The experiments for mechanical properties of 20Cr2Ni4 steel and the coefficient definition of constitutive equation

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Abstract. The 20Cr2Ni4 alloy steel has the properties of high strength, toughness and hardness. It is used in large cross-section carburized parts, such as gears, shafts and components which are required high strength and good toughness. In order to study the static mechanical properties and dynamic mechanical properties of 20Cr2Ni4 steel, the static compression experiment and the Hopkinson Pressure Bar test are conducted. The stress-strain relationship within the scope of 25~400°C is obtained by experiments, and softening effect of strain rate and strengthening effect of temperature is comprehensively analyzed. The paper has a more comprehensive understanding on mechanical response of 20Cr2Ni4 steel within the scope of 25~400°C. Based on the experiment data the parameters in Johnson-Cook constitutive equation of 20Cr2Ni4 have been gotten. The research results of this paper lay a foundation for the further applications of 20Cr2Ni4 steel.

1. Introduction

The constitutive relation is the inherent nature of the material and the objective law that follows in the deformation process. In the process of machining, metal material has large deformation, which accompanies with strain hardening, reply, recrystallization. The phenomenon is affected by strain, strain rate, temperature and other factors. Therefore, the constitutive relation of metal materials describes the relationship between the factors such as stress, strain and strain rate in the process of deformation, the expression is [1]:

\[ \sigma = \sigma(\epsilon, \dot{\epsilon}, T) \]  \hspace{1cm} (1)

The 20Cr2Ni4 is alloy steel of high strength, good toughness and good hardenability. Table 1 shows its chemical composition, and table 2 shows the basic mechanical property.

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
C  & Si  & Mn  & Cr   & Ni  & S  & P  \\
\hline
0.17~0.23 & 0.17~0.37 & 0.3~0.6 & 1.25~1.65 & 3.25~3.65 & \leq 0.03 & \leq 0.03 \\
\hline
\end{tabular}
\caption{Chemical composition of 20Cr2Ni4 (mass fraction/%).}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
 & & & & & & \\
\hline
\end{tabular}
\caption{Basic mechanical performance of 20Cr2Ni4.}
\end{table}

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| Tensile strength | Yield strength | Elongation | Shrinkage | Impact strength |
|-----------------|---------------|------------|-----------|----------------|
| ≧ 1175MPa       | ≧ 1080MPa     | ≧ 10%      | ≧ 45%     | ≧ 78J          |

The experiment results under different loading conditions of materials are the most direct and the most effective response to mechanics performance. It can fundamentally show the physical structure of the material properties, and it has incomparable advantages compared with the theoretical research with all kinds of ideal assumption. To study 20Cr2Ni4 mechanics performance, we conduct the tests of static mechanics performance and dynamic mechanical performance respectively. The purpose of the experiment for static mechanical performance is not only to research static mechanics properties of 20Cr2Ni4 at room temperature, but also provide data support for the subsequent experiment for dynamic mechanical performance. While the purpose of the experiment for dynamic mechanical properties is to get the stress-strain relationship, the softening effect of the strain rate and strengthening effect of the temperature, and the parameter in Johnson-Cook constitutive equation of 20Cr2Ni4 steel.

2. The experiment for static mechanical properties

2.1. The scheme
The purpose is to obtain the stress-strain curve of 20Cr2Ni4 steel at $10^{-3}$ s$^{-1}$ and $10^{-2}$ s$^{-1}$ respectively at room temperature. Due to the high stability of the static compression experiment, we do two groups under each strain rate, a total of four groups.

2.2. The device and the process of the experiment
We conducted the static compression experiment using the universal testing machine called INSTRON. Figure 1 shows the experimental device. By the requirements for test preparation, the sample is $\phi 5 \times 5mm$. Two groups of different strain rate are got by controlling the speed of beam displacement.

