Tensile testing of Inconel 600 wire at high temperatures

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Abstract. This paper presents how to determine some mechanical properties of wires subjected to tensile testing. Additional equipment was added to an existing tensile testing machine for wires at high temperatures. A tensile testing procedure for wires at high temperature is described. Tensile tests of Inconel 600 wire were conducted at 700, 800 and 900 °C. The ultimate strength, the yield strength and the percentage elongation after fracture are determined. Analysis of the gathered results is done.

1. Introduction

Composite materials are becoming more widely used in different industries. Their share rapidly increases in automotive, boatbuilding, aircraft and military industries, building of skis and other sports equipment, as well as in production of construction materials. The composite materials are also known as reinforced materials because they often consist of reinforcing fibers (wires) inside polymer, wooden, ceramic, metal or other matrix. The composites are materials of which lightweight parts can be made, having high strength at the same time.

One of the major applications of Inconel wire is as reinforcing component in composite materials.

Stress-stain analysis of parts made from composite materials is most often done using numerical analysis. This kind of analysis demands the mechanical properties of the materials of which the matrix and the reinforcing fibers are made at the working conditions of the relevant part.

The mechanical properties of Inconel 600 at room temperature vary in wide ranges depending of the production technology – table 1 [1]. This table shows mechanical properties of Inconel 600 wires with diameter varying from 1,6 mm to 6,4 mm.

The study of material behaviour at temperatures higher than 600 °C is accompanied by overcoming significant difficulties set by the reliability of used devices and maintaining specified test conditions for a long period of time. Therefore, little data is available in literature for the materials behaviour at high temperatures.

The elasticity modulus, the shearing modulus and the Poisson’s ratio of Inconel 600 at temperatures up to 1000 °C are given in table 2.

Figure 1 shows the mechanical properties of cold-drawn rod of Inconel 600, determined at high temperatures tensile tests.

The literature does not provide data for the yield strength, the tensile strength and the strain of Inconel 600 wires at high temperatures.

The following problem arises – to determine the yield strength, the tensile strength and the strain of Inconel 600 wire at 700 °C, 800 °C and 900 °C. A cold-drawn wire with diameter of 0,25 mm is used. The chemical composition of the wire material is given in table 3.
Table 1. Mechanical properties of Inconel 600 at room temperature.

| Form and Condition | Tensile Strength | Yield Strength (0.2% Offset) | Elongation, % | Hardness, Rockwell |
|--------------------|------------------|------------------------------|---------------|--------------------|
|                    | kgi | MPa  | kgi | MPa  |                  |
| Rod and Bar        |     |      |     |      |                  |
| Cold-Drawn         |     |      |     |      |                  |
| Annealed           | 80-100 | 550-690 | 25-50 | 170-345 | 55-35 | 65-85B |
| As-Drawn           | 105-150 | 725-1035 | 80-125 | 550-850 | 30-10 | 90B-30C |
| Hot-Finished       | 80-100 | 550-690 | 30-50 | 205-345 | 55-35 | 65-85B |
| Plate              |     |      |     |      |                  |
| Hot-Rolled         |     |      |     |      |                  |
| Annealed           | 80-105 | 550-725 | 30-50 | 205-345 | 55-35 | 65-85B |
| As-Rolled          | 85-110 | 580-750 | 35-65 | 240-450 | 50-30 | 80-95B |
| Sheet              |     |      |     |      |                  |
| Cold-Rolled        |     |      |     |      |                  |
| Annealed           | 80-100 | 550-690 | 30-45 | 205-310 | 55-35 | 88B max. |
| Cold-Drawn         |     |      |     |      |                  |
| Annealed           | 80-100 | 550-690 | 30-45 | 205-310 | 55-35 | 84B max. |
| Wire               |     |      |     |      |                  |
| Cold-Drawn         |     |      |     |      |                  |
| Annealed           | 80-120 | 550-830 | 35-75 | 240-520 | 45-20 | - |

Table 2. Elasticity modulus, shearing modulus and Poisson’s ratio of Inconel 600.

