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Yield Stress characterisation of commercial Aluminium AA7075 by three different methods and its comparison.

Bachelor Thesis

WB3BEP-12EC

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1. Introduction to the subject.

The Yield Stress is the main feature when characterizing the mechanical properties of a material. It indicates the limit of elastic behaviour and the beginning of plasticity. It is crucial for engineers to know this value in order to choose the right material for the right purpose.

In this report the concept of Yield Stress is studied focusing on how its value on aluminium alloy AA7075 changes depending on the calculation method used. Several experiments are carried out to determine this value from AA7075 specimens after different precipitation hardening treatments, in order to have a broader spectrum of results.

The comparison is made between the classical 0,2% offset Yield Stress from tensile test and Yield Stress value calculated from Vickers hardness test; versus the Yield Stress value calculated from a physically based Yield Stress criterion, following the analysis of pre-yield dislocation behaviour (method developed by Peter van Liempt and Jilt Sietsma). [1]

The physical criterion is a more accurate adjustment, whereas the two classic methods are proved to be more conservative estimations.

2. Theoretical basis.

2.1. Material.

The material used in this report is aluminium alloy AA7075, Al-Zn-Mg alloy from the 7000 series, which main alloying element is zinc. This series alloys feature the highest strength among all age-hardenable Al-based light alloys. Due to their high strength-to-density ratio, 7000 series alloys are often used in transport applications, including marine, automotive and aviation.

AA7075 has a very high strength and a good fatigue resistance, therefore it is commonly used for highly stressed structural parts.

Its typical mechanical properties values are:

- Density: 2,81 g/cm^3.
- Modulus of Elasticity: 71,7 GPa.
- Poisson's Ratio: 0,33.

Some other mechanical properties such as hardness or deformation depend in large measure on the heat treatment to which it has been subjected. [2] This values are studied further on in 9 specimens subjected to different heat treatments.

Some AA7075 elements wt% can vary between different ranges. For this report, two different alloys with different compositions are used, referred to from now on as "Alloy A" and "Alloy B". The differences between them are small enough not to notice any evident change in their mechanical behaviour.

Table 1. Composition and weigh % of a theoretical AA7075 and the two different heat-treated alloys A and B. [3]

Element	Theoretical wt%	Alloy A wt%	Alloy B wt%
Al	Bal.	89,632	89,717
Zn	5,1-6,1	5,29	5,094
Mg	2,1-2,9	2,514	2,563
Cu	1,2-2	1,712	1,678
Fe	0,5	0,241	0,29
Si	0,4	0,207	0,22
Cr	0,18-0,28	0,162	0,206
Mn	0,3	0,101	0,096
Ti	0,2	0,06	0,073
Zr	0,25%[1]	-	-
Other	0,15[2]	0,079[3]	0,062[4]

[1] A maximum of 0,25% of (Zr + Ti) may be used.

[2] A maximum of 0,05 wt% of a single element, accumulating to a total of 0,15.

[3] Other elements: 0,04 Pb; 0,018 Cl; 0,011 P and 0,01 Ni.

[4] Other elements: 0,033 Pb; 0,019 P and 0,01 Ni.

2.2. Precipitation hardening.

As previously mentioned, precipitation hardening via heat treatment has been applied to AA7075 specimens. This is a process that aims to increase the Yield Stress of malleable materials, such as aluminium alloys. This process consists on the formation of fine particles of an impurity phase, which obstruct the movement of dislocation, leading to a strengthening of the material.

The material must be exposed first to solution treatment in order to dissolve the possible existent precipitates (phase θ) and transform them into solid solution (phase α). This happens when the alloy is heated above the solvus temperature and maintained there until the homogeneous solid solution is produced.

It is then rapidly quenched so there is no time for θ precipitates to form, leaving a supersaturated solid solution of α_{ss}.

