TELKOMNIKA, Vol. 11, No. 2, February 2013, pp. 985~990
ISSN: 2302-4046

Mechanical Behavior of MTMoCr Under High Temperature and High Strain-rate

Jingkui Ruan[1], Zhengwei Dong[1]
[1]Department of Mechanical Engineering, Hubei University of Automotive Technology, Shiyan, Hubei, 442002, China
Corresponding author, e-mail: gerry_r@tom.com

Abstract

MTMoCr is a kind of Mo-Cr alloy cast iron often used to make automobile panel dies. To study high-speed machining process of automobile panel dies, the material's elastic modulus and rupture critical values of MTMoCr at 20℃-800℃ were studied based on the high temperature elongation test. The material's stress-strain diagram at various temperatures set-points (20℃-500℃) and various strain-rates (500/s-5000/s) were studied and the dynamic tensile yield strength values were obtained by dynamic SHPB (Split Hopkinson Pressure Bar) high-speed compression test. The experimental results indicate that MTMoCr has heat resistance and its behavior is between toughness and brittleness materials. Its toughness is enhanced with temperature increasing. The strain-rate strengthening effect prevails over temperature softening effect.

Keywords: *experimental study, MTMoCr, SHPB, temperature softening effect, strain-rate strengthening effect.*

1. Introduction

MTMoCr(JIS GM241, NF FGL240HB) is one kind of Mo-Cr alloy cast iron, developed from 1980s with many advantages such as high strength, better wear resistance and heat resistance [1]. As its eutectic structure consist of one kind of M7C3 carbide and austenite, its matrix changed to martensite by annealing, showing high wearing resistance, meanwhile, it also includes several alloy elements such as Mo, Mn and Cu, etc. Which enhance it's hardenability, thus its hardness can reach above 50HRC after quenching. The main parts of the auto panel dies are large even ultra-large casting, which requires the materials of dies with the capacity of anti-deformation, anti-wear, anti-rupture, anti-fatigue and anti-adhesion [2]. Based on the above characteristics, MTMoCr is suitable for mold parts, which has moulding surface and high wear resistance, such as drawing die punch, pressure ring, flanging and sizing die and pressure plate, etc. MTMoCr is one of the most important materials of auto panel dies.

Auto panel dies has great cutting quantity, especially for the milling process of MTMoCr. MTMoCr has a bad impact on application because of its bad machinability: its high intensity and heat resistance properties. The cutting of the metal materials is a complex nonlinear problem because there are heat, force, machine and coupling phenomena among it. The study on the mechanical properties of MTMoCr, especially the dynamic mechanical properties under the conditions of high temperatures, high strain and high strain-rate, is one of the most important problems for auto panel dies manufacturing field. Yongxin Z [3] has a research on the mechanical properties of bainite white iron as cast. Meiling C [4] studied the mechanical properties of surface modified SiC nanometer powders reinforced nodular cast iron. Wenbang G [5] studied the mechanical properties of high toughness isothermal quenching nodular cast iron. All of these papers mainly focus on the impact of the cast iron components, casting process, and thermal treatment on the static mechanical properties of the material under normal temperature, but there is little study on the static and dynamic mechanical properties of MTMoCr under the high temperature, high strain and high strain-rate.

Experimental studies are research designs that evaluate material behavior or machine performance. Ramdan D [6] took experimental studies to research the flow visualization of the plastic ball grid array chip encapsulation process considering of the rheology effect. Nasution H [7] took experiments to study the compressor performances at various temperature set-points

Received September 21, 2012; Revised January 4, 2012; Accepted January 15, 2013

with different internal heat loads. This paper takes the research on high-speed cutting of moulding surface of large auto panel dies as background, does material's mechanical properties experiment through high temperature stretch and high-speed compression test, so as to test the modulus of elasticity under different temperatures, rupture critical point and to test the stress-strain relationship under different temperatures and strain-rates, and to find out the influence rules of temperature and strain-rate on the dynamic yield strength, finally to lay the foundation for the study on high-peed machinability of MTMoCr.

2. Research Method

The chemical composition of MTMoCr except Fe is shown as table1.

