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High Temperature Strength of Three 6060 Extrusion Alloys with Different Content of Alloying Elements

J-A. Saeter, T. Iveland, O. Reiso

Hydro Aluminium, R&D Materials Technology, 6600 Sunndalsøra, Norway

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Abstract

The high temperature strength of three 6060-alloys, with different contents of Mg and Si has been determined by Gleeble tensile testing. Testing has been carried out in the temperature range 470-580°C with strain rates of 5/sec or 0.5/sec. It has been found that: (1) the strength increases with increasing amounts of Mg and Si, (b) the strength differences between the three alloys increases with decreasing temperature, and (c) the strength difference in percentage seems to be more or less similar for all temperatures. There is a significant adiabatic heating of the samples. It is found that the adiabatic heating depends upon the content of Mg and Si in the alloys.

1. Introduction

The high temperature strength is an important parameter during extrusion of AlMgSi-alloys. This strength determines the breakthrough pressure and the acceleration time for the extrusion press, which again influences on the productivity. Extrusion trials have shown that the breakthrough pressure and the acceleration time depend upon the content of alloying elements. In order to investigate in more detail how Mg and Si influences on the properties, the high temperature strength of three 6060-alloys, with different contents of Mg and Si has been determined by Gleeble tensile testing.

2. Experimental Procedures

Extruded profiles of three different 6060-alloys were received for testing. The alloys were designed for different strength classes and had therefore different contents of Mg and Si. The chemical compositions of the investigated alloys were measured on the profiles with the results shown in Table 1. Alloy 6060-a contains the smallest amount of Mg and Si while alloy 6060-c has the highest amount (sum) of these two alloying elements. The difference in the alloy content is, however, small.

Flat, rectangular Gleeble tensile testing samples were machined with the dimensions 90mm x 15mm. It should be commented that the high temperature strength is most conventionally measured by compression or torsion experiments. Since this investigation was focused towards extruded profiles, tensile testing was found to be the most sensible method.

Table 1: Chemical composition of the investigated alloys in wt%. Average value of 3 burns at the Optical Emission Spectrometer.

Alloy	Fe	Mg	Si	Mn	Cu	Cr	Ni	Ti	Mg + Si
6060-a	0.20	0.36	0.44	0.024	0.004	0.001	0.003	0.010	0.80
6060-b	0.18	0.45	0.39	0.031	0.004	0.003	0.004	0.013	0.84
6060-c	0.19	0.41	0.55	0.032	0.004	0.001	0.002	0.011	0.96

For the experiments, a Gleeble 3500-machine was used. Two different stroke rates were used as settings, either é=0.5/sec or é=5/sec. Temperature, stress, elongation and other parameters were recorded with logging rates of 100 Hz or 500 Hz. The tests were carried out with a 4 kN load cell. The samples were held in place by "hot jaws," which ensures a curved temperature profile over the sample length. One should notice that due to geometry and heating effects in the sample, the resulting strain rate will deviate somewhat from the selected stroke rate. The temperatures chosen for the testing were 470°C, 530°C and 580°C. It should be commented that a temperature of 470°C is below the solvus limit for the 6060-b and the 6060-c alloys.

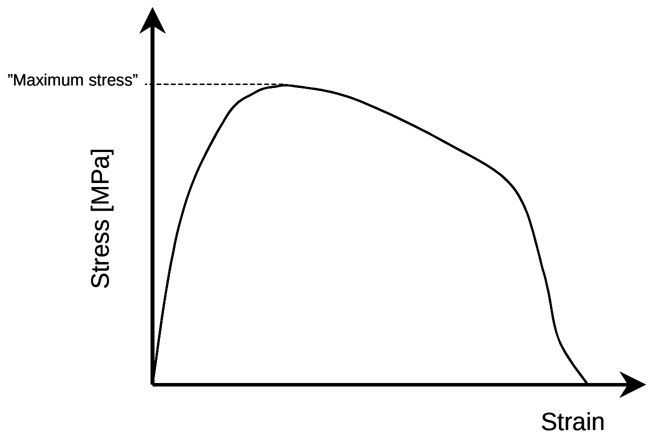

Figure 1: Typical Gleeble tensile curve during high temperature testing with the definition of the "flow stress" (maximum stress).

A number of 3 parallel samples were investigated for each of the parameter combinations. Each sample was heated up and kept on testing temperature for about 30 seconds prior to testing. The heating of the samples were done by doing electricial resistance heating, while the temperatures were controlled by two thermocouples which were welded to the centre of the sample. The electrical heating gives a temperature gradient along the sample, with the highest temperature in the mid-section. From the tests, the maximum tensile strength or "maximum stress" is recorded for each sample, see Figure 1 for an explanation. This stress will in the following be reported as the "flow stress."

