Design, manufacture and test of a high temperature tensile and compression testing device

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Abstract

This paper describes the design and manufacture of a low-cost laboratory test device capable of testing metallic materials at elevated temperatures. The device, which consists of an environmental chamber, specimen gripping mechanism, and associated instrumentation, is fitted to a standard tensile-compression machine. Standard tensile test samples, notched specimens and compression test samples can be tested in the device at temperatures up to 1200°C. This paper describes the operation of the device and the results of a series of validation tests, on various metallic materials, carried out on the machine.

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Keywords: Elevated Temperature, Tensile/Compression Testing; Metallic Materials

1. Introduction

The changing environment for higher education in Ireland is exerting increasing pressure on many Irish Universities and Colleges. While university attendance has been on the rise over the past 10 years, government funding has been on the decline. Indeed, the presidents of Irish universities bemoan their international rankings and collectively call on the government heads to increase their funding, to allow them to climb back up the global rankings.

The cost of infrastructure has long been a complaint of Irish universities, many of which have struggled financially over the last decade. Consequently, large pieces of science and engineering laboratory equipment are outside the reach
of many third level institutions. At the University of Limerick in Ireland, there is a frequent requirement to characterize metallic materials by tensile testing either for consultancy or research projects.

The most common testing machine used in tensile testing is the universal testing machine. This type of machine has two crossheads; one is adjusted for the length of the specimen and the other is driven to apply tension to the test specimen. Typically the machine is hydraulically or electrically powered. The four main test parameters are: force capacity, speed, precision and accuracy. Force capacity refers to the fact that the machine must be able to generate enough force to fracture the specimen. The machine must be able to apply the force quickly or slowly enough to properly replicate the actual force application. Finally, the machine must be able to accurately and precisely measure the gauge length and forces applied; for instance, a large machine that is designed to measure long elongations may not work with a brittle material that experiences short elongations prior to fracturing. To allow testing of metallic materials at high temperatures, an environmental chamber is typically fitted to the tensile testing machine.

The strain measurements are most commonly measured with an extensometer, but strain gauges are also frequently used on small test specimens.

1.1. Tensile test samples

Most tensile tests are carried out on round specimens. Critical dimensions for the test specimens are the gauge length and the cross sectional area. The majority of the elongation occurs in a local area of the gauge length. A modification, commonly carried out on cylindrical specimens, is to cut a notch on the gauge section of the specimen. The reason for this is that it changes the stress state in the notch region from uniaxial to triaxial. For certain products and material form such as sheet metal, round test specimens are not practical. For this reason, flat specimens are used.

1.2. High temperature testing

The recent resurgence and growing interest in high temperature structures to maximize design space and performance in aerospace, motorsport and power plant applications, has led to the need for greater understanding of high temperature materials [1]. The suitability of materials to perform in these environments is difficult to ascertain due to a limited availability of high temperature design data.

Mechanical property data is required to understand the behavior and limitations of metallic materials at high temperatures, and to allow accurate modelling to take place. Several mechanical tests are available to assess the mechanical properties of a material, of which tensile and flexural testing are the most common. Tensile testing is generally preferred to flexural testing, as flexural testing produces maximum stresses only in small regions at the test specimen surface, which can lead to localized effects. Tensile testing produces maximum stresses throughout the test specimen as a whole, and the data acquired is more established and appropriate regarding the design and modelling of structures.

Many properties of a material are affected by the temperature of the material. The majority of those properties found in databases today quote properties at room temperature, which differ greatly if the material is heated. In general, with increasing temperature the strength of a material will decrease as the energy required to initiate plastic flow of the material is reduced, while the materials ductility increases. Furthermore, structural changes such as precipitation, strain aging, or recrystallization may occur in certain temperature ranges to alter this general behavior [2].

It is therefore essential to establish the elevated temperature properties of materials for particular applications, the most important application being the hot working of materials, but also include any applications where a component is subjected to elevated temperatures for a long period.