Table 1. Chemical Composition of MTMoCr [mass %]

C	Mn	Si	Cr	Mo	P	S
2.9~3.2	0.6~0.9	1.4~1.8	0.3~0.4	0.9~1.1	<0.2	<0.12

2.1. Modulus of Elasticity Test

To obtain the modulus of elasticity of MTMoCr, a specimen of this material is made into a "standard" shape and size, with 10mm working diameter, 120mm total elongation and both ends of it threaded, which is shown in Figure 1. Test is implemented on a 25 tons electronic universal testing machine which can be used to test stretch, compression and bending test specimens.

Figure 1. The Test Specimen

Concerning modulus of elasticity experiment, there are two categories: ductile materials and brittle materials. The tensile failure occurs after localization of deformation or necking phenomenon in ductile materials, which means there is displacement between the maximum load and fracturing load. Wheras, there is little displacement in brittle materials, which will rupture immediately. So standard two-point methods and stagnant methods are respectively used on ductile materials and brittle materials. MTMoCr matrix, which belongs to brittle material, doesn't have close internal grain structure, so stagnant method is applied to it. The steps are as follows:

(1) Two loads cyclic loading: the minimum and maximum loads are respectively 10% and 70% of the tensile strength, which results in two stagnant curve-1 and 2.

(2) Obtain the modulus of elasticity with standard two-point method by making a straight line linking the vertex point of curve-1 and the rock-bottom of curve-2.

In order to ensure the reliability of the data, an average of three sets of valid data is adopted from each group of tests under different temperatures. The testing data treatment software is TRAPEZIUM2, which matches with the electronic stretch testing machine. It can show the stress-strain curve, the modulus of elasticity of materials, the yield strength, the ultimate strength, etc. in real time.

The stretch process curve and stagnant curve can be obtained when the test sample is stretched at 20°C, 400℃ and 800℃. Figure 2 is the stretch stagnant curve at 400℃.

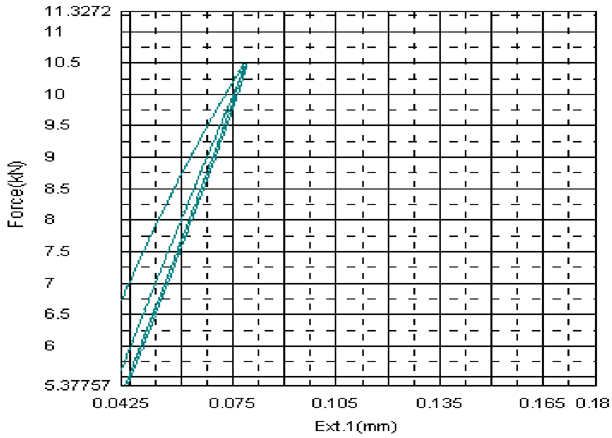

Figure 2. Stretch Stagnant Curve of MTMoCr at 400℃

2.2. Rupture Critical Point of Materials Experiment

A 25 tons electronic universal testing machine is applied as the test instrument. Stretch the test sample to get stretch rupture curve at 20℃, 400℃ and 800℃. Figure 3 shows the stretch rupture curve at 400℃.

The mechanical property of MTMoCr material is between ductile and brittle materials, so in stretch process, it doesn't show necking phenomenon. Under this single-stress state, the maximum principal stress equals with the equivalent stress, both of which equals yield strength. This equation is applied to Mises Criteria, which is the Cockroft-Latham Criteria [8] in simple tension.

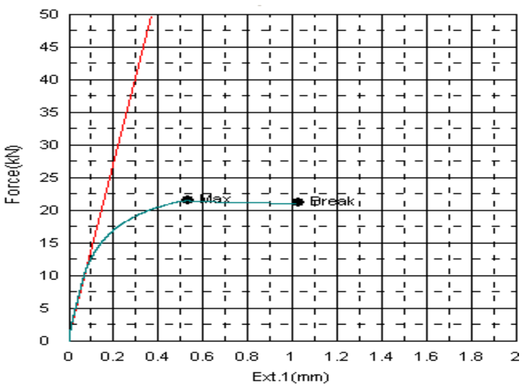

Figure 3. Stretch Rupture Curve of MTMoCr at 400℃

$$D_f = \int_0^{\varepsilon_f} \sigma^* d\bar{\varepsilon} \qquad (1)$$

Where D_f is the tension rupture critical value, ε_f is the total strain in tension fracture, $\bar{\varepsilon}$ is the equivalent strain, and σ^* is the maximum tension stress.