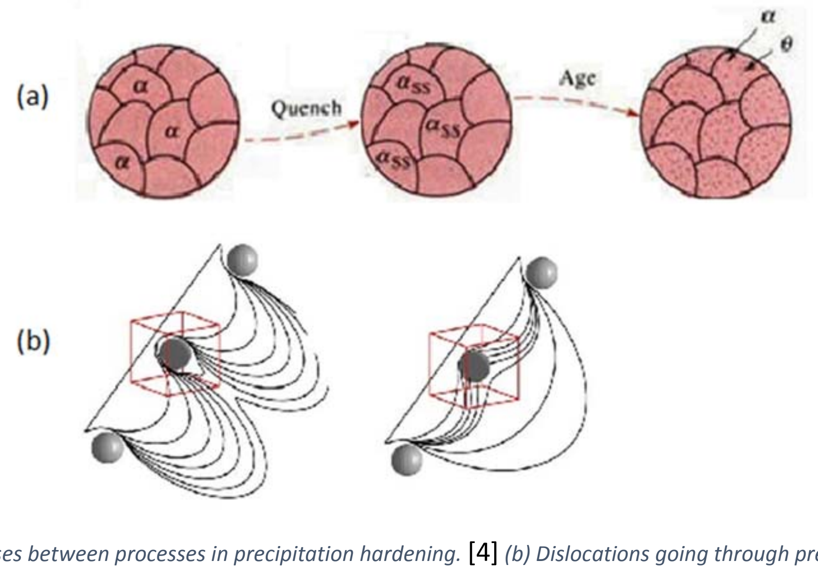


Figure 1. (a) Phases between processes in precipitation hardening. [4] *(b) Dislocations going through precipitates.* [5]

From here, the aging takes place, heating the alloy below the solvus temperature, during more time. As α_{ss} phase is not stable, equilibrium phase precipitates ($MgZn_2$) are formed. This fine precipitates impede the movement of dislocations, by forcing them to cut through the precipitates or go around them.

Dislocations are atomic-scale defects. They are areas where atoms are out of position in the crystal structure and they are generated (and move) when a stress is applied. Dislocation movement freedom allows the material to suffer plastic deformation.

The precipitates occurring in the transition between α_{ss} phase and the final equilibrium phase have been a matter of study, being generally accepted the next sequence: Supersaturated solid solution → VRC (vacancy-rich clusters) → Spherical GP zones → Ordered GP zones → η' intermediate phase → η ($MgZn_2$) equilibrium phase. [6]

VRC are formed in the beginning of the quenching process and its concentration is very important in the nucleation of metastable (η') and stable (η) precipitates when there are no dislocations or GP zones yet, although it is true that it acquires more relevance when Zn and Mg concentrations are lower than in the used alloy (2 wt% Zn and 1-2 wt% Mg). [7]

GP zones are meta-stable solute enriched regions that precede the formation of stable precipitates. In AA7075 alloy GP zones are Zn-Mg clusters.

2.3. Characterization.

•0.2% offset Yield Stress.

Due to the fact that some materials like aluminium alloys don't define a clear yield point at their stress-strain curves, an offset yield point is used to determine the Yield Stress. This is an arbitrary point chosen as the point of the stress-strain that intersects with a line with slope equal to Young's Modulus starting from the point with 0 stress and 0,2% strain.

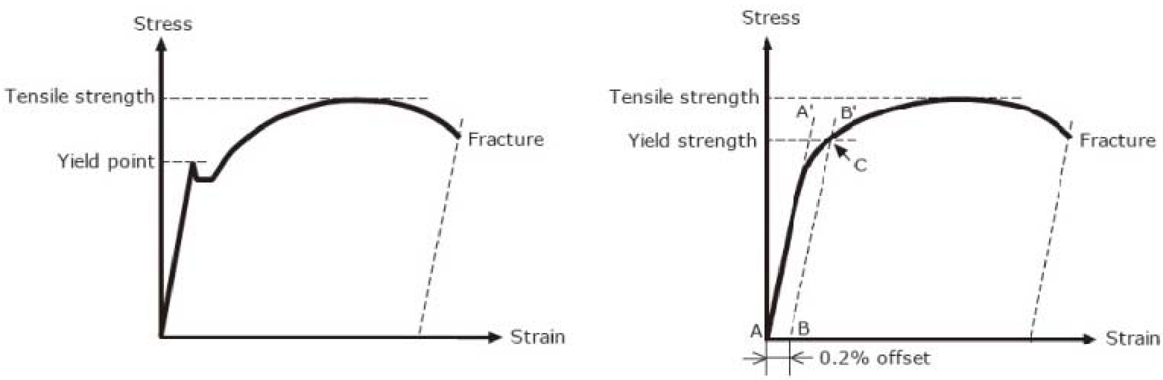


Figure 2. Stress-Strain curve with defined yield point and with 0,2% offset yield point (C).

This arbitrary value is good enough for most of the cases where the Yield Stress is needed, so it is accepted worldwide for materials without a specific yield point.

•Physical yield criterion.