After testing, the total elongation and the contraction of the samples were calculated. This was done by engraving lines 12 mm from each other in the samples before testing. The distance between the lines were measured after fracture and the total elongation was calculated on the basis of these numbers. The transverse contraction was calculated by measuring the width of the samples before testing and the width of the necking after fracture. Strains measured by these methods represent local strains in the necked region of the samples. Because of the longitudinal temperature variations in the sample this method is thought to represent ductility in a better way than if the full length of the samples are used for strain calculations.

3. Results

A typical curve from the Gleeble testing is shown in Figure 2. The curve shows the stress and the temperature in an arbitrary chosen sample during the test. The temperature in the sample increases with about 15°C, which demonstrates that there is a pronounced adiabatic heating of the sample during testing.

The results from all Gleeble tests are presented in Figure 3. Each data point represents the average of three measurements. The figure shows that there is a difference in strength for the materials investigated and that this strength difference increases with decreasing testing temperature. The strength difference in percentage seems, however, to be more or less similar for all temperatures.

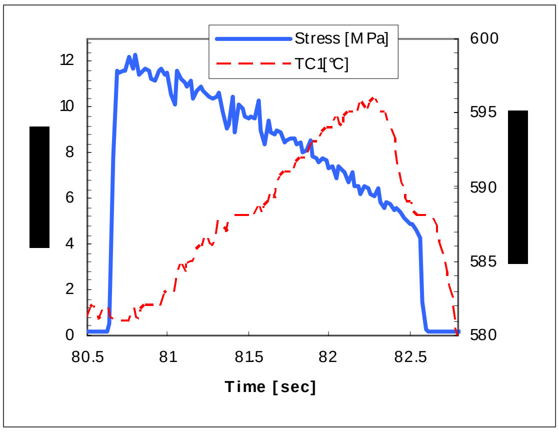

Figure 2: Stress and temperature in one of the samples during Gleeble-testing. Alloy: 6060-a, temperature: 580°C, strain rate: 0.5 s^{-1}.

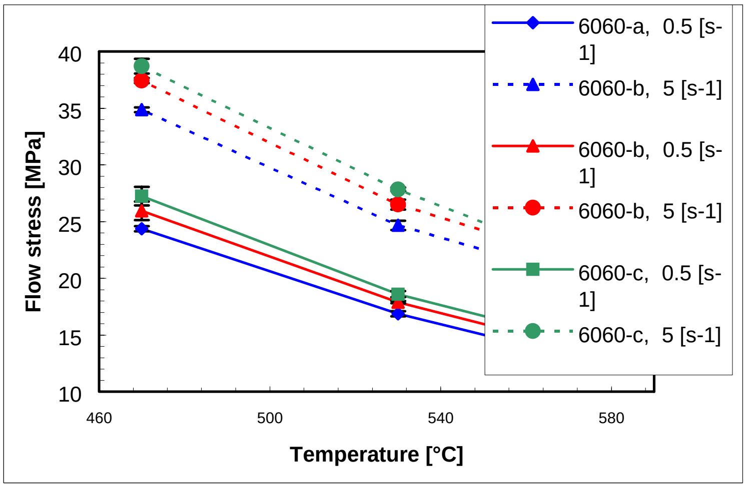

Figure 3: Maximum stress as function of testing temperature. The error bars show the standard deviation of the samples.

It must, however, be noted that the strength differences between the samples are small. For tests at low strain rates (é=0.5/sec), the difference between 6060-a and 6060-b is 0.8 MPa at 580°C and 1 MPa at 530°C. This represents a strength difference of about 6%. The standard deviations for the three parallel samples are in the range 0.1-0.8 MPa, which means that the difference between the alloys is of the same magnitude as the accuracy of the measurement. At high deformation rates (é=5/sec) the difference between 6060-a and 6060-b is 1.5 MPa at 580°C and 1.8 MPa at 530°C.