The Criteria shows the area encircled by the stress curve and the stress-strain curve when stretch rupture happens. According to the rupture theory of materials, the area reflects the ductility of the materials, in close relation with the rupture characteristics of materials.

2.3. Shock Compression Experiment

The shock compression experiment was carried out on the SHPB equipment with the diameter Φ14.5, the test specimen size Φ9×5. The SHPB test system is shown as figure 4. It contains a constant temperature heating devices with the composition of thermocouple probe, electrical source, and electrical relay. Under the setting test temperature, the electrical relay can control electrical source to keep constant temperature according to the temperature feedback of the thermocouple.

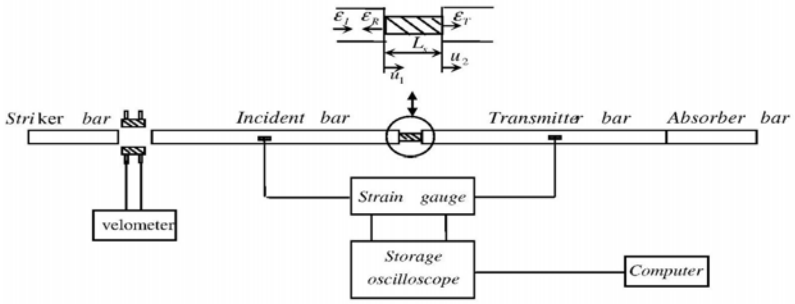

Figure 4. Split Hopkinson Press Bar Test System

In metal cutting environment, the strain is about 1, and the strain-rate is between 103 and 105s-1 [9]. The maximum temperature of the cutting area is 815□ [10], with the use of TiAlN coated cutting tools. Considering the limitation of the experimental equipments and the conditions, the strain-rate of shock compression experiment is set to 500/s, 1000/s, 2000/s, 3000/s, 5000/s, correspondingly, and the four ambient temperatures are 20□, 100□, 300□ and 500□, with an average of five sets of valid data adopted from each group of tests under different conditions. In all dynamic compression test, in addition to the individual specimens, the test data is discrete in low strain-rate (500/s). Because reflected wave is too small and excessive relative error, the vast majority of test data incarnate corking repeatability. Dynamic mechanical property curve of materials at different temperatures and each strain-rate can be obtained through data processing. Figure 5 shows the stress-strain curve of MTMoCr at each strain-rate at 300□.

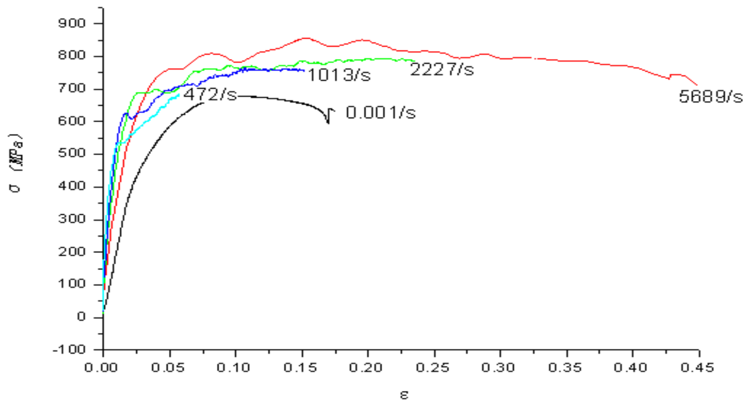

Figure 5. Stress-stain Curves of MTMoCr at 300□

3. Results and Analysis
3.1. Influence of Temperature on the Modulus of Elasticity of Materials

The modulus of elasticity of materials at different temperatures can be be achieved by analysis and treatment on the data of experiment about modulus of elasticity, which is shown in table 2.

Table 2. The Modulus of Elasticity at Different Temperatures

Temperature (℃)	Modulus of elasticity (GPa)
20	85.80
400	84.56
800	84.21

As we can note from the modulus of elasticity at different temperatures (table 2), the temperature has little influence on the modulus of elasticity of MTMoCr, and its modulus of elasticity at 800□ decrease less than 2% compared with its modulus of elasticity at ambient temperature. Therefore, MTMoCr has good heat resistence. That is the main reason why MTMoCr, used as materials of auto panel dies, shows good performance.

