Abstract

The aim of this thesis is to study the behavior of a material (AA1050 aluminum) in dynamic conditions that resemble today's manufacturing processes. This study was performed with a compression test, coupled with the application of a Viscoelastic model, followed by a relaxation test. Starting with the processing of the raw material, followed by an entire maintenance process applied to the equipment, this work established a methodology suitable for modeling the mechanical behavior of a material under high strain rate conditions.

Keywords: Viscoelasticity, Relaxation Test, AA1050 Aluminum, Electromagnetic Actuator

1. INTRODUCTION

The deformation process of a material can be represented by a constitutive equation, which describes the relationship between stress, strain, strain rate, and temperature. This is important in today's effort of simulating manufacturing processes with the Finite Element Method in order to better understand and optimize them. Each of these equations uses a group of parameters that depend on the material in study. These parameters can only be determined with experimental tests, such as traction, compression, or torsion configurations. This is the main subject of this thesis, to characterize a material (AA1050 aluminum) and determine its parameters for a model used in a previous work from IST (Eurico Kupessa [1]) and developed by Carlos Silva [4]. This was achieved with a compression test performed in a special equipment also developed in IST [8].

The other important subject of this thesis is to fill a gap in a very specific field of study which is Viscoelastic models for metals, more precisely the relaxation phenomenon in metals. The studies in the relaxation phenomenon are mainly focused in polymers, with fewer studies performed for metals [9]. So a new model for Viscoelastic stress relaxation was proposed for the AA1050 aluminum. A better understanding of this phenomenon in metals can also help in the process of designing better manufacturing tools and processes.
2. BIBLIOGRAPHIC REVIEW

Exact modeling of the dynamic mechanical behavior of materials is a prerequisite for an effective analysis of a specific production process [10], although this kind of studies poses great complexity. Throughout the years a series of empirical constitutive models have been developed in order to predict the flow stress with high accuracy for the manufacturing processes. However, most of these models are based on several assumptions in order to reduce the complexity of the problem. The success of a particular constitutive model depends on how effective it is at reproducing the actual conditions of the manufacturing process, as well as its ability to incorporate all relevant parameters in the equation.

2.1 Viscoplastic Models

Viscoplasticity is a theory that describes the strain rate dependance of solids. Strain rate dependence means that the deformation of the material depends on the rate at which the load is applied. The inelastic behavior described in Viscoplasticity pertains to plastic deformation which translates into an unrecoverable deformation suffered by the material when a certain load level is achieved. Rate-dependent plasticity is important for transient plasticity calculations, especially when studying manufacturing processes. The main difference between rate-independent plastic and Viscoplastic material models is that the latter exhibit not only permanent deformations after the application of loads but continue to undergo a creep flow as a function of time under the influence of the applied load [2].

For metals and alloys, Viscoplasticity is a macroscopic phenomenon caused by the movement of dislocations inside the grain structure, with additional effects of inter-crystalline movement. This phenomenon usually becomes dominant at temperatures greater than approximately one third of the absolute melting temperature, in quasi-static conditions.

In the constant effort to estimate and simulate today's manufacturing processes to improve our knowledge of them, engineers have been using the Finite Element Method as a very powerful tool to perform this work. To apply this technique, it is essential to use empirical models based on the traditional traction or compression tests in quasi-static and dynamic conditions in order to accurately estimate the flow stress in every operation.

Various dynamic hardening models have been suggested to represent the effect of the strain, the strain rate, and the temperature on the hardening characteristics of metallic materials. In this section, two well known models are presented: the Johnson–Cook model and the Zerilli–Armstrong model [3]. Next, a special reference is made to the new Hybrid model developed in IST (by Carlos Silva [4]), which is the one used in this work. A drawback of these models is that they can’t model some of the more complex Viscoplastic phenomenons, like relaxation or creep in metals. Fixing this problem is one of the objectives of this thesis, which can have an important impact in the manufacturing industry [10].
This new model takes into account the combined effects of strain and strain rate variation in the flow stress, allowing for a better estimation of the material's behavior in a wide range of strain rates. The only drawback of this model is that it doesn't take into account the temperature influence in the flow stress, reducing its applicability to manufacturing processes were temperature isn't a predominant factor.

\[
\sigma = [A + \exp(m \varepsilon^n)] [B + C \ln(D + \dot{\varepsilon})]
\]

The material constants A, B, C, D, m and n are closely dependent on the conditions under which the experimental tests are performed. Looking at the mathematical expression, you can separate the content of the two brackets that are involved in the equation: the first directly related to the influence of strain and strain hardening in the flow stress and the second with strain rate.