| Temperature | Young Modulus | Shear Modulus | Poisson’s Ratio |
|-------------|---------------|---------------|-----------------|
| °C          | GPa           | GPa           |                 |
| 22          | 214           | 80.8          | 0.324           |
| 100         | 210           | 79.6          | 0.319           |
| 200         | 205           | 78.0          | 0.314           |
| 300         | 199           | 77.2          | 0.306           |
| 400         | 193           | 74.2          | 0.301           |
| 500         | 187           | 71.9          | 0.290           |
| 600         | 189           | 69.2          | 0.281           |
| 700         | 177           | 65.9          | 0.275           |
| 800         | 164           | 62.1          | 0.264           |
| 900         | 154           | 57.9          | 0.254           |
| 1000        | 143           | 53.4          | 0.239           |

Figure 1. High-temperature tensile properties of Inconel 600 cold-drawn rod.

Table 3. Chemical composition of the tested wire (in %).

| Ni | Cr | Fe | Si | Co | Mn | Cu | C  | S  |
|----|----|----|----|----|----|----|----|----|
| ≥72.0 | 15.5 | 8 | 0.5 | < 1 | < 1 | < 0.5 | < 0.15 | < 0.015 |
2. Metallic materials. Tensile testing. Method for tensile testing at high temperature

2.1. Test pieces with diameter less than 4 mm
The initial gauge length ($L_o$) must be $(200 \pm 2)$ mm or $(100 \pm 1)$ mm [2]. The distance between the grips of the machine must be no less than $(L_o + 20)$ mm. If test pieces with small diameter are tested, the distance between the grips of the machine may be equal to $L_o$ [3].

2.2. Testing conditions
The test piece must be heated to a predetermined temperature and it must be held at this temperature for no less than 10 minutes. The strain rate of test piece working area should be 0,001 min$^{-1}$ to 0,005 min$^{-1}$ from the beginning of the test until the yield strength is reached. After the yield strength is reached strain rate of 0,20 min$^{-1}$ is allowed [4].

2.3. Determination of proof strength, plastic extension for given percentage elongation
Proof strength, plastic extension ($R_p$) for given percentage elongation is determined from the force-extension curve of the material by drawing a line parallel to the linear portion of the curve at distance from it equivalent to the given percent of the percentage elongation, for example 0,2%. The ordinate of the point at which this line crosses the stress-percentage elongation curve corresponds to the proof strength, plastic extension. An index showing the percentage of elongation is added to the designation of the yield strength for example $R_{p0.2}$.

2.4. Determination of percentage elongation after fracture
The two broken parts of the test piece must be carefully fitted back together so that their axes lie in a straight line. The final gauge length is determined ($L_u$).

The elongation after fracture ($L_u - L_o$) to the nearest 0,25 mm or better, should be determined using a measuring device with sufficient resolution.

The percentage elongation after fracture ($A$) is calculated using:

$$A = \frac{L_u - L_o}{L_o} \times 100, \%.$$

Index to the designation A must be added which shows the used original gage length in mm, for example: $A_{100\text{ mm}}$ is percentage elongation for original gauge length ($L_o$), equal to 100 mm.

3. Adding of additional equipment to existing tensile testing machine of wires at high temperatures

3.1. Available machine
In “Strength of materials” department at Technical University Sofia, a tensile testing machine at high temperatures is available – figure 2.

3.1.1. Tensile testing machine – it has the following features:
- The loading module of the machine is made using stepper motor, reduction gear and lead screw. To ensure the smooth and precise application of the force created by the lead screw, a reduction gear with large transfer ratio ($i = 50$) and stepper motor with large number of steps (200) per revolution are used;
- The grips of the machine (called upper and lower stem) are designed to test cylindrical test pieces with 6 mm diameter of the working area;
- The load cell of the machine is designed to measure loads up to 10 kN;
• An elastic body is present which assures smooth loading and minimizes the shock after the test piece fractures;
• The tensile testing machine complies with the requirements of EN ISO 7500-1 standard.

Figure 2. Available tensile testing machine at high temperatures.

