Research on Inconel 690 material test data analysis method

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Abstract. The quasi-static and dynamic tensile behavior of Inconel 690 alloy are studied by universal material testing machine and split-Hopkinson bar. In this paper, seven batches of nickel-based alloy samples were tested. Through these tests, the tensile stress-strain curve and tensile stress-strain rate curve of the material and the corresponding failure parameters are obtained. The Johnson-Cook (J-C) dynamic constitutive model was used to fit the experimental data by batch and non-batch analysis methods. By comparing the fitting parameters of the two analysis methods, it is possible to obtain the fitting parameters without batches. This analysis method is more suitable for the actual situation.

1. Introduction

Inconel alloy 690, a high-chromium nickel alloy, has good formability, high strength and excellent corrosion resistance. Owning to these attractive properties, it finds use in applications such as combustion systems, turbines and the nuclear reactors\cite{1}. Over the past few decades, extensive research has been conducted on the dynamic deformation behavior of materials\cite{2-4}. In this paper, the mechanical tension behavior of materials is tested under quasi-static and dynamic conditions. The electronic universal material testing machine has been used to test the quasi-static mechanical properties of materials in this thesis. And the split-Hopkinson bar technology has been used to evaluate the dynamic deformation behavior of materials.

The Johnson-cook (J-C) dynamic constitutive model is used to fit the experimental data, and the fitting parameters A, B, n, m, C are obtained. The present work use two analysis methods to analyze the test data. The first method is to perform reliability analysis according to batch fitting parameters; the second method is to do the reliability analysis and before fit the parameters without batch.

2. Experimental procedure

2.1. Quasi-static tensile test

The quasi-static test is divided into normal temperature quasi-static tensile test and high temperature quasi-static tensile test. 7 batches of nickel-based alloy samples were subjected to quasi-static tensile test. Through the test, we can get the elastic modulus, yield strength, tensile strength, elongation after fracture and reduction of area of each batch of materials.

The normal temperature quasi-static test will be tested by electronic universal material testing machines. According to GB/T 228.1, the tensile test pieces required for the test are designed.
The high-temperature quasi-tensile tests were conducted at 155°C and 350°C. According to the GB/T 4338, the tensile test pieces required for the test are designed. The high temperature tensile mechanical properties of the material will be studied using the MTS test system of the constant temperature heating furnace device. When conducting high-temperature tensile tests at 155°C and 350°C, the specimens are placed in a high-temperature furnace for testing. The working temperature of the high-temperature furnace is 100°C-1100°C.

2.2 Material dynamic mechanical properties test
The dynamic tensile tests were carried out by using a split-Hopkinson tensile bar. The Hopkinson rods in our laboratory are made of TC4 with a diameter of 19mm. The incident rod and transmission rod have lengths of 2.5m and 1.2m, respectively. There are three types of impact rods: 0.5m, 0.35m, and 0.2m. The compressed air pressure usually used for launching bullets is 0.1~0.6MPa, which can accelerate the bullet to 30~40m/s.

The dynamic tensile tests were carried out using a split-Hopkinson tensile bar with a diameter of Φ19 mm. In this test, seven batches of 690 nickel-based alloys with three different specifications of dynamic tensile tests were completed. Their sizes are Φ2×2, Φ2×4, and Φ2×8, respectively, and the load strain rate range are 5000~8000, 2000~5000 and 500~1000. Because the actual strain rate of the specimen has a certain degree of uncertainty due to comprehensive factors such as air pressure and friction in the Hopkinson bar experiment, so the specific strain rate needs to be calculated according to the results of each experiment. The electrical signals of the incident wave, reflected wave and transmission waveform of the loaded pulse are measured by the strain gauges pasted on the incident rod and the transmission rod. The strain rate, dynamic stress and deformation parameters of the specimen can be calculated through the stress wave theory.

