A Comparative Study of Various Flow Instability Criteria in Processing Map of the Powder Metallurgy High Speed Steel

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Abstract. The deformation behavior of the 1.15C-4.00Cr-3.00V-6.00W-5.00Mo powder metallurgy high speed steel in hot working processes was investigated by the isothermal compression tests carried out at the temperature of 1000-1150°C and the strain rate of 0.001-1.0 s⁻¹ with the height reduction of 60%. The processing maps were constructed, identification of the instability regions and optimization of hot deformation parameters. Different types of instability criteria of PRASAD, MALAS, GEGEL, MURTY and SEMIATIN were compared. It was found that the hot working process of the steel can be carried out safely in the domain of 1040-1130 °C /0.01-1.0 s⁻¹. Furthermore, the temperature and the strain rate had a great effect on microstructures. To obtain a homogeneous microstructure with fine grain, the hot working process should be carried out under the condition of 1050-1100 °C /0.01-0.06 s⁻¹.

1. Introduction
High speed steel is widely used as a cutting tool, to stabilize the combination of hardness and good toughness [1-2]. High speed steel is mainly used for manufacturing Thin blades with complex shapes and vital resistant cutting tools, as well as high temperature bearings and cold extrusion dies due to its good process performance, good strength and toughness compatibility. High-speed steel produced by powder metallurgy (PM) to avoid deterioration of mechanical properties and heat treatment deformation due to carbide segregation[3]. The forming behavior of this type of high speed steel was rarely researched and most previous research concentrate on the traditional casting steel[4-5].

As one of the effective methods to study the forming process of metals, processing map have been widely used to research the machinability of various metal materials [6-8]. For the most research, only one instability criterion is used to study the forming behavior. Compare the different criterions, the results show that the standards are completely different and even contradictory in theoretical basis, formulas and physical sense. However, little information is available on thermal processability analysis in conjunction with these different instability criteria. However, there is little available information on thermal processability analysis in conjunction with these different instability criteria.

In this work, the deformation at high temperature of a PM high speed steel was researched. In the basis of the concepts of dynamic material model [9], different instability criteria of PRASAD, GEGEL [10], MALAS [11], MURTY [12] and SEMIATIN [13] were applied to studying the hot deformation and compared above instability criteria.

2. Experiments
The experimental material is a PM high speed steel produced by hot isostatic press. The alloy ingots were cut and processed into cylindrical samples with diameter of 8mm and height of 12mm. Thermal
compression tests were carried out on Gleeble-1500D simulator in the various temperatures (1000°C, 1050°C, 1100°C and 1150°C), various strain rates (0.001 s⁻¹, 0.01 s⁻¹, 0.1 s⁻¹ and 1.0 s⁻¹). Compress the sample to 60% of its original height, and then spray quenched. Slice the deformed sample parallel to the compression axis, the grain structures were observed by an Olympus PM3 optical microscope.

3. Experimental Results and Discussion

3.1. DMM Thermal Processing Map Theory

It is considered that the sum of absorbed power $P$ is:

$$P = \sigma \dot{e} = \int_0^k \sigma \, d\dot{e} + \int_0^\sigma \dot{e} \, d\sigma = G + J \quad (1)$$

$$\eta = \frac{1}{l_{max}} = \frac{2m}{1+m} \quad (2)$$

Make a contour map of $\eta$ to get a dissipation map, as shown in Figure 1.

3.2. Analysis and Application of Different Instability Criteria for the PM High Speed Steel

3.2.1. PRASAD’s criterion for instability.

By means of the irreversible thermodynamic extremum principle applicable to large plastic flows, Prasad has developed an instability criterion as follows:

$$\frac{\partial D}{\partial R} < \frac{D}{R} \quad (3)$$

Replaced D with J:

$$\frac{\partial \ln J}{\partial \ln \dot{e}} < 1 \quad (4)$$

Taking logarithm on both sides, strives for the partial derivation of $\ln \dot{e}$:

$$\frac{\partial \ln J}{\partial \ln \dot{e}} = \frac{\partial \ln (\frac{m}{m+1})}{\partial \ln \dot{e}} + \frac{\partial \ln \sigma}{\partial \ln \dot{e}} + 1 \quad (5)$$

In short, if:

$$\xi(\dot{e}) = \frac{\partial \ln (\frac{m}{m+1})}{\partial \ln \dot{e}} + m < 0 \quad (6)$$

Figure 2 shows the processing diagram based on the PRASAD’s instability criterion.

3.2.2. GEGEL’s criterion for instability.

GEGEL believes that the temperature sensitivity parameter $S$ has a great influence on flow instability:

$$S = \frac{1}{T} \left[ \frac{\partial \ln \sigma}{\partial \ln P} \right] = \frac{\partial \ln \sigma}{\partial \ln T} \quad (7)$$

Both $\eta$ and $S$ decrease with the increase of strain rate.

$$\frac{\partial S}{\partial \ln \dot{e}} = -\frac{\partial}{\partial (\ln \dot{e})} \frac{(\partial \ln \sigma)}{(\partial \ln T)} = -\frac{\partial m}{\partial \ln T} \quad (8)$$

$$\frac{\partial \eta}{\partial \ln \dot{e}} > 0, \quad \frac{\partial m}{\partial \ln T} < 0 \quad (9)$$

Figure 3 shows the processing diagram based on the GEGEL’s instability criterion.
Figure 1. DMM-based power consumption rate at different strain rates and temperatures.

