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ON THE COMPRESSION OF AA6082-T6 ALUMINUM ALLOY AT DIFFERENT STRAIN RATES AND ASPECT RATIOS: A FORMULATION TO CORRECT THE ELASTIC MODULUS OBTAINED EXPERIMENTALLY

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Abstract. *Concerning compression test of linear hardening materials, friction and oblique contact between platen and specimen along with the aspect ratio of the specimen and strain rate may lead to low values of the elastic modulus measured* (E_{exp})*. Solid cylindrical specimens of AA6082-T6 aluminum alloy were evaluated experimentally at room temperature, varying the aspect ratio (length-to-diameter ratio:* L_0/D*) and strain rates. It was observed that the higher the aspect ratio, the higher the elastic modulus and the lower the strain, but buckling may occur and thus limits the load (or displacement) to be applied on the specimen. A formulation to correct* (E_{exp}) *was proposed but, as expected, the agreement with the reference value for aluminum alloys (69,9 GPa) was obtained only for long specimen. Yet, AA6082-T6 showed slight sensitivity to the strain rate.*

Keywords: *Aluminum alloys, compression test, strain rate, aspect ratio, elastic modulus.*

1. INTRODUCTION

In order to determine the mechanical properties of ductile materials, tensile tests are generally performed. However, when the plastic deformation is the aim of the study, the compression test is the most suitable as it allows large deformations without the fracture of the specimen. For this test, the solid cylindrical specimen is the most adopted, but the aspect ratios (length-to-diameter ratios) plays an important role in the test results. ASTM E9-09 (2009) classifies the aspect ratios in short ($L_0/D = 0.8$ or 2.0), medium ($L_0/D = 3.0$) and long ($L_0/D = 8.0$ or 10.0). Although long specimens lead to elastic modulus closer to the reference value, buckling may occur, which limits the maximum deformation in the experimental test. Yet according to ASTM E9-09 (2009), the strain rate should be 0.005 min-1 (= 8.310-5 s-1).

But simple compression test may present some difficulties in measuring mechanical properties (eg.: the elastic modulus obtained experimentally by compression test is usually lower than the reference value) and has been the aim of many studies. Kalidindi et al (1997) identified two major disadvantages with the simple compression when compared to tensile test: the frictional forces between the specimen and the compression platen (when this interface is not properly lubricated) and the length of the specimen that do not allow direct use of extensometers, and concluded that the machine compliance factor depends on the type of material being tested and the geometry of the specimen. Wei and Chau (2009) derived a solution for the non-uniform stress and displacement fields elastic cylinders under compression tests. Chen et al. (2009) tested AA6xxx and AA7xxx aluminum alloys in T6 temper at different strain rates, and showed that AA6082-T6 is slight sensitive to strain rate. Darras et al. (2013) studied the damage in 5083 aluminum alloy at room temperature and at three different strain rates ($0.1\ \mathrm{s}^{-1}$, $0.01\ \mathrm{s}^{-1}$ and $0.001\ \mathrm{s}^{-1}$), and observed that aluminum in general has very small strain rate sensitivity. Hossain and Kurny (2013) studied Al-Si-Mg alloys with Cu contents and observed that, due to the high percentage of cupper, the strain rate affects the tensile properties significantly. Liu et al. (2015) studied the influence of the aspect ratio on the compression of 2024 aluminum alloy at $10^{-3}\ \mathrm{s}^{-1}$ strain rate, and proposed a formula to correct the elastic modulus obtained experimentally. Dong et al (2017) observed that the friction between compression platen and the specimen makes a major influence on plastic behavior, resulting in barreling deformation, and the oblique contact between compression platen and specimen is the key factor that influences the elastic modulus measured.

The main subjects of studies cited above are: (i) friction and oblique contact between platen and specimen; (ii) strain rate and temperature sensitive; (iii) aspect ratio of the specimen (L_0/D).

This paper deals with axial compression of solid cylindrical specimens of AA6082-T6 aluminum alloy at room temperature, concerning the influence of the aspect ratio and the strain rate. Also, a formulation is proposed to correct the experimental elastic modulus.

2. PROPOSED EQUATION TO CORRECT THE ELASTIC MODULUS

The elastic modulus is given by the slope of the stress-strain relationship (Dowling, 2007):

$$E = d\sigma/d\varepsilon \tag{1}$$

Considering compression test of linear hardening materials, when the contact between the upper platen and the upper surface of the specimen changes from point contact to plane contact, the straight line of the elastic region begins (ε_A). This line ends when the yield point of the linear hardening material is achieved (ε_B – see Figure 1).