The hot working characteristics of materials are most commonly determined using hot tensile tests. In order to produce high quality wrought products, the appropriate hot-working temperature and deformation rate must be established, which also affect the levels of cavitation caused by internal tensile stresses. The tensile ductility, flow stress and cavity formation conditions should be established as a function of temperature and strain rate [3]. Significant studies on the high temperature properties of metallic materials have previously been carried out. The temperature dependency of true strain hardening and plastic-instability properties for austenitic stainless steels including annealed 304, 316, 316LN, at test temperatures from 150°C to 450°C was established in one particular study.
Above room temperature, it was observed, that the true strain-hardening rate decreased monotonically with strain in the uniform deformation region. In another study, a test program was carried out to investigate the material properties of cold-formed high-strength steel at elevated temperatures. Coupon specimens were extracted from cold-formed high strength steel square and rectangular hollow sections with nominal yield stresses of 700 and 900 MPa at ambient temperature. The coupon tests were carried out through both steady and transient state test methods at temperatures up to 1000 °C. The test results were compared with the design values in the European, American, Australian and British standards. The comparison results revealed the necessity of proposing specified design rules for material properties of cold-formed high strength steel at elevated temperatures [5]. The mechanical properties of cold formed steel at temperatures between 20°C and 700°C were established using tensile tests in another study [6]. From the results of this study, a consistent drop of mechanical properties with increasing temperature was observed. Other researchers performed a study on the experimental characterization of cold-formed steel at high temperatures. The variation of the constitutive relations was measured for temperatures ranging from 20°C to 600°C. The obtained experimental results indicated a clear distinction with the models proposed by other authors [7].

2. Machine design

In the current research project, a small high-temperature testing furnace was reconditioned and reconfigured to allow its attachment to a standard tensile testing machine. The furnace is heated by an array of silicon carbide heating elements and is insulated by high quality alumina fibre insulation hardened with colloidal silica. A PID controller is used to control the furnace temperature.

2.1. Furnace modifications

Significant modifications were made of the furnace to allow its integration with the existing 25kN tensile testing machine frame. These modifications included the manufacture of a split front door to accommodate specimen mounting and fitting an extensometer, specimen grips, rebuilding of insulation, water cooling circuit and data acquisition system.

2.2 Furnace door

Stainless Steel AISI Type 321 was selected to manufacture the furnace door. This is a stabilized stainless steel, which offers as its main advantage an excellent resistance to intergranular corrosion following exposure to temperatures in the chromium carbide precipitation range. The doors were attached to the furnace body by stainless steel hinges. A locking mechanism the doors latched during testing. A central slot was machined in each door to allow its attachment to a standard tensile testing machine frame. These modifications included the manufacture of a split front door to accommodate specimen mounting and fitting an extensometer, specimen grips, rebuilding of insulation, water cooling circuit and data acquisition system.

2.3 Specimen grips and pull heads

One of the design criteria for the test device was to enable it to test samples of varying type. An example of such specimens is presented below in Fig. 1. The upper and lower specimen pull heads were machined from Inconel 625. This material is a nickel-based super alloy that possesses high strength properties and excellent strength at elevated temperatures. It also demonstrates remarkable protection against corrosion and oxidation. Its ability to withstand high stress and a wide range of temperatures as well as being able to resist corrosion while being exposed to highly acidic environments makes it a fitting choice for this use.
To eliminate the need for a threaded end on the tensile test samples, a split-design clamp was manufactured to hold the tensile sample in position during testing. Machine threads on samples with diameters less than 5mm is problematic, time consuming and adds to the overall cost of machining the samples. Stavax premium grade stainless steel from the Uddeholm family of steels was the material selected for the split-design tensile test grip attachments. This split-design clamp is shown below in Figure 2. A locking ring was manufactured to keep both halves of the clamp secured around the sample during testing.