![INSTRON universal testing machine](image)

**Figure 1.** INSTRON universal testing machine.

2.3. The results
Figure 2 shows the stress-strain relationship of 20Cr2Ni4 steel at room temperature. Figure 3 shows the contrast figure of the sample before and after the experiment, in which the middle one is the sample at the initial state, the left one is the compressed sample at the strain rate of $10^{-3}$ s$^{-1}$, and the right one is the compressed sample at the strain rate of $10^{-2}$ s$^{-1}$. The size in figure 3 is 2 times of its...
real size. From the figure, we can see obviously that the deformation of the sample becomes bigger when strain rate increases.

**Figure 2.** The stress-strain relationship of 20Cr2Ni4 under the static environment at room temperature.

**Figure 3.** The contrast figure of the sample before and after the experiment (scale: 2:1).

As you can see from the figure 2, the coincidence degree for the stress-strain curves of 20Cr2Ni4 steel at room temperature under different strain rate is high. Under the condition of quasi-static at room temperature, yield strength increases when the strain rate becomes higher. Yield strength of 20Cr2Ni4 steel at the strain rate of $10^3$ s$^{-1}$ is 1112 MPa, more than $10^2$ s$^{-1}$ by about 30 MPa. The experiment results show that elastic modulus of the material is not affected by the strain rate under the condition of quasi static, and elastic modulus is about 226 GPa.

3. The experiment for dynamic mechanical properties

3.1. The scheme

In this paper, we study the dynamic mechanical of 20Cr2Ni4 through the Split Hopkinson Pressure Bar (SHPB) experiment. The SHPB technique is considered to be the main experimental method to get the relations between stress and strain within $10^2$ s$^{-1}$-$10^4$ s$^{-1}$ of the material [2-4]. The experiment is made up of dynamic at room temperature and dynamic at high temperature. Because the experiment for dynamic is less stable than the experiment for static mechanical properties, every experiment should take at least three groups of valid data to ensure the reliability of the experimental data.

3.2. The scheme

The SHPB system consists of compressive bar system, heating device, data acquisition and processing system, which is shown in figure 4. The dynamic compression experiment at room temperature achieves loading the samples under different strain rate by controlling the air pressure. The experiment adopts the strain rates of $1000$ s$^{-1}$, $2000$ s$^{-1}$ and $3000$ s$^{-1}$. The dynamic compression experiment at high temperature achieves loading the samples under the different temperature by the heating device. The experiment selects four kinds of temperature which are $100^\circ\text{C}$, $200^\circ\text{C}$, $300^\circ\text{C}$ and $400^\circ\text{C}$, and strain rate is selected as the $2000$ s$^{-1}$, the specific design of the experiment is shown in table 3.

**Table 3.** The experimental design for dynamic mechanical properties.

| Temperature (°C) | Strain Rate (s$^{-1}$) | Experiment Times |
|-----------------|------------------------|------------------|
| 25              | 1000                   | 3                |
| 25              | 2000                   | 3                |
| 25              | 3000                   | 3                |
| 100             | 2000                   | 3                |
3.3. Analysis of the experimental results

Research of mechanical properties of the material under static loading condition has been relatively mature, but the parts do not always work under static conditions, they are likely to be affected by dynamic loading. Especially in cutting process, the whole deformation process of the material will be done in a very short period. Therefore, mechanical properties of the material under dynamic loading are quite different from that under static loading. Strain rate, temperature and many other factors produced in the process of deformation of the materials will have an impact on the mechanical properties of the material, and the most basic influence presents in two aspects: one is that the stress-strain curve moves up with the increase of strain rate, that is strain rate hardening; Second, the stress-strain curve moves down with the increase of temperature, namely thermal softening.

- Dynamic Compression Experiments at Room Temperature

The room temperature is 25°C during the experiment, the effect of strain rate on dynamic mechanical properties of 20Cr2Ni4 can be found by comparing the data under the condition of different strain rate at the same temperature. Figure 5 is the stress-strain curve of 20Cr2Ni4 under conditions of dynamic loading at 25°C, and figure 6 shows the yield strength of 20Cr2Ni4 under different strain rate at 25°C.