3.1.2. Heating module – it has the following features:
• It assures heating of the test piece up to 1100 °C;
• To assure even distribution of temperature field the heaters are located in three sections each of which is controlled by a separate thermocouple and separate thermo-regulator [5]. Each section is comprised of two heaters (one situated in the left part of the module and the other - in the right part);
• The heating module complies with the requirements of BDS EN ISO 6892-2 standard [6].

3.1.3. Extensometers – they are designed to be attached to cylinder test pieces with diameter of the working area of 6 mm.

3.1.4. Electronic control unit – it controls the testing parameters: force and temperature [7].

3.1.5. Personal computer – the electronic control unit sends in real time all of the measured signals to the computer. The computer records processes and visualizes the received information using specialized software. The parameters processed by the software are: assigned force and real measured force, longitudinal strain, transverse strain, temperatures in all three sections of the heating module and the number of steps made by the stepper motor.
3.2. New additional equipment
To realize tensile testing of wires at high temperatures with the available testing machines, the following is required:

- To design and build new load cell, which allows accurate measurement of loads up to 0.1 kN;
- To design and build gripping device to test wires at tensile loading at high temperatures;
- To design and build new stems (upper and lower), which allow to attach the new gripping devices to the testing machine;
- The available extensometers cannot be attached to the wire under the test. It is planned the longitudinal strain to be measured using the stepper motor. To do this, the elastic body of the tensile testing machine should be removed and the lower stem of the machine should be extended with additional stem, which is connected directly to the load cell.

Figure 3 shows 3D model of the designed strain gauge load cell. It is comprised of body 1, cap 2 and electrical plug 3 to send the measured signal to the testing machine. The load cell body is also used as elastic element and strain gauges 4 are mounted on it. The strain gauges are connected in “full bridge” circuit. This assures compensation for temperature influence on the measurement and manufacturing inaccuracies of the elastic body. The load cell body is made of 1.7045 steel.

Figure 4 shows 3D model of the gripping device for tensile testing of wires at high temperatures. The device comprises of two holding pieces – upper holding piece 1 and lower holding piece 2. Each holding piece consists of two halves, pin 3 and screws 4. The pins have diameter of 5 mm and radial holes are drilled through which the wire passes. A horizontal and vertical channels are machined in the holding pieces. The horizontal channels are needed to mount the pins. The vertical channels allow the wire to pass without touching the holding pieces. The two halves of the holding pieces are attached to each other using four screws M6x20. The gripping device is made of temperature-resistant alloyed steel with high ultimate strength.

The shape and the size of the upper holding piece of the grip are designed taking into account the already available upper stem of the tensile testing machine (designed for testing 6 mm test pieces). It is necessary to build only one new lower stem for the tensile testing machine – figure 5. The upper holding piece is attached to the upper stem of the testing machine using attachment head. The lower holding piece is attached to the lower stem of the machine using thread connection. The machine’s lower stem is made of temperature-resistant alloyed steel with high ultimate strength.

Figure 5 shows 3D model of the extension stem with which the lower stem of the machine is extended. The connection between the load cell and the lower stem is made using thread connection. For this purpose, an adapter is needed, also shown on figure 5. The lower stem and adapter are built using common carbon steel S355JR.

![Figure 3. 3D model of the load cell.](image)

![Figure 4. 3D model of the gripping device for tensile testing of wires.](image)

![Figure 5. 3D models of the lower stem, the extension stem and the adapter.](image)
Figure 6 shows a photograph of the machined and mounted additional equipment needed for tensile testing of wires at high temperatures with the available tensile testing machine.