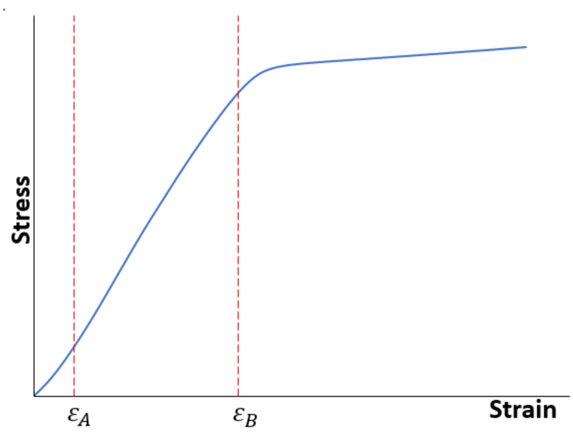

Figure 1- Definition of ε_A and ε_B from stress-strain curves obtained by compression test.

The stress-strain relationship "$d\sigma/d\varepsilon$" obtained experimentally (E_{exp}) is generally lower than the reference value and it is due to, as pointed out previously: (i) friction and oblique contact between platen and specimen; (ii) strain rate and temperature sensitive; (iii) aspect ratio of the specimen (L_0/D). So, the correct elastic modulus (E_c) depends on the relationship among the data obtained experimentally by compression test of linear hardening materials. Therefore, this work proposes the following equation to correct the elastic modulus of linear hardening materials obtained experimentally:

$$E = E_c = \frac{\left|\tan \frac{\log_{10}(\sigma_{y\,\mathrm{exp}})}{\log_{10}(\varepsilon_B)}\right|}{\sigma_{y\,\mathrm{exp}}^{\varepsilon_B} \cdot \left(L_0/_D\right)^{\varepsilon_B}} \cdot E_{\mathrm{exp}} \tag{2}$$

where:

- E_c : corrected elastic modulus;
- E_{exp} : elastic modulus obtained experimentally;
- ε_A : strain at the beginning of yielding (see Fig. 1);
- ε_B : strain at the end of yielding (see Figure 1);
- $\sigma_{y\,\mathrm{exp}}$: yield stress obtained experimentally by the compression test.

3. 3. EXPERIMENTAL PROCEDURE

Ten medium specimens and ten long specimens (see Fig. 2) of solid cylindrical shape were subjected to compression tests. They were made of AA6082 T6 aluminum alloy, which presents yield stress $\sigma_y = 250$ MPa and ultimate stress $\sigma_{\mathrm{u}} = 290$ MPa (MATWEB, 2021). The elastic modulus, for cubic materials, depends on the crystallographic orientation (Hestzberg, 1996). For aluminum, the elastic modulus in the $< 100 >$ direction is equal to 63.7 GPa whereas for the $< 111 >$ direction, 76.1 GPa, leading to a mean value 69.9 GPa.

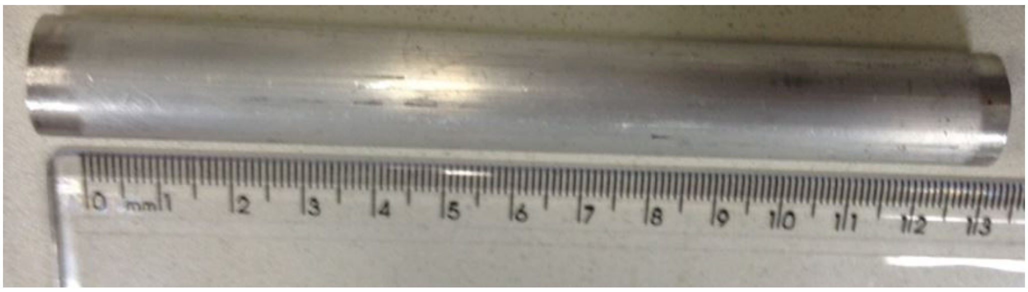

Figure 2- Cylindrical specimen before compression test.

The compression tests were performed on a EMIC DL 20000 press, which capacity is up to 20000 kgf and the velocity range is from 0.01 to $500\ \mathrm{mm/min}$. The data acquisition is made by the software TESC, developed by EMIC.