Figure 2. Processing map according to PRASAD’s instability criterion.

Figure 3. Processing map according to GEGEL’s instability criterion.

Figure 4. Processing map according to MALAS’s instability criterion.

3.2.3. MALAS’s criterion for instability. Based on GEGEL criterion, the instability criterion of MALAS was proposed:

$$\frac{\partial m}{\partial \ln k} > 0, \quad \frac{\partial m}{\partial \ln T} < 0$$

(10)

MALAS instability criterion processing map as shown in Figure 4.

3.2.4. MURTY’s criterion for instability. By definition of J:

$$J = \int_0^\sigma \frac{\partial }{\partial \varepsilon} = 2 \frac{\sigma}{\dot{\varepsilon}} = \frac{\partial \ln \sigma}{\partial \ln \varepsilon} = \frac{m}{\varepsilon}$$

(11)

$$\eta = \frac{J}{J_{\max}} = 2 \left(1 - \frac{1}{(\sigma)\dot{\varepsilon}^-} \right) \int (\sigma) \dot{\varepsilon} = \frac{f}{\varepsilon} = \frac{\eta}{2}$$

(12)

Based on the above Equation 5, MURTY’s instability criterion is as follows:

$$2m < \eta$$

(13)

The processing map is obtained from the Murty instability criterion, as shown in Figure 5.

3.2.5. SEMIATIN’s criterion for instability. With reference to the force equilibrium parameter $\alpha$, Semiatin’s derives the instability criterion and describes the relationship between the rheological softening rate and the strain rate sensitivity parameter:

$$\alpha = - \frac{\gamma}{m}$$

(14)
Based on the SEMIATIN’s flow localization instability criteria, limitations on machinability parameters for flow localization or fracture have been determined:

\[ \alpha > 5 \]  

(15)

The processing map on SEMIATIN’s instability criterion is shown in Figure 6.

3.3. Analysis of Hot Forming Properties for the PM High Speed Steel

Instability map of PM high-speed steel plot by different instability criteria is shown in Figure 7. It can be seen that within the range of strain rate of 0.001-1.0 s\(^{-1}\) and temperature of 1000-1030°C, the shaded area is obtained by the superposition of 5 flow instability criteria, now in the upper right corner, upper right corner and lower right corner of the processing diagram, respectively. In addition, these instability zones are all within the temperature range of 1130°C to 1150°C and the strain rate is 0.05-1.0s\(^{-1}\) and 0.001-0.01s\(^{-1}\). In the actual formation process, the above deformation zones should be avoided. Flow instability may also appear in the instability domain where the flow instability criteria are less overlapped. However, areas with high power dissipation rate and flow stability are more suitable for forming.
Figure 8 illustrates the typical microstructures of the PM high speed steel distorted under the different conditions. Figure 8 (1#) shows the microstructure under the circumstance of 1000°C /1.0s⁻¹. It can be observed that numerous tempered martensite grains are stretched along 45 degrees after deforming when temperature was relatively low. Figure 8 (2#) reveals the microstructures under the circumstance of 1000°C /0.001s⁻¹. It can be found that a handful of coarse carbide precipitates through the grain boundary, which will induce the instability during deformation. Figure 8 (3#) shows the microstructures under the circumstance of 1050°C /0.1s⁻¹. It serves to show some grains have undergone dynamic recrystallization because of the increase in temperature and the decrease in strain rate. Figure 8 (4#) shows the uniform and fine microstructures under the circumstance of 1050°C /0.01s⁻¹. Figure 8 (5#) exhibits the microstructures under the circumstance of 1100°C /0.1s⁻¹. It is obvious that the structure consists of some workhardening grains and small recrystallized grains and is distributed along the initial grain boundaries. Figure 8 (6#) shows the microstructures under the circumstance of 1100°C /0.01s⁻¹. As can be seen from the picture, complete dynamic recrystallization occurred and the structure is uniform and fine. Figure 8 (7#) presents the aggregation and coarsening of carbides belt which will result in unstable flow of PM high speed steel machined at 1150°C /1.0s⁻¹. The grain coarsening during continuous dynamic recrystallization is found under the condition of 1150°C /0.001s⁻¹ as illustrated in Figure 8 (8#).
4. Conclusions

(1) The instability chart is established by different instability criteria. Processing maps predict the region of flow instability that occurred in some deformation temperature and deformation strain rate. Based on the microstructures, MURTY's instability criterion accurately predicted the machinability of PM high speed steel.

(2) On account of the instability map and the microstructure, thermal working process can be in 1040-1130°C and 0.01−1.0 s⁻¹ within the scope of security. To get to a homogeneous texture with fine grains, thermal processing should be conducted under the circumstance of 1050−1100°C and 0.01−0.06 s⁻¹.

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6. References

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