![Figure 6. Photograph of the machined and mounted additional equipment.](image)

3.3. **Sequence for tensile testing of wires at high temperature**

3.3.1. *The wire is mounted in the pins* – figure 7. Steps:

- A wire with 200 mm length is cut;
- The wire is passed through the radial hole of the first pin in such a way that it extends beyond the pin by 45 mm;
- The hole of the pin is filled with Pyro-Paint, while making sure that the wire doesn’t touch any edges of the hole. It is necessary to wait for 2 hours for Pyro-Paint to dry out. This procedure allows to avoid stress concentration caused by the hole edge during tensile testing.
- The previous two steps are made for the other side of the wire;
- The wire with the two pins attached, is heated to 93 °C for 2 hours (this procedure is recommended by Pyro-Paint manufacturer);
- The two parts of the wire with 45 mm length each are wound to each of the pins;
- On each of the wound wires a few drops of stain gauge adhesive X60 are dropped (this assures easy mount of the pins in the holding pieces);
- The wire is straightened and the length of the wire between the pins is measured (the original gauge length $L_0$ is needed to calculate the percentage elongation after fracture A) – $L_0 = 100$ mm.

3.3.2. *The pins with the wire are mounted in the holding piece and the attaching screws are tightened* – figure 8.

3.3.3. *The grips are mounted in special plastic brackets to prevent deformation of the wire during its mount in the heating module* – figure 9.
3.3.4. The grips with the wire are mounted to the stems of the tensile testing machine and the brackets are removed – figure 6.

3.3.5. The desired testing temperature is set and the heating module is switched on, it is necessary to wait for the heating module to reach the set temperature after which additional 10 min have to pass.

3.3.6. The measuring equipment is zeroed.

3.3.7. The wire under test is subjected to pure tension until its fracture – during the loading, continuously the values of the force and the number of the steps made by the stepper motor are recorded (the number of steps is used to measure the strain of the test length on the wire).

3.3.8. The stress – percentage elongation curve of the material is drawn and the values of $R_{p0.2}$, $R_m$ and $A_{100mm}$ are determined.

4. Tensile testing

Twelve wires were tested (3 at room temperature, 3 wires at 700 °C, 3 at 800 °C and 3 at 900 °C). Figure 10 shows the gathered stress-percentage elongation curves. Table 4 presents the values of the determined mechanical properties are given.

![Stress-percentage curves](image)

**Figure 10.** Stress-percentage curves.

At room temperature the Inconel 600 wire has the behaviour of brittle material, while at high temperatures it has the behaviour of ductile material.

As expected, the values of the stress properties decrease with the rise of the temperature. It is interesting to note that at 800 °C the longitudinal percentage elongation is less than the longitudinal percentage elongation at 700 °C, while at 900 °C we have the largest value of longitudinal percentage elongation. It is highly probable that this is due to structural change in the material. Such decrease followed by rise of the longitudinal percentage elongation with respect to the rise of the temperature is gathered in [1] – figure 1 – for Inconel 600 cold-drawn rod.
Table 4. Mechanical properties.

| $T$, °C | Wire № | $R_{me}$, MPa | $R_{p0.2}$, MPa | $A_{100mm}$, % |
|---------|--------|---------------|-----------------|----------------|
| 20 °C   | 1      | 1136          | -               | 2,2            |
|         | 2      | 1118          | -               | 1,8            |
|         | 3      | 1124          | -               | 2,4            |
|         | Average| 1126          | -               | 2,1            |
| 700 °C  | 1      | 338           | 260             | 20,4           |
|         | 2      | 318           | 256             | 23,1           |
|         | 3      | 324           | 249             | 21,9           |
|         | Average| 327           | 255             | 21,8           |
| 800 °C  | 1      | 180           | 142             | 16,1           |
|         | 2      | 190           | 150             | 14,2           |
|         | 3      | 184           | 138             | 15,5           |
|         | Average| 185           | 143             | 15,3           |
| 900 °C  | 1      | 102           | 80              | 27,2           |
|         | 2      | 108           | 78              | 24,3           |
|         | 3      | 104           | 74              | 25,1           |
|         | Average| 105           | 77              | 25,5           |

5. Conclusion
Some mechanical properties of Inconel 600 are determined at 700, 800, 900 °C. The collected results shall be used for:
- Stress-strain analysis of composite materials (materials reinforced with Inconel 600 wires) exposed to high temperatures for short period of time.
- Determination of the impact of heat treatment of the Inconel 600 wire on its stress properties.
- Further study of the behaviour of Inconel 600 wire exposed to high temperatures for prolonged period of time.

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