A physically based method to determine Yield Stress is applied, following Peter van Liempt and Jilt Sietsma investigations. This method is based on the analysis of the pre-yield dislocation behaviour, by means of the hardening rate.

In metallic alloys (such as AA7075) dislocations do not behave the same before and after the yield point is reached. In the pre-yield stage, their movements are reversible, dislocation structure doesn't change and new dislocations don't appear, thus, the dislocation density remains constant. After the yield point is reached, the dislocation density starts to grow and affects the structure of the material, by allowing plastic deformations.

This effect is clearly noticeable when plotting the hardening rate (θ) vs. the flow stress (σ) in the Kocks-Mecking plot. This can be obtained with the points of the stress-strain curve from the tensile test, since the hardening rate represents the derivative of the stress with respect to the strain: $= \frac{d\sigma}{d\epsilon}$. [1]

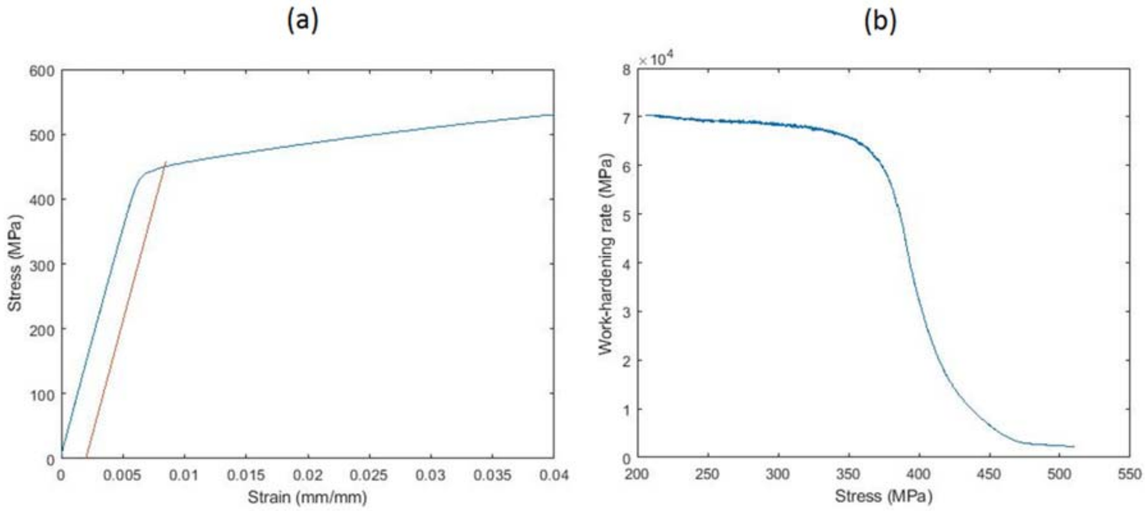


Figure 3. Example of AA7075 heat treated 70℃ during 6 h: (a) Stress-Strain curve. (b) Kocks-Mecking plot.

In the Figure 3 (b) the Kocks-Mecking plot is represented and the difference between the 2 phases can be appreciated: the first straight slope represents the elastic behaviour, starting at a hardening rate equal to the Young's Modulus (70 GPa). The sudden decrease of the slope concurs with the end of the elastic deformation in the stress-strain curve until it reaches the Yield Stress (in this case 457,5 MPa) or the 0,2% offset Yield Stress in the stress-strain curve (449,5 MPa). After this point, the plastic deformation takes place.

•Material hardness testing and its respective Yield Stress.

A non-destructive method to determine the Yield Stress of materials can be a very useful asset when a tensile or compression tests on the materials studied is not possible

David Tabor developed some equations to define some mechanical properties like the Yield Stress (σ_y) or the Ultimate Tensile Stress (σ_u) from hardness measurement. The equation: $\sigma y = \frac{H}{3} * 0{,}1^{m-2}$ is an approximation to the 0,2% offset Yield Stress value that works well for different materials such as brass, steel and aluminium alloys, in either the cold rolled or aged condition. In this equation H represents the Diamond pyramid hardness and m is the Meyer's hardness coefficient.