An oxide layer typically forms on the surface of the grip attachments when testing at elevated temperatures. This could cause seizure of the locking rings which are slipped over the split-design clamp. This problem was overcome by applying a high temperature release compound to the outer surface of the grips and also the inside of the locking rings before they are attached together. Once the furnace returns to room temperatures the locking rings slip off with ease. The complete split-design clamp with tensile test specimen is shown below in Figure 3.
2.4. Mounting furnace to tensile test machine

One of the design requirements for the test machine was to ensure that it afforded flexibility to the various users of the machine. Therefore, the method of attaching the furnace to the tensile test machine frame had to ensure that the furnace was easily removed when it was not required. Consequently, the furnace was mounted onto a machined plate which itself was attached onto a linear rail system so the furnace could be retracted from tensile test machine bed when not in use. This ensured that the tensile test machine could be quickly changed over to room temperature testing of other samples and structures. The linear rail system and linear bearings ensured precise location, alignment and balancing of the furnace was achieved when moving it into position for testing. A frame was manufactured to house the temperature controller, cooling water tank, power supply and water pump. The complete tensile test machine and furnace was mounted on this frame and the entire assembly was mobile due to the attachment of castors on the frame. The complete setup is shown in Fig. 4. An epsilon high temperature extensometer was used to measure sample strain.

2.5. Validation of Test System

Tensile test specimens for three different metallic materials were machined on a CNC lathe. The specimens were machined in accordance with existing tensile standards EN10002-1, ASTM E8 and ISO 6892. The specimens were machined from Stainless Steel Grade 316, Tool Steel 1.2210, Aluminum 2011-T3 and Free Cutting Brass UNS C36000. Five samples were manufactured from each material to determine if the machine could successfully perform the tensile testing.

![Fig. 4. (a) Complete test machine setup (front doors open); (b) machine instrumentation](image)

3. Experimental programme results

A comprehensive experimental programme of testing was conducted on the test machine. Initially, room temperature tests on Silver Steel 1.2210 (115CrV3) and Free Cutting Brass UNS C36000 were carried out using the newly designed specimen gripping system. The tensile test specimens were prepared to ASTM E 8M-04 standard specification and tested at a strain rate of 0.025%/sec at 20°C. Two samples of each material were tested. The results of this test, which are presented below in Tables 1 and 2 compare favorably to the reference data for these materials.

<table>
<thead>
<tr>
<th>Property</th>
<th>Reference</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
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<tr>
<td>Young's Modulus (GPa)</td>
<td>200</td>
<td>204</td>
<td>203</td>
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<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>750</td>
<td>742</td>
<td>740</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>370</td>
<td>372</td>
<td>375</td>
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<th>Sample 2</th>
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<tbody>
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<td>Young's Modulus (GPa)</td>
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<td>Ultimate Tensile Strength (MPa)</td>
<td>550</td>
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<tr>
<td>Yield Strength (MPa)</td>
<td>290</td>
<td>305</td>
<td>296</td>
</tr>
</tbody>
</table>

Elevated Temperature Tests

Tensile tests were performed on samples of Grade 316 Stainless Steel. This steel is commonly used for its high temperature properties due to the retention of its mechanical strength and its oxidation resistance at high temperature.

Tensile tests were carried out at both 20°C and 400°C. The samples were allowed to soak at the test temperature for 15 minutes and subsequently tested at a strain rate of 0.025%/sec. The results of the elevated temperature tests were compared to the relevant literature as presented in the stress-strain plots shown below in Fig. 5 [8, 9].
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One of the design requirements for the test machine was to ensure that it afforded flexibility to the various users of the machine. Therefore, the method of attaching the furnace to the tensile test machine frame had to ensure that the furnace was easily removed when it was not required. Consequently, the furnace was mounted onto a machined plate which itself was attached onto a linear rail system so the furnace could be retracted from tensile test machine bed when not in use. This ensured that the tensile test machine could be quickly changed over to room temperature testing of other samples and structures. The linear rail system and linear bearings ensured precise location, alignment and balancing of the furnace was achieved when moving it into position for testing. A frame was manufactured to house the temperature controller, cooling water tank, power supply and water pump. The complete tensile test machine and furnace was mounted on this frame and the entire assembly was mobile due to the attachment of castors on the frame. The complete setup is shown in Fig. 4.

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Table 1. Room temperature tensile test results for Silver Steel.