Table 1 presents the dimensions and strain rates adopted for the specimens. For the medium specimens, five were compressed with $0.0006975\ \mathrm{s}^{-1}$ and, the five remaining, with $0.000083\ \mathrm{s}^{-1}$. This last (and lowest) strain rate is the recommended by ASTM E9-09 (2009).

Table 1- Specimens data.

Specimens	L_0[mm]	D[mm]	$L_0/D[--]$	$\dot{\varepsilon}\,[s^{-1}]$
Medium	47.79	15.95	3.00	$6.975E-4$ and $8.3E-5$
Long	127.27	15.95	7.98	$2.6E-4$

The prescribed platen displacements adopted for the compression tests are presented in Tab. 2. In order to verify the uniformity of the material, two identical specimens were used for each displacement. Yet, the stress-strain curve for each of the twenty specimens was determined, together with the yield stress and the elastic modulus.

Table 2- Displacements applied on the specimens.

Specimens	1 and 1,	2 and 2	3 and 3	4 and 4'	5 and 5'
Prescribed displacements applied on the medium specimens [mm]	1.00	1.50	2.00	2.25	2.50
Prescribed displacements applied on the long specimens [mm]	0.50	1.50	1.75	1.00	0.75

4. RESULTS AND DISCUSSION

4.1 Medium specimens

Table 3 presents the experimental results summary (change in length, force applied) for each medium specimen subjected to compression test, and also the calculation results (strain, stress and elastic modulus). The stress-strain curves obtained experimentally are presented in Fig. 3.

Table 3- Experimental results summary – medium specimens.

Specimen	$\Delta\mathbf{L}$[mm]	$\mathbf{F}$[N]	$\dot{\varepsilon}\,[s^{-1}]$	Stress [MPa]	ε	$\mathbf{E}$[MPa]	σ_y[MPa]
1	0.48387	53527	$6.975E-04$	267.9	0.01012	27301.4	163.1
$1'$	0.82355	63627	$8.300E-05$	318.4	0.01723	28384.1	220.7
2	0.61334	62481	$6.975E-04$	312.7	0.01283	27316.7	153.4
2	0.80080	63120	$8.300E-05$	315.9	0.01676	25352.7	234.9
3	1.40282	66809	$6.975E-04$	334.4	0.02935	27315.5	168.9
$3'$	1.31599	65843	$8.300E-05$	329.5	0.02754	25803.8	209.5
4	2.09834	73081	$6.975E-04$	365.8	0.04391	23172.2	294.7
$4'$	1.96439	69288	$8.300E-05$	346.8	0.04110	25907.9	186.8
5	1.64672	70976	$6.975E-04$	355.2	0.03446	24830.7	256.0
$5'$	0.50120	55243	$8.300E-05$	276.5	0.01049	27625.6	148.8

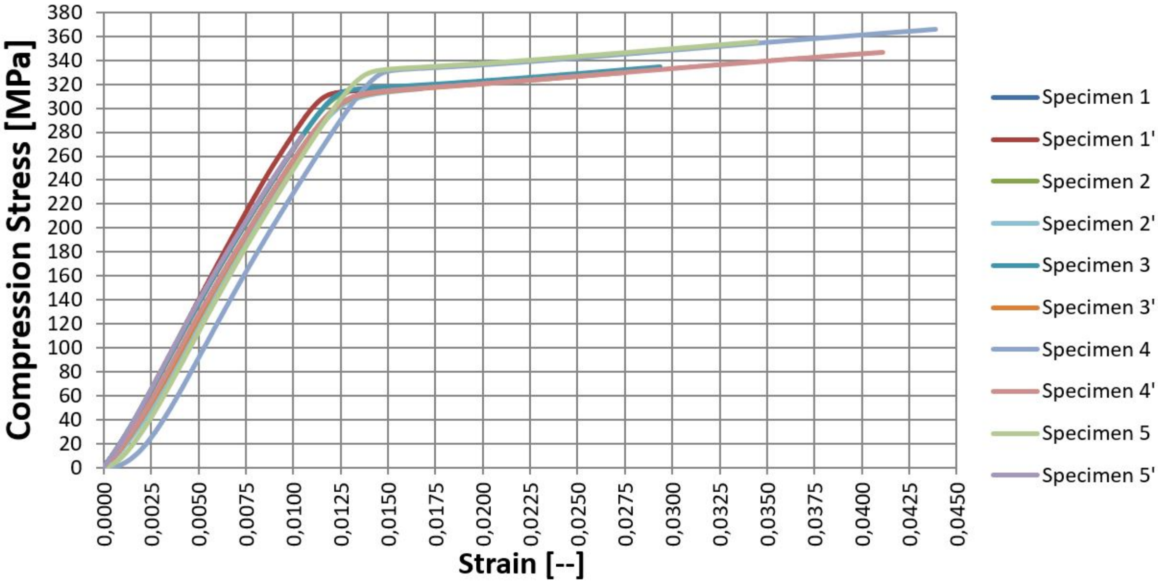

Figure 3- Stress-strain curves from compression tests - medium specimens.