### 2.2 Dynamic Experimental Tests

There are two generic experimental procedures used to determine the viscosity of the material to be studied, which can be important in the followup material characterization tests in dynamic conditions [3]:

- **Creep tests**, which are used to determine the evolution of strain as a function of time in a material subjected to uniaxial stress at a constant temperature. Creep is the tendency of a solid material to slowly move or deform permanently under constant load and is closely related to its viscosity value.

- **Relaxation tests**, where the stress response due to a constant strain during a set period of time can be determined. In viscous materials, relaxation tests demonstrate the stress relaxation in uniaxial loading at a constant strain, complementing the information obtained in the creep test.

Having this information, a strain hardening test can be performed in order to obtain the stress-strain curve for the material in dynamic conditions, whose shape usually isn't very different from the quasi-static one. Still, three important differences can be perceived:

- at the same strain, the higher the strain rate the higher the stress;

- a change in the strain rate during the test results in an immediate change in the stress–strain curve;

- the concept of a plastic yield limit is no longer strictly applicable.

There are multiple examples of experimental procedures that can be used to perform dynamic mechanical characterization tests, one being the SHPB which is one of the more popular. Other example are high speed hydraulic presses and drop hammers. For relaxation tests in metals, a typical procedure includes using a screw-driven press in displacement mode with fixtures that allows the experiments to be done at room temperature or surrounded by a furnace for high temperature tests.
3. MATERIAL AND EXPERIMENTAL PROCEDURES

Given the high standards required in material characterization tests in dynamic conditions, it's important to develop an experimental methodology that allows the characterization of the material itself and at the same time gives the user control over the deformation speed of the test specimen and the value of displacement to be applied. In this context, this chapter presents the experimental procedure developed in this work along with a brief description of the equipment used, from the preparation of the AA1050 test specimens to the test plan implemented. Also a full maintenance procedure was applied to the equipment by the author, which was highly required after the extensive use the equipment underwent in previous theses.

As previously explained, the objective of this work was to perform a compression test in Aluminum AA1050 specimens followed by a relaxation test. Both of these tests require very specific conditions to be met, mainly tool stability and durability for the first and the ability to apply the same displacement to all the specimens and hold it during a short time period for the latter.

3.1 Material Preparations

Since the AA1050 was supplied in a 5mm thick plates and the objective was to produce 6×6 mm cylinders as the test specimens, there was a need for an unusual manufacturing procedure to be developed, since metal casting was discarded due to it's inherent difficulty and time consumption.

The first step to obtain the specimens required for the tests from the AA1050 plates was to cut off smaller 100×25 mm strips from the plates. Then using a hydraulic press, the strips were compressed into 100 mm long bars with an almost quadrangular section.

Next these bars were machined with a lathe into circular rods with 8 to 9 mm of diameter. Then, still using the lathe, the specimens were machined out from the rods one by one into the test specimen's final shape, 6×6 mm cylinders.

The final step was to perform an annealing procedure on the specimens. They were placed in the oven at 350 °C for 3 hours and then cooled down at room temperature.

In the end, 40 specimens were made using this process (see table 3.1).

<table>
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<th>Height (L)</th>
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3.2 Experimental Set-Up

The process selected to perform the material characterization test with high strain rates and the subsequent relaxation test was a compression test using a special equipment design by Vasco Ezequiel [7], Gonçalo Vargas [11] and Carlos Silva (hereby refereed as compression tool, see figure 3.1 a.). This tool was coupled with another unique equipment also design and built in IST [8], an electromagnetic actuator, as the source of the force required to perform the tests together with the capability of applying that force with the required speed to perform them.