From the experimental results, with the increase of strain rate, the stress-strain curve moves up as a whole. Repeatability of the three sets of data is bad when the strain rate is 1000 s⁻¹, the stress-strain curve fluctuates slightly larger, and the main reason is that Hopkinson Pressure Bar has experimental error when strain rate is low. Since 20Cr2Ni4 has no obvious yield stage under the action of dynamic
load, according to experience, the stress when the plastic strain is 0.2% is taken as the Yield Stress. According to the fitting result, the yield strength increases 100MPa when the strain rate is 3000 s⁻¹ than when it is 2000 s⁻¹, presenting the strengthening effect of strain rate, but not obvious.

![Figure 5. The stress-strain curve of 20Cr2Ni4 under conditions of dynamic loading at room temperature.](image)

![Figure 6. The yield strength of 20Cr2Ni4 under different strain rate at room temperature.](image)

- High-temperature dynamic compression experiment

Take the strain rate of 2000 s⁻¹ during the experimental. The effects of temperature on dynamic mechanical properties of 20Cr2Ni4 can be found by comparing the data under the condition of the same strain rate but different temperature. Figures 7 and 8 respectively shows the stress-strain and yield strength curve of 20Cr2Ni4 under the condition of different temperature when the strain rate is 2000 s⁻¹.

![Figure 7. Stress-strain curve of 20Cr2Ni4 under different temperature at 2000 s⁻¹.](image)

![Figure 8. Yield strength of the 20Cr2Ni4 under different temperature at 2000 s⁻¹.](image)

From figure 7, it can be seen that stress-strain curve integrally moves down as temperature rises. When the temperature is 100°C and 200°C, the difference of stress-strain curve is small, in this way it illustrates that the temperature has a little effect on mechanical properties of 20Cr2Ni4 near the two temperatures. As can be seen from the figure 8, as temperature rises, yield strength comes down. When the temperature is 25°C, the yield strength is 1201 MPa, and when the temperature is 200°C, the yield strength is 867 MPa, reduced by 27.8%, showing obvious softening effect of temperature. When the temperature is 400°C, the yield strength is 780 MPa, reduced by 10% compared with that of 200°C. Thus it can be seen, when the temperature is less than 200°C, the temperature has greater effects on the mechanical properties of the 20Cr2Ni4, the temperature effect on 20Cr2Ni4 decreases gradually when the temperature exceeds 200°C.
4. Construction of constitutive equation

4.1. Johnson-Cook model

It will be able to build a suitable constitutive relation model by getting stress-strain relationship through the above analysis of the test results. In recent years, these constitutive relations are widely used: Johnson-Cook (JC) model, Zerilli Armstrong model, Bodner-Parton model. JC model’s form is [5-7]:

\[ \sigma = (A + B\varepsilon^p)(1 + C\ln\dot{\varepsilon}^*)(1 - (T^*)^m) \]  

(2)

In the Eq. (2), \( \sigma \) is stress, \( \varepsilon \) is the equivalent plastic strain, \( \dot{\varepsilon}^* \) is the relative plastic strain rate \([8]\), usually take \( \dot{\varepsilon}^* = 1.0s^{-1} \). \( T^* \) is dimensionless temperature, \( T^* = (T - T_{\text{room}})/(T_{\text{melt}} - T_{\text{room}}) \), and \( T \) is the internal temperature of the material, \( T_{\text{room}} \) is the room temperature, \( T_{\text{melt}} \) is the melting point, \( 0 \leq T^* \leq 1.0 \). \( A, B, C, n \) and \( m \) are the material constants. \((A + B\varepsilon^p)\), \((1 + C\ln\dot{\varepsilon}^*)\) and \((1 - (T^*)^m)\) respectively describes the material’s strain hardening effect, strain rate effect, temperature effect. From the above equation, the JC model can solve the problems of deformation in the process at the condition of high stress, high temperature and high temperature, and can truly reflect constitutive behavior of the flow stress [9]. The paper selects the JC model to express the constitutive relation of 20Cr2Ni4.