3. Results and discussion

3.1. Quasi-static tensile test results
A total of 7 batches of materials were tested in the quasi-static tensile test at room temperature. And each batch of materials had two test pieces. Figure 1 shows quasi-static tensile stress-strain curves at room temperature by the two test pieces. Table 1 lists Summary of quasi-static tensile test results at room temperature. A total of 49 high-temperature tensile specimens were tested, including 22 specimens at 155°C and 27 specimens at 350°C. Table 2 lists the yield stress of the materials at different temperatures in quasi-static.

| Strain | Stress/MPa |
|--------|------------|
| 0.0    | 100        |
| 0.1    | 200        |
| 0.2    | 300        |
| 0.3    | 400        |
| 0.4    | 500        |
| 0.5    | 600        |

Figure 1. Normal temperature tensile test curve of two test pieces.

Table 1. Summary of quasi-static tensile test results at room temperature.
3.2. High temperature dynamic tensile test results
Due to the limitation of dynamic test conditions, the yield stress of the material cannot be accurately obtained. According to the experimental results of the material at 155°C and 350°C, the yield stress under different strain rates of each batch is plotted as shown in Table 3 and Table 4. And the experiment is repeated 2-3 times.

**Table 3. Yield stress of materials at different strain rates at 155°C.**

| Strain rate | Batch | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-------------|-------|-----|-----|-----|-----|-----|-----|-----|
| 500/s-1     |       | 402 | 476 | 500 | 536 | 525 | 450 |     |
| 500/s-2     |       | 522 | 490 | 504 | 578 | 525 | 500 |     |
| 500/s-3     |       |     | 430 |     | 550 | 500 |     |     |
| 1000/s-1    |       | 600 | 549 | 580 | 750 | 647 | 610 | 522 |
| 1000/s-2    |       | 520 | 587 | 730 | 610 | 560 | 533 |     |
| 1000/s-3    |       | 560 | 572 | 780 |     | 540 |     |     |
| 2000/s-1    |       | 753 | 618 | 692 | 787 | 755 | 790 | 612 |
| 2000/s-2    |       | 652 | 710 | 640 | 810 | 843 | 720 | 672 |
| 2000/s-3    |       | 720 |     |     | 785 |     |     |     |
| 5000/s-1    |       | 720 | 702 | 776 | 730 | 745 | 745 | 700 |
| 5000/s-2    |       | 793 | 704 | 758 | 741 | 777 | 755 | 662 |
| 5000/s-3    |       |     | 792 | 790 | 745 | 745 | 745 | 700 |
| 8000/s-1    |       | 629 | 854 | 720 | 1131| 714 | 730 | 737 |
| 8000/s-2    |       | 698 | 835 | 730 | 1136| 692 | 700 | 673 |
| 8000/s-3    |       | 787 | 712 |     |     | 693 | 744 |     |

**Table 4. Yield stress of materials at different strain rates at 350°C.**

| Strain rate | Batch | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-------------|-------|-----|-----|-----|-----|-----|-----|-----|
| 500/s-1     |       | 402 | 476 | 500 | 536 | 525 | 450 |     |
| 500/s-2     |       | 522 | 490 | 504 | 578 | 525 | 500 |     |
| 500/s-3     |       |     | 430 |     | 550 | 500 |     |     |
| 1000/s-1    |       | 600 | 549 | 580 | 750 | 647 | 610 | 522 |
| 1000/s-2    |       | 520 | 587 | 730 | 610 | 560 | 533 |     |
| 1000/s-3    |       | 560 | 572 | 780 |     | 540 |     |     |
| 2000/s-1    |       | 753 | 618 | 692 | 787 | 755 | 790 | 612 |
| 2000/s-2    |       | 652 | 710 | 640 | 810 | 843 | 720 | 672 |
| 2000/s-3    |       | 720 |     |     | 785 |     |     |     |
| 5000/s-1    |       | 720 | 702 | 776 | 730 | 745 | 745 | 700 |
| 5000/s-2    |       | 793 | 704 | 758 | 741 | 777 | 755 | 662 |
| 5000/s-3    |       |     | 792 | 790 | 745 | 745 | 745 | 700 |
| 8000/s-1    |       | 629 | 854 | 720 | 1131| 714 | 730 | 737 |
| 8000/s-2    |       | 698 | 835 | 730 | 1136| 692 | 700 | 673 |
| 8000/s-3    |       | 787 | 712 |     |     | 693 | 744 |     |
4. Experimental data analysis