![Experimental set-up](image)

**Figure 3.1 - Experimental set-up used: (a) compression tool and (b) electromagnetic actuator**

The electromagnetic actuator, powered by 5 capacitor banks (20 capacitors), drives the kinematic set (ram inside the actuator coupled with a translation cam inside the compression tool) to force the compression tool's follower into moving the upper compression plate against the fixed one, performing the pretended compression test. During this theses, a pneumatic actuator was added to this experimental set-up as an additional damper for the remaining kinematic energy to be dissipated after each test (see figure 3.2 for a full schematic of the experimental set-up). This apparatus allow for dynamic tests with lower levels of vibrations because the impulse direction is perpendicular to the compression direction, stopping the wave propagation from interfering with the tests.

![Experimental schematic](image)

**Figure 3.2 - Experimental schematic: 1- pneumatic actuator, 2- Translation Cam, 3- Compression Tool, 4- Displacement Sensor, 5- Load Cell, 6- Compression Follower, 7- Ram, 8- Electromagnetic Actuator**
3.3 Data Acquisition

The data extracted from the compression tests was the usual pair: force applied on the test specimen and the displacement imposed by the compression plates. In order to obtain this data, a force transducer and a displacement sensor were installed in the compression tool.

All this data was acquired by a DAQ NI-USB-6251 terminal with 16 analogue inputs (16-bit), 1.25 MS/s single-channel (1 MS/s aggregate) and processed by a LabView program made by the author where the data is compiled into a text file to be later analyzed. The data is acquired at 200k Hz during 2 seconds in order to accurately register the compression test and the relaxation test.

3.4 Experimental Plan

As previously mentioned, the experimental tests were divided into 4 sets, each with different energy levels. Since the easiest way of monitoring the energy stored in all the capacitors was reading their electrical voltage, the 4 sets used were as follow: 120 V, 200 V, 280 V and 360 V (see table 3.2).

To obtain the necessary quasi-static properties of the material and the corresponding engineering curve, an additional set was performed using the compression tool and part of the pneumatic actuator in a “manual mode”, which consisted in applying the compression force with a wrench against the screwed rod of the pneumatic cylinder. The results obtained with this procedure weren’t very accurate, but good enough to continue the tests.

4. RESULTS AND DISCUSSION

4.1 Experimental results

Of the 40 specimens tested, only 16 were usable in the end (see table 4.1), due to the difficulty in obtaining repeatable results in these tests, consequence of the compression tool and electromagnetic actuator inherent unreliability.

<table>
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<tr>
<th>Test Type</th>
<th>Voltage (V)</th>
<th>Average Cam Speed (mm/s)</th>
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<tr>
<td>Quasi-static</td>
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<tr>
<td>Dynamic</td>
<td>120</td>
<td>3500</td>
</tr>
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<td></td>
<td>200</td>
<td>5500</td>
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<td></td>
<td>280</td>
<td>7000</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>8000</td>
</tr>
</tbody>
</table>

Table 3.2 - Test Plan

Table 4.1 - Most representative tests

<table>
<thead>
<tr>
<th>Test Type</th>
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<th>3500 mm/s</th>
<th>5500 mm/s</th>
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<td>39</td>
<td>40</td>
</tr>
<tr>
<td>Initial Diameter (mm)</td>
<td>5.92</td>
<td>5.99</td>
<td>6.03</td>
</tr>
<tr>
<td>Final Height (mm)</td>
<td>5.92</td>
<td>5.99</td>
<td>6.03</td>
</tr>
<tr>
<td>Initial Height (mm)</td>
<td>1.62</td>
<td>1.624</td>
<td>1.668</td>
</tr>
<tr>
<td>Initial Diameter (mm)</td>
<td>7000 mm/s</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>Final Height (mm)</td>
<td>1.592</td>
<td>1.567</td>
<td>1.578</td>
</tr>
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</table>
4.2 Model Application

The final objective of this work was to apply two models to this data. First, use the Hybrid model previously mentioned in order to further study it’s applicability to this type of situations. Second, develop a new Viscoplastic model for metals with the intent of describing the relaxation process visible in these tests.