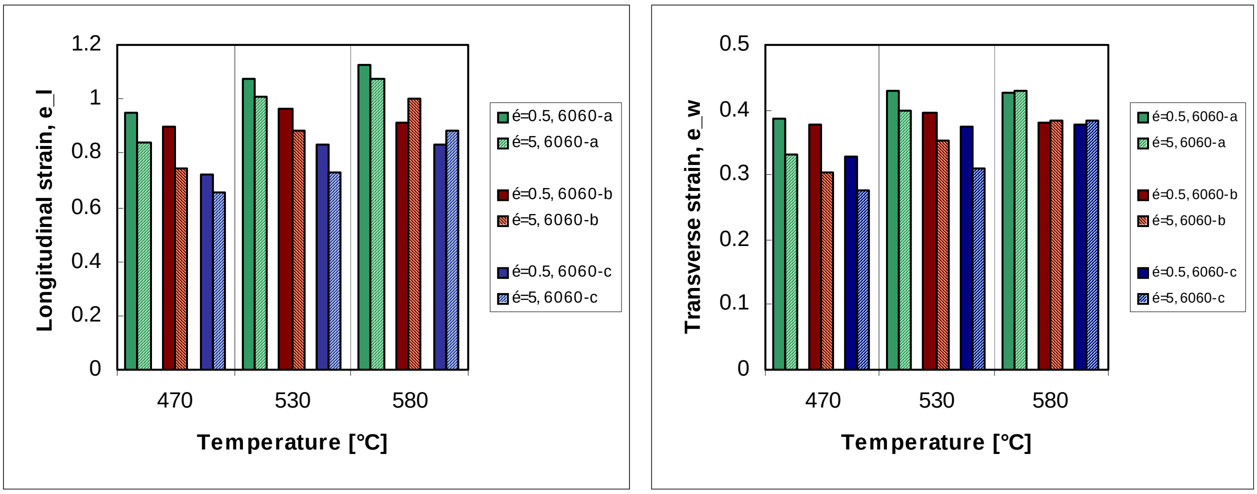

Figure 4: Total strain in the longitudinal and transverse direction for the different alloys. Each bar represents the average of three samples.

3.1 Total Elongation

The linear strains ($e = l - l_0 / l_0$) in the longitudinal and transverse directions of the samples are shown in Figure 4. From the figure it can be seen that the strain increases with increasing temperature and that the softer alloy is more ductile than the harder alloys. It can further be seen that in most cases, but not all, the strain is highest for the lowest strain rate.

3.2 Adiabatic Heating of Samples

As shown in Figure 2, there is a significant adiabatic heating of the samples during the tests. This heating has been measured from the test records for all samples with the results shown in Table 2. It is interesting to observe that the adiabatic heating is largest for the 6060-a alloy that has the lowest content of Mg and Si, while the alloy with most Mg and Si, the 6060-c, has the smallest adiabatic heating. The effect of decreased adiabatic heating with increased content of Mg and Si in 6XXX-alloys has been previously observed by Pettersen [1] who compared 6060 and 6082-alloys. Table 2 also shows that the adiabatic heating increases with increasing strain rate and decreases with decreasing temperature. This last observation is in contradiction with findings reported in [1].

Table 2: Adiabatic heating for the investigated alloys. All values represents the average of three tests.

T [°C]/strain rate [s^{-1}]	6060-a, adiabatic heating T [°C]	6060-b, adiabatic heating T [°C]	6060-c, adiabatic heating T [°C]
580/ 0.5	13.8	13.5	7.33
530/ 0.5	12.8	12.7	5.83
470/ 0.5	11.0	7.5	5.17
580/ 5	20	20.7	9.0
530/ 5	15.5	16	10.33
470/ 5	14.7	14	10.55

4. Discussion

As already pointed out the difference in strength between the investigated alloys is of the same magnitude as the accuracy of the measurements. It may therefore be questioned if the observed difference is a physical effect or if it is solely due to random variations in the measurements. We prefer, however, to conclude that there is a small, but significant difference in strength between the three alloys at elevated temperatures. The reason for this conclusion is that the strength is consequently higher for all deformation conditions when the Mg and Si content is increased.

The results from the Gleeble investigation can be presented in a traditional plot of the flow stress as function of the Zener-Hollomon parameter, Z, as shown in Figure 5. (The Zener-Hollomon parameter, Z=é∃exp(Q/R∃T), where Q is selected to be 156 kJ/mole). In the calculation of the Z-value, corrected strain rates and temperatures were used. The corrected temperature is the registered temperature when the peak stress is reached. The figure shows that the maximum stress increases with increasing the Zener-Hollomon parameter, i.e. with decreasing temperature or increasing strain rate. It is, however, interesting to observe that there is a shift in the maximum stress when changing from one strain rate to the other. Apparently, one measures a lower stress when doing Gleeble testing at a high strain rate and a low temperature, as compared to a lower strain rate and higher temperature. A similar type of observation has earlier been made by Pettersen, Nord-Vardhaug and Nes [2] who deformed 5005, 6082 and 6060-alloys by torsion testing to different Z-values.