According to the quasi-static and dynamic test results obtained by the experiment, the Johnson-Cook (J-C) dynamic constitutive model is used to fit them. It represents the flow stress as the product of strain hardening $f_1(\varepsilon)$, strain rate strengthening $f_2(\dot{\varepsilon})$ and thermal softening $f_3(T)$. And the flow stress may be expressed by

$$\bar{\sigma} = f_1(\varepsilon)f_2(\dot{\varepsilon})f_3(T)$$

(1)

For the analysis of the experimental data in this article, two different analysis methods will be used for analysis. The first method is to fit parameters by batch and then do reliability analysis; the second method is to do the reliability analysis and before fit the parameters without batch.

4.1. Fit parameters by batch and then do reliability analysis

Table 5 lists the fitting parameters of each batch according to the quasi-static and dynamic test results.

**Table 5.** Fitting parameters.

| Batch | A/MPa | B/MPa | n   | m   | C   |
|-------|-------|-------|-----|-----|-----|
| 1     | 287.1 | 1264.6| 0.722| 1.13| 0.1159 |
| 2     | 296.2 | 1303.4| 0.728| 1.06| 0.1144 |
| 3     | 289.2 | 1320.6| 0.747| 1.06| 0.1287 |
| 4     | 240.8 | 1243.6| 0.785| 1.52| 0.1709 |
| 5     | 286.7 | 1271.5| 0.757| 1.09| 0.1413 |
| 6     | 216.4 | 1221.3| 0.796| 1.69| 0.1372 |
| 7     | 270.2 | 1352.1| 0.796| 0.96| 0.1220 |
| Mean  | 269.5 | 1282.4| 0.762| 1.216| 0.1329 |
| Standard deviation | 29.862 | 45.520 | 0.0312 | 0.275 | 0.0196 |

Use the relevant knowledge of probability statistics, we analyze the average and standard deviation of the $A$, $B$, $n$, $m$ and $C$ in the table above.

The average formula is as follows:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

(2)
The standard deviation formula is as follows:

\[ \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 \]  

(3)

The Normal distribution probability density function is as follows:

\[ f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]  

(4)

The analysis results of the above parameters are as follows:
1) The fitting results of the parameters A, B and n meet a satisfy normal distribution rules
2) There is a certain difference between the fitting result of the parameter m and the normal distribution law.

4.2. Regardless of batch, first perform reliability analysis before fitting parameters

4.2.1. Analysis of quasi-static parameters A, B, n
First, use the data obtained from the room temperature quasi-static experiment to fit the respective A, B, and n. At the room temperature quasi-static experiment, we did a total of seven groups of experiments, each group of experiments repeated twice. 14 groups of A, B, and n values can be fitted accordingly, as shown in Table 6. Then we analyze A, B, and n separately.

The analysis results of the above parameters are as follows:
The fitting results of the parameters A, B and n meet a satisfy normal distribution rules