H is directly determined by the hardness testing and m can be easily determined as: $m = n + 2$; where n is the index in the potential approximation of the plastic deformation part of the stress-strain curve: $\sigma = K * \epsilon^n$. [8]

However, it has been proved that for Al-Zn-Mg alloys Tabor's equations do not fit accurately, so following S. C. Chang investigations, a second pair of equations were found to characterize them (σ_y and σ_u). The resulting Yield Stress equation is: $\sigma y = \left(\frac{H}{2,9}\right)^{\frac{1}{3-m}} * \left(\frac{12,5}{E}\right)^{\frac{m-2}{3-m}} + 25 * (m-2)$. H represents the Vickers Hardness value and E is the Young Modulus. [9]

3. Experimental methods.

For this study, cylindrical pieces of aluminium alloy AA7075, 12 cm initial length and 8mm initial diameter are used, as shown in Figure 4 (a).

3.1. Heat treatments.

To obtain a wider spectrum of results, the material characterization is applied to a total of 9 different precipitation hardened specimens. This process consists of 3 steps, previously explained.

- Solution treatment: every specimen is equally exposed to 1 hour of heating at 470 °C, above its solvus temperature. In this process the solution of the existent precipitates takes place. This is done in a hot air circulation furnace (with a T_{max} of 650 °C).
- Quenching: the specimens are rapidly cooled down in water, in a quenching tank at room temperature, leaving the shortest time possible between the end of the solution treatment and the drowning. The specimens almost instantly reduce their temperature and therefore, the supersaturated solid solution is produced.

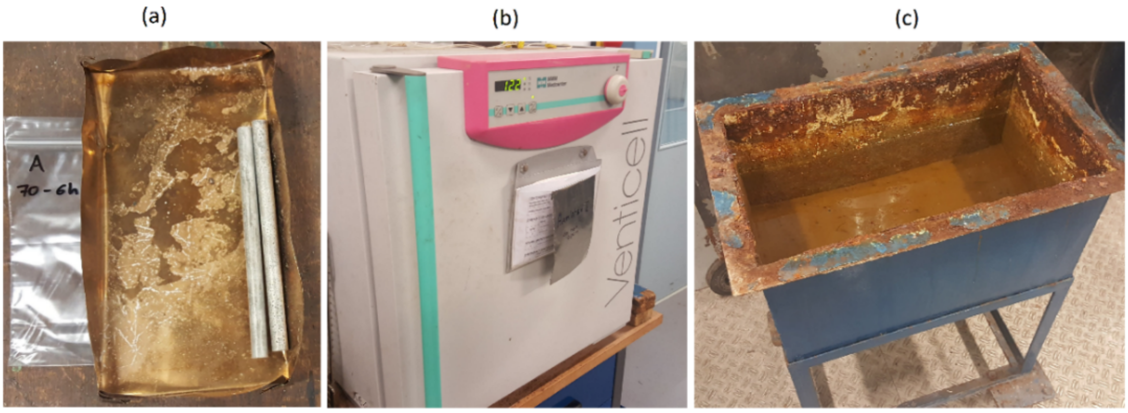


Figure 4. (a) Specimens on a tray ready for heat treatment. (b) Hot air circulation furnace, with a maximum temperature of 650 ℃. (c) Quenching tank full of water.

- Age hardening: in this part is when the differentiation between specimens is made. After drying, every specimen is heat-treated a second time, at a lower temperature, without surpassing the solvus temperature. In total, 9 treatments are performed, combining the temperatures of 70, 120 and 170 °C with the times of 6, 24 and 96 hours. This second heat treatment is done in the same hot air circulation furnace, and the subsequent cooling down at room temperature.

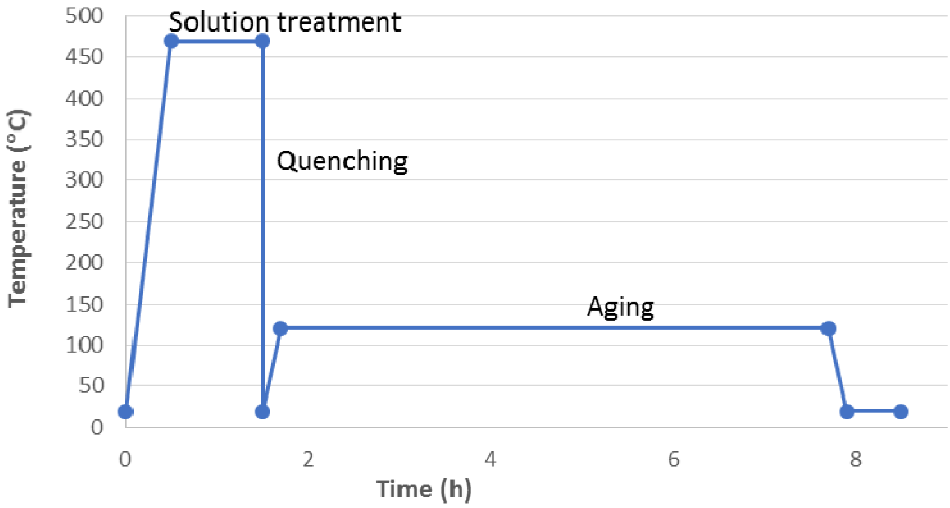


Figure 5. Example plot: temperature-time of precipitation hardening process applied to a specimen: 6 hours - 120 ℃.