According to Tab. 3 and Fig. 3:

- Specimens 1 and 5' did not enter the plasticity region;
- The average elastic modulus is 26.4 GPa, lower the reference value (69.9 GPa). This was expected and is due to the L_0/D = 3.00 ratio and to the friction among the loading platens and the specimens;
- The yield stress varied from 148.8 MPa to 294.7 MPa. Specimens 1, 2, 3, 4' and 5' presented values less than 200 MPa. Excluding these specimens, the average yield stress obtained is 243.2 MPa, consistent with the reference value of 250 MPa;
- The influence of strain rate on the results was imperceptible, which agrees with the results presented by Chen et al. (2009), Darras et al. (2013) and Hossain and Kurny (2013).

4.2 Long specimens

Long specimens 3 and 3' presented buckling during the compression test. So, the displacements imposed on specimens 4, 4', 5 and 5' were lower than 1.75 mm (see Tab. 4). The experimental results for each long specimen are presented in Tab. 4 and, the stress-strain curves, in Fig. 4.

According to Tab. 4 and Fig. 4:

- Specimens 1 and 1' did not enter the plasticity region;
- The average elastic modulus is 42.2 GPa, lower the reference value (69.9 GPa). This was expected and is due to the friction among the loading platens and the specimens;
- From specimen 3' to 5, the yield stress obtained were consistent with the reference value of 250 MPa whereas the other specimens presented low values that may be disregarded;

- The strains obtained for the long specimens were about ten times less than those of the medium specimens.

Table 4- Experimental results summary – medium specimens.

Specimen	$\Delta\mathbf{L}$[mm]	$\mathbf{F}$[N]	$\dot{\varepsilon}$ [s^{-1}]	Stress [MPa]	ε	$\mathbf{E}$[MPa]	σ_y[MPa]
1	0.50301	29292	$2.6E-4$	146.6	0.00395	37092.6	146.6
1,	0.50008	30549	$2.6E-4$	152.9	0.00393	38910.8	152.9
2	1.50471	57813	$2.6E-4$	289.3	0.01182	44767.0	103.4
$2'$	1.50076	60675	$2.6E-4$	303.7	0.01179	43892.6	167.0
3	1.75176	61300	$2.6E-4$	306.8	0.01376	43197.6	202.4
3	1.75983	63961	$2.6E-4$	320.1	0.01383	43022.8	241.6
4	1.00006	62523	$2.6E-4$	312.9	0.00786	42449.3	236.3
4	0.99893	63204	$2.6E-4$	316.3	0.00785	42135.2	239.9
5	0.74854	49763	$2.6E-4$	249.1	0.00588	42353.2	233.8
5	0.75129	51430	$2.6E-4$	257.4	0.00590	44081.5	185.7