| Batch | A/MPa  | B/MPa  | n      |
|-------|--------|--------|--------|
| 1-1   | 285.3  | 1261.9 | 0.717  |
| 1-2   | 288.8  | 1267.3 | 0.726  |
| 2-1   | 288.3  | 1307.7 | 0.726  |
| 2-2   | 304.1  | 1299.1 | 0.729  |
| 3-1   | 287.4  | 1319.2 | 0.747  |
| 3-2   | 290.9  | 1322.0 | 0.747  |
| 4-1   | 242.6  | 1250.9 | 0.790  |
| 4-2   | 239.0  | 1236.3 | 0.779  |
| 5-1   | 281.5  | 1243.3 | 0.759  |
| 5-2   | 291.8  | 1299.6 | 0.755  |
| 6-1   | 215.0  | 1208.2 | 0.780  |
| 6-2   | 217.8  | 1234.3 | 0.812  |
| 7-1   | 274.6  | 1375.7 | 0.800  |
| 7-2   | 265.8  | 1328.5 | 0.791  |
| Mean  | 269.5  | 1282.4 | 0.761  |
| Standard deviation | 28.995 | 46.477 | 0.0309 |

4.2.2. Fitting analysis of strain rate hardening coefficient C
The parameter C is obtained using the yield stress of the material at the same temperature and different strain rates. At the reference temperature, the relationship between yield stress and strain rate can be written as:

\[ \sigma_{eq} = A \left( 1 + C \ln \varepsilon_{eq}^* \right) \]  

(5)
$$\frac{\sigma_{eq}}{A} = 1 + C \ln \dot{\varepsilon}_{eq}$$

Let \( y = \frac{\sigma_{eq}}{A} \), \( x = \ln \dot{\varepsilon}_{eq} \)

\[ y = 1 + Cx \quad (6) \]

It can be seen from the above formula that \( C \) satisfies the linear regression form, so linear regression can be used to analyze \( C \). Perform linear regression analysis on the data in Table 3, the fitted straight line equation is:

\[ y = 1 + 0.1367x \quad (7) \]

We can get \( C = 0.1367 \), and the 95% confidence interval of \( C \) is (0.1296, 0.1439).

Perform linear regression analysis on the data in Table 4, the fitted straight line equation is:

\[ y = 1 + 0.1315x \quad (8) \]

We can get \( C = 0.1315 \), and the 95% confidence interval of \( C \) is (0.1261, 0.1369).

4.2.3. Analysis of temperature influence coefficient \( m \)

For the fitting analysis of the temperature influence coefficient \( m \), the yield stress at different temperatures is used for fitting \( m \).

Under the reference strain rate, that is, under quasi-static conditions, the relationship between yield stress and temperature can be written as

\[ \sigma_{eq} = A \left( 1 - T^* m \right) \quad (9) \]

Let \( y = \sigma_{eq}/A \), \( x = T^* \)

\[ y = 1 - x^m \quad (10) \]

Regression analysis was performed on the data in Table 3, and the fitting curve expression was:

\[ y = 1 - x^{1.164} \quad (11) \]

which resulted in \( m = 1.164 \), and the 95% confidence interval of \( m \) was (1.037, 1.291).

5. Conclusions

The following conclusions can be obtained by analyzing the conclusions of the above two analysis methods.

1. For the fitting parameters \( A, B \) and \( n \), the conclusions drawn by the two test data analysis methods are basically the same.
2. For the fitting parameters \( m \) and \( C \), the conclusions drawn by the two test data analysis methods are consistent within the 95% confidence interval.
3. Both of the above methods can be used to analyze experimental data. But considering the distribution of actual experimental data, the second method is more suitable for the actual situation.

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References

[1] Woei-Shyan L, Chen Y L and Tai-Nong S 2004 Deformation behavior of Inconel 690 super alloy evaluated by impact test J Mater Process Technol vol 153/154 219-225.
[2] Yang Y F, Gai G S, Zhao X J and et al 2005 Dynamic mechanical properties of whisker/PA66 composites at high strain rates Polymer J Sci Technol. vol 46(10) 3528-34

[3] Belyaev S, Petrov A, Razov A and et al 2004 Mechanical properties of titanium nickelide at high strain rate loading Mater Sci Eng A. vol 378 122-4

[4] Qiang Li, Y. B. Xu and Bassim M. N 2004 Dynamic mechanical behavior of pure titanium J Mater Process Technol. vol 155/156 pp 1889-92