the case of 1,100°C. According to Figure 5, it could be demonstrated that under the condition of a strain rate of 0.01 s\(^{-1}\) and deformation temperatures in the range of 900 to 1,200°C, the banded structure of the Cr–Mo–Ni–V steel almost vanishes in the deformed microstructure. In terms of the evolution of banded structure in the deformed microstructure, the results under the condition of strain rates of 0.1 and 1 s\(^{-1}\) are very similar to that at a strain rate at 0.01 s\(^{-1}\).

According to previous study, the evolution and distribution of banded structure of the steel are related to the alternating distribution of coarse and fine prior austenite grains [6]. The evolution of the fine-grain area and coarse-grain area of Cr–V–Ni–Mo steel at 10 s\(^{-1}\) and various hot working temperatures is presented in Figure 6. As shown in Figure 6a, no obvious dynamic recrystallization occurs in both fine/coarse-grain areas. The grains in the coarse-grain area are obviously elongated along the compression direction, while the fine-grain area is distributed in a narrow strip after deformation. The deformation degree of the grains in this region is much lower than that in the coarse-grain zone and the proportion of the fine-grain area in the deformed microstructure is decreased. In Figure 6b, with the hot deformation temperature increasing to 1,000°C, obvious dynamic recrystallization can be observed in the fine-grain area, while a certain number of large grains still extends along the compression direction in the coarse-grain area. The banded structure is still visible in the deformed microstructure. With the hot working temperature increasing to 1,100°C, obvious dynamic recrystallization occurs in both the fine-grain area and coarse-grain area, and the banded structure gradually vanishes in the deformed microstructure, as shown in Figure 6c. However, it should be noted that the grain size distribution in the deformed microstructure is not homogeneous. Under the condition of hot deformation temperature increasing to 1,200°C, obvious dynamic recrystallization could occur in both the fine-grain area and coarse-grain area, and the grains are basically equiaxed with a uniform size, and the banded structure totally vanishes in the deformed microstructure, as shown in Figure 6d.
4 Conclusions

The mechanical behaviors of Cr–V–Ni–Mo steel at high temperatures were studied by a hot working process under various conditions. The influences of hot working parameters on the inhomogeneous structure of Cr–V–Ni–Mo steel were also discussed. The following conclusions can be obtained:

(1) Both the grain recrystallization mechanism and the dislocation recovery mechanism occur in the hot working process of Cr–V–Ni–Mo steel. Under the conditions of high hot working temperatures and low strain rates, the dynamic recrystallization softening mechanism in the studied steel dominates.

(2) The safe hot working parameters for the deformation process of the studied Cr–V–Ni–Mo steel were evaluated at the hot working temperature window of 1,050–1,150°C and the strain rate window of 0.01–1 s\(^{-1}\).

(3) Under the strain rate window of 0.01–1 s\(^{-1}\) and the hot working temperature window of 900–1,200°C, the banded structure of the steel almost vanishes in the deformed microstructure.

(4) At the strain rate of 10 s\(^{-1}\) and the hot working temperature range of 900–1,000°C, the banded structure of the steel is visible in the deformed microstructure. However, with the temperature increasing to the range of 1,100–1,200°C, the banded structure gradually vanishes in the deformed microstructure.

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