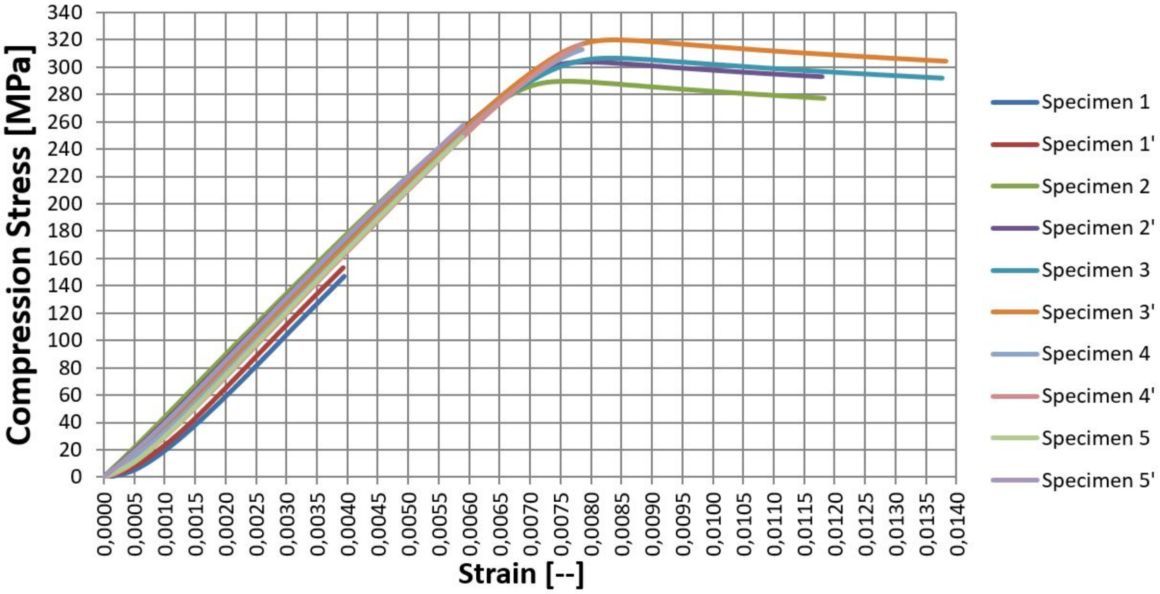

Figure 4- Stress-strain curves from compression tests - long specimens.

4.3 Comparison between medium and long specimens results

Concerning the experimental results for the medium (Tab. 3 and Fig. 3) and long (Tab. 4 and Fig. 4) specimens, it may be seen that:

- Higher aspect ratio leads to lower values of strain and, consequently, higher value of the elastic modulus. This is in accordance with the results presented by Liu et al. (2015);

- The stress-strain curves for the medium specimens (Fig. 3) have upward behavior after the yielding while for the long specimens (Fig. 4), downward behavior is observed. This indicates buckling of the long specimens during the compression tests;

- Considering the strain at the beginning of yielding (ε_B - see Fig. 4), the difference in the $(L_0/_D)^{\varepsilon_B}$ relation considering the data obtained for the medium and for the long specimens is very small ($\pm$ 0.3%) and thus can be considered as constant.

4.4 Validation of the formulation to correct the elastic modulus

From the results presented in Tab. 3 and Tab. 4 , it can be seen that the elastic modulus obtained experimentally is lower than the reference value. So, to verify Eq. 2, the experimental data for the medium specimen 1 ' and for the long specimen 3' were used (see Tab. 5). Yet, for short specimen, the experimental data were taken from Scari et al (2014) where the experimental elastic modulus (15.8 GPa - see Tab. 5) agrees with the obtained by Kalidindi et al (1997) (15.9 GPa).

Table 5- Experimental data for the short, medium and long specimens.

L_0/D	1.82	3.00	7.98
specimen	short	medium	long
ε_A	0.00274	0.00132	0.00069
ε_B	0.01377	0.00778	0.00562
$(L_0/_D)^{\varepsilon_B}$	1.0083	1.0086	1.0117
E_{exp}[GPa]	15.8	28.4	43.0
$\sigma_y exp$[GPa]	242.5	220.7	241.6
E_c[GPa]	57.8	54.6	73.4
Error [%]	17.4	21.9	−5.0

According to Tab. 5:

- The values of E_c obtained for the short and medium specimens presented a large error (17.4% and 21.9%, respectively) when compared with the reference value (69.9GPa);

- E_c obtained for the long specimen presented low error (−5.0%) when compared with the reference value (69.9 GPa), which is in agreement with ASTM E9-09 (2009);

- The relation $(L_0/_D)^{\varepsilon_B}$ presents almost null deviation.

5. CONCLUSIONS

In this study, the influence of three aspect ratios and three strain rates on the elastic modulus and yield stress obtained by compression tests were evaluated. Ten cylindrical specimens of each medium and long aspect ratios, made of AA6082-T6 aluminum alloy, were tested and, for short aspect ratio, the data were taken from Scari et al. (2014). It was shown that the influence of strain rate on the experimental results was imperceptible, while the aspect ratio plays a major role in this study: the higher the aspect ratio, the higher the elastic modulus and the lower the strain, but buckling may occur and thus limits the load (or displacement) to be applied on the specimen. It was observed that the $(L_0/_D)^{\varepsilon B}$ relation remains constant and, as the elastic modulus obtained experimentally is lower than the reference value, and an equation to correct the elastic modulus for short, medium and long specimens was presented. The validation of this equation with the experimental results showed that it is suitable only for long specimens.

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