<table>
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<th>Reference*</th>
<th>Sample 1</th>
<th>Sample 2</th>
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<tr>
<td>Young’s Modulus (GPa)</td>
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<td>740</td>
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<tr>
<td>Yield Strength (MPa)</td>
<td>370</td>
<td>372</td>
<td>375</td>
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</tbody>
</table>

Table 2. Room temperature tensile test results for Free Cutting Brass.

<table>
<thead>
<tr>
<th>Property</th>
<th>Reference†</th>
<th>Sample 1</th>
<th>Sample 2</th>
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<tr>
<td>Young’s Modulus (GPa)</td>
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<td>Ultimate Tensile Strength (MPa)</td>
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3.1. Elevated Temperature Tests

Tensile tests were performed on samples of Grade 316 Stainless Steel. This steel is commonly used for its high temperature properties due to the retention of its mechanical strength and its oxidation resistance at high temperatures. Tensile tests were carried out at both 20°C and 400°C. The samples were allowed to soak at the test temperature for 15 minutes and subsequently tested at a strain rate of 0.025%/sec. The results of the elevated temperature tests were compared to the relevant literature as presented in the stress-strain plots shown below in Fig. 5 [8, 9].

![Stress-strain plots](image)

* Abrams premium steel database
† Total Materia database

Fig. 5. Test results on Grade 316 Stainless Steel at temperatures of 20°C and 400°C
The numeric data from the tests conducted at 400°C are presented below in Table 3.

<table>
<thead>
<tr>
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<th>Reference [10]</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (GPa)</td>
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<td>197</td>
<td>195</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>492</td>
<td>490</td>
<td>488</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>175</td>
<td>240</td>
<td>245</td>
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</tbody>
</table>

Tensile tests were also conducted on Aluminum 2011-T3 at temperatures of 20°C, 100°C, and 200°C. This aluminum alloy has good machinability, good free-cutting qualities, good mechanical properties, and excellent surface finish capability. This alloy has many applications in engineering, including machine and tool parts. The results of the tests are presented below in Figure 6.

![Fig. 6. Test results on Aluminum 2011-T3 at temperatures of 20°C, 10°C and 200°C](image)

4. Summary

The tensile test equipment operated successfully. The engineering changes made to the existing furnace have given the School of Engineering at the University of Limerick the capability of perform tensile testing on metallic materials at elevated temperatures. Importantly, the equipment can be quickly transitioned from the high temperature
testing mode to common room temperature testing of tensile or compression samples and other structures. The newly fitted insulation, PID control algorithm and sealed front access door have allowed the furnace to reach its test temperature quickly and maintain the temperature to within ±2°C of the target temperature.

The high temperature extensometer has proved to operate excellently over a wide temperature design. The furnace half-door design allows it to close around the extensometer without interference when closing or during machine operation.

Cycle times for testing are significantly reduced from a previous setup at the engineering laboratories at the University of Limerick. This is mainly due to the novel specimen holders that clamp around the Shouldered ends of the specimen. The elimination of the requirement to machine a thread at both ends of the sample significantly reduces both the sample machining time and the time required to load the sample in the machine.

An economic analysis of the project was undertaken to determine the savings made. Commercially available high temperature tensile test machines are available at costs starting from $150k. The machine described in this project was manufactured at a cost of $12k. Because of the chamber design, high specification insulation, and test sample size, the heating costs are approximately 15% of those for high end commercial machines. Furthermore, the device can be retrofitted to any standard existing tensile/compression machine typically found in an engineering test laboratory.

Plans are currently underway with the equipment to allow testing to be performed within an inert environment. This will require the use of a non-contact strain measuring device such as a camera or laser extensometer. Modifications required are sealing of the existing extensometer port and connection of an argon or similar inert gas circuit to the furnace body. In conclusion, the furnace has been developed for a total cost of approximately €5k. This is very favorable, considering that the cost of a commercially available high temperature tensile testing machine is 20-30 times this cost. The machine is widely used for both undergraduate and postgraduate research projects as well as having an important role in consultancy projects frequently undertaken at the University of Limerick.

References