4.2.1 Compression Model

Having the model in hand [4], a new parameter set was determined, either because the material wasn’t in the same metallurgical condition as from previous tests or the tool was further worn out from previous works (see table 4.2). The D parameter wasn’t used in this work.

\[
\sigma = \left[ A + \exp \left( m \varepsilon \right) \right] \left[ B + C \ln \left( D + \dot{\varepsilon} \right) \right]
\]  \hspace{1cm} (1)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>m</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>195.19</td>
<td>0.35</td>
<td>-0.12</td>
<td>0.47</td>
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</tbody>
</table>

Table 4.2 - Viscoplastic model new parameters

The predictable results from this models application are that the flow stress should increase throughout the test as the material sustained more strain, until the test stopped. This flow stress would also be higher as the test energy levels increased, because higher strain rates would be in use.

As expected, the flow stress is higher throughout the test when higher strain rate values were used (higher energy) (see figures 4.1). Also the duration of compression part in the test became shorter with increase in the compression speed (more energy used).

Figure 4.1 - Viscoplastic curve example (test 16)
Regarding the model, its application was successful, further illustrating the influence of the strain rate in the aluminum's flow stress, while being able to follow the material's stress-strain response accurately in all tests, all with the same set of parameters.

### 4.2.2 Relaxation Model

As previously stated, there aren't Viscoelastic models specifically for metals that describe the relaxation phenomenon. So in this work a new model is proposed to describe the relaxation process metals undergo if submitted to a constant strain for a set time period.

- Logistic Model

\[ \sigma = A + \frac{B}{1 + \left(\frac{t - t_0}{C}\right)^{10}} \]

After trying several models, the previous equation was the one that could adapt more accurately do the data. So with the new model determined, it was then necessary to perform a fitting process to each data batch in order to obtain the equation parameters for each one. The new parameters were determined and later analyzed (see figure 5.1 and table 4.3). The value \( t_0 \) is the time when the relaxation process begins.

**Table 4.3 - Viscoelastic parameters**

<table>
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<tr>
<th></th>
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<th>17</th>
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<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
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<td>217.2</td>
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<td>0.011</td>
<td>0.006</td>
<td>0.005</td>
<td>0.006</td>
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<tr>
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In accordance with the Visco-plastic theory accepted at the time of this work, the flow stress after the relaxation process should be close to the flow stress of the same material strained to the same mark in quasi-static conditions (at room temperature). This was exemplified in the tests and further accurately reproduced by the model.

Since each test has its parameter set instead of a parameter group for the pair (material + tool) in use like in the previous Visco-plastic model, the problem of estimating these parameters in order to apply the model in other tests became evident. The parameters A and B can be estimated with a Visco-plastic model (like the Hybrid Model used) by introducing the initial conditions of the relaxation test (strain, strain rate and temperature) in the model and extracting the corresponding flow stress.
values. A+B (Final Compression stress), obtained from the Viscoplastic Model in dynamic conditions; B (Relaxation Stress), obtained from the Viscoplastic Model in quasi-static conditions for the final strain value; A = (A+B) – B.

5. CONCLUSION

The main objective of this work was to further study the dynamic characteristics of AA1050 aluminum, with a special focus on Viscoplastic relaxation properties. A new model was developed for the relaxation curve that can describe this behavior, but the author was unable to verify it's reliability on this or other material types which would require further tests and analysis that couldn't be performed in this thesis time frame. Also the application of the Hybrid model to a new batch of tests further demonstrated it's capability to accurately describe this type of phenomenons, increasing our understanding of metal deformation in dynamic conditions.

Secondary objectives of this thesis were to perform an upgrade and some improvements to the original set-up. This was achieved with the addition of a pneumatic damper to the kinematic set which helped improve it's durability and longevity.

As a final remark, the relaxation model developed in this work can potentially be extremely useful in the industry sector, for those situation were there is a need to estimate the surface conditions a given material after it was submitted to the manufacturing process (ex: estimate the residual stress level in the new surface after a machining process [10].

Figure 5.1 - Viscoplastic curve example (test 17)
6. REFERENCES