4.2. Determination of constitutive equation parameters

JC expression is:

\[ \sigma = (A + B\varepsilon^p)(1 + C\ln\dot{\varepsilon}^*)(1 - (T^*)^m) \]

(3)

In the equation, A and B are constants related to the materials, n is the influence coefficient of strain hardening, C is the sensitivity coefficient of strain rate, m is softening coefficient of temperature. According to the data of the quasi-static compression experiment, dynamic experiments at normal temperature and high temperature of the 20Cr2Ni4, the coefficients of Johnson-Cook model can be determined, specific steps are as follows [10-13]:

- When the samples are at room temperature (\( T=T_{\text{room}} \)), \( \dot{\varepsilon} = \dot{\varepsilon}_0 = 10^{-3}s^{-1} \) the JC expression is simplified as:

\[ \sigma = A + B\varepsilon^p \]

(4)

According to the stress-strain curve, when the samples are at room temperature and the strain rate is \( \dot{\varepsilon} = \dot{\varepsilon}_0 = 10^{-3}s^{-1} \), \( A, B \) and \( n \) can be determined. First, make sure of \( A \). \( A \) represents the yield strength of material, \( A \) is the corresponding value when the plastic strain is zero from the quasi-static experiments. \( A \) is 1112 MPa obtained by fitting, according to Eq. (3), \( B \) and \( n \) can be calculated. \( A=1112 \text{ MPa}, B=1063 \text{ MPa}, n=0.2 \).

- when the plastic strain \( \varepsilon = 0 \), and temperature is room temperature, namely \( T = 25^\circ C \), the relationship between the dynamic stress and the strain rate can be obtained at room temperature based on Eq. (2):

\[ \sigma = A(1 + C\ln\dot{\varepsilon}^*) \]

(4)

From the fitting result of figure 5, \( C = 0.01 \).

- when the plastic strain \( \varepsilon = 0 \), the relationship among dynamical yield stress, strain rate and temperature can be obtained based on Eq. (2):

\[ \sigma = A(1 + C\ln\dot{\varepsilon}^*)(1 - (T^*)^m) \]

(5)
By data fitting, \( m = 0.62 \).

After determining the five parameters \( A, B, C, n \) and \( m \), we can get the expression of Johnson-Cook model for the 20Cr2Ni4 as follow:

\[
\sigma = (1112 + 1063e^{0.2})(1 + 0.01\ln e^{*})(1 - (T^{*})^{0.62})
\]  

(6)

5. Conclusions

According to the experiments for mechanical performance of 20Cr2Ni4 alloy steel, its stress-strain curves at different strain rate and different temperatures are obtained, which confirms the relationship between stress and strain when temperature ranges from 25\( ^\circ \)C to 400\( ^\circ \)C and the strain rate is within the range of 10\(^3\) s\(^{-1}\) -3000 s\(^{-1}\). Based on the curves, the strengthening effect of strain rate and softening effect of temperature of 20Cr2Ni4 is analyzed, drawing the conclusions which are shown as follows.

- Under the dynamic condition, Yield Stress of 20Cr2Ni4 steel increases over the strain rate, but it is not obvious. That is to say, the strengthening effect of strain rate of 20Cr2Ni4 is not evident unless the magnitude of strain rate changes.
- The dynamic Yield Stress of 20Cr2Ni4 steel decreases with the increase of temperature when the strain rate is about 2000 s\(^{-1}\). Yield Stress at 400\( ^\circ \)C is reduced by 35% than that at 25\( ^\circ \)C. When the strain rate is constant, the influence of temperature changes on the dynamic yield stress of 20Cr2Ni4 is significant, which means that the softening effect of temperature of 20Cr2Ni4 is notable.
- The parameters of Johnson-Cook constitutive relationship of 20Cr2Ni4 steel are determined by experimental data, which are obtained by experiments under the condition of quasi-static, dynamic at room temperature and dynamic at high temperature.

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