Pettersen et al. [2] claimed that the reduction in flow stress with increasing strain rate at a constant Z-value, was due to dynamic precipitation. It should be noted that they used a deformation temperature in the range 250-420°C, which is very prone to precipitation of, for instance, Mg_2Si. In the present investigation, the deformation temperature was much higher. For most of the samples, the deformation temperature was above the solvus temperature of the alloys, dynamic precipitation seems therefore unlikely in this case. For two of the alloys, one of the actual deformation temperatures was slightly below the solvus temperature. However, due to the short durance of the test and the low driving force for precipitation at this temperature, dynamic precipitation seems not to be a possible explanation in this case.

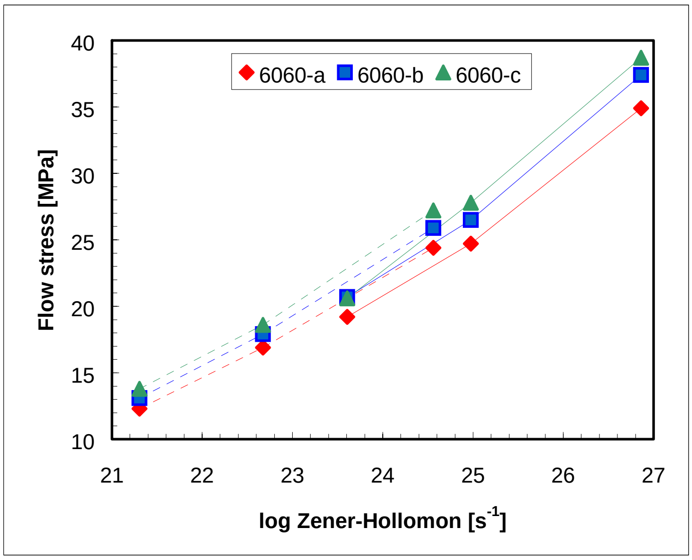

Figure 5: Maximum stress as a function of Zener-Hollomon parameter for the three investigated alloys.

An alternative explanation for this shift in the curves is the inaccuracy in the temperature measurements when testing at the highest strain rate. When a strain rate of 5/sec. is used, the tests are completed in typically 0.2 second. At the same time, the temperature in the sample increases by 9-20°C due to adiabatic heating. If the response time of the thermocouples is a bit long, the recorded temperature may, as a consequence, be significantly lower than the actual temperature in the sample. Factors that influence on the response time are for instance:

- the thermocouple diameter,
- the quality of the welding between the thermocouple and the sample,
- connection of the thermocouple to earth, and
- measurements in still air or high velocity air.

For the present investigation, earthed thermocouples with a diameter of 0.22-0.24 mm welded to the sample were used and the tests were carried out in still air. A data sheet for thermocouples used at the Sintef extrusion press in Trondheim shows that the actual response time for a 0.25 mm thermocouple under such conditions can be as high as 0.4 second [3]. For the present experiments the response time for the thermocouples is estimated to be approximately 20 ms. For the investigated alloys, it is found that the temperature in the most extreme condition can increase with 4-5°C during such a small time interval. It seems therefore reasonable that the actual temperature is higher than the recorded temperature for the highest strain rates. Since the Zener-Hollomon parameter is very sensitive to temperature variations, due to the exponential factor, the Z-values presented in Figure 5 may therefore not be the correct value. This may explain, at least, part of the shift in the curves when going from one strain rate to another.

6. Summary

In the present investigation the high temperature strength of three 6060-alloys with different contents of Mg and Si has been investigated by Gleeble tensile testing. Testing has been carried out in the temperature range 470-580°C and at the nominal rates of 5/sec. or 0.5/sec. It has been found that:

- The strength increases with increasing amount of Mg and Si, i.e. the 6060-a is the softest alloy, the 6060-b is stronger and 6060-c is the strongest alloy.
- The strength differences between the three alloys increases with decreasing testing temperature.
- The strength difference in percentage seems to be more or less similar for all testing temperatures.

It should be commented that the strength difference is of the same magnitude as the accuracy of the measurements.

There is a significant adiabatic heating of the samples. It is found that the adiabatic heating is largest for the 6060-a alloy that has the lowest content of Mg and Si, while the alloy with most Mg and Si, the 6060-c, has the smallest adiabatic heating.

References

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