3.2. Influence of Temperature on Rupture Critical Point of Materials

Rupture critical point at different temperatures can be got by analysis and treatment on the data of experiment about rupture critical point of materials, which is shown in table 3.

As we can note from the rupture critical point at different temperatures (table 3), temperature has much more influence on yield strength, as that toughness and rupture critical point of materials is low when the temperature is low, and they grow up when the temperature rises. The main reason is that when the temperature rises, internal atomic activities are intensified, and adhesion of atoms is decreased, so plastic deformation of materials happens easier.

Table 3. Rupture Critical Point at Different Temperatures

Temperature（℃)	Cockcroft-Latham criterion (Mpa)
20	1.26
400	4.94
800	9.23

3.3. Influence of Temperature and Strain-rate on Dynamic Yield Strength

From the stress-strain curve, we can get the dynamic yield strength of MTMoCr, which is shown in table 4.

Table 4. The Dynamic Yield Strength of MTMoCr

Strain-rate \ Temperature	20□	100□	300□	500□
500/s	575	492	483	474
1000/s	672	628	592	553
2000/s	776	722	687	633
5000/s	976	827	778	738

The mechanical property of materials has a close relationship with stress, strain-rate and temperature. And the property of materials will change greatly in the conditions of finite strain, high strain-rate and high temperature. For example, with the increase of yield strength and ultimate strength, as well as the decrease of elongation-rate, material shows fragility and strengthening effect of the strain-rate [11].

From table 4, we can see that temperature has evident effect on the dynamic yield strength of the material. As the temperature rises, the dynamic yield strength of the MTMoCr decreases obviously. At various strain-rate and with temperature increased from 20□ to 500□, the dynamic yield strength of the MTMoCr decreases in ratio of 17%~24%. That is to say, in the changes of the dynamic mechanical property of MTMoCr, the temperature has a softening effect to the dynamic yield strength. The main reason is that the high temperature provide more slipping plane and slipping direction for dislocation movement in the interior of material, leading to the decrease of flow stress [12].

From table 4, we can also see that strengthening g effect of the strain rate of MTMoCr becomes more obvious. At various temperatures, along with the increase of the strain rate, dynamic yield strength of the MTMoCr increases obviously. And the value of the dynamic yield strength increases 56%-70% when strain-rate increases from 500/s to 5000/s, that is to say, the strain rate has a strengthening effect on the flow stress in the change of the dynamic mechanical property of MTMoCr. The main reason is that along with the increase of the strain-rate, the strain in unit time increases, and dislocation emerges in the interior of material, the number of dislocation movement increases, and speed of dislocation movement pushes up, thus the critical shearing stress of material deformation increases [13].

It also can be seen from table 4 that the dynamic yield strength in the case of temperature (500□) and strain rate (5000/s) increases 28% comparing with that in the case of temperature (20□) and strain rate (500/s). It means that the strain-rate strengthening effect prevails over temperature softening effect. This conclusion is in contrast to the conclusion summarized in reference [10] on the test of the dynamic mechanical property of 45 steel by Hu Changming et al. That is to say, MTMoCr is distinguished from other materials by higher strain rate strengthening effect.

4. Conclusion

From the test of modulus of elasticity, the rupture critical point of materials experiment and the SHPB high-speed shock compression experiment of MTMoCr, it is discovered that MTMoCr has good heat resistence, and its behavior is between ductile and brittleness materials, and Its toughness is enhanced with the increase of temperature, which is the main reason why MTMoCr has good serviceability but poor machinability; the dynamic yield strength of the MTMoCr changes greatly under large strain, high temperature and high strain-rate, as high temperature provides more slipping plane and slipping direction for dislocation movement, so flow stress decreases and temperature softening effect appears; Meanwhile, dislocation energy in the interior of material increases because large strain-rate, causing critical shearing stress of material deformation increases, strain-rate strengthening effect turns out, and furthermore, strain-rate strengthening effect holds major positions. These discoveries are useful for the study on processing technology of high speed cutting of MTMoCr.

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