3.2. Machining.

Firstly, 3 cylindrical slices of 9,1 mm each are cut from every 12 cm specimen. This slices are the samples used later for the hardness testing.

The remaining 92,5 cm long cylinders are then drilled on one end's centre, making small cone-shaped holes. This holes allow them to be held by a lathe, which is programmed to machine the central neck of 5 ± 0,17 mm. This shape, represented in Figure 6, is the ideal for a tensile test.

Three different devices are used for this machining processes:

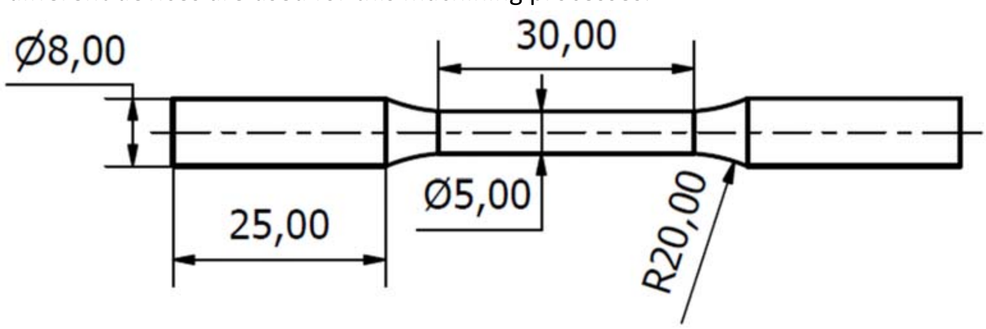


Figure 6. Design of tensile testing specimens.

- A manual saw is used for slicing, done inside a closed chamber while projecting a water jet on the saw, to avoid high temperatures affecting the specimen.
- A frontal lathe is used to drill the centre holes. This is a quick process where the movement is activated manually.
- A CNC lathe is programmed to machine the neck. It is also done into a closed chamber, to contain the generated swarf.

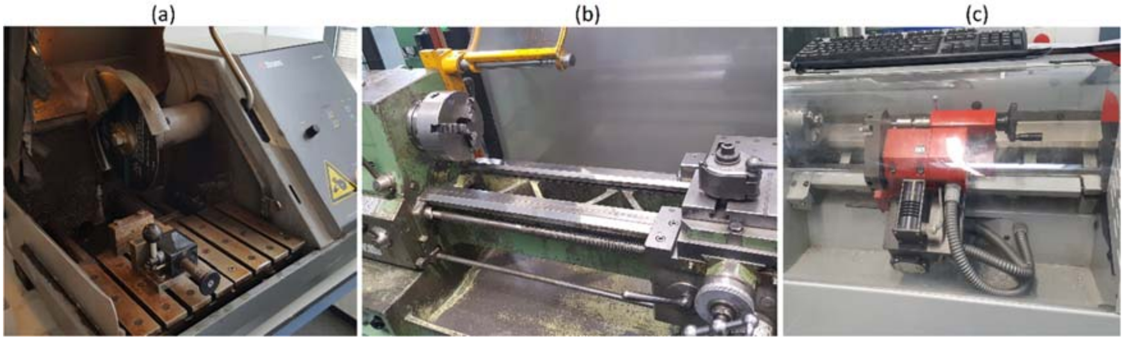


Figure 7. (a) Manual saw. (b) Frontal lathe. (c) CNC lathe.

3.3. Sample preparation.

In order to obtain good results at the hardness testing, a good sample preparation must be performed in advance.

It starts with the process of embedding the three slices (already cut) of each specimen in a single plastic container. This is done with a cold embedding process (it reaches 30 °C during 30 minutes, maximum) consisting in a mould, where the small slices are placed, and the addition of a liquid resin that reacts with a powdered catalyst (ratio: powder 2:1 liquid) curing itself into a strong container, which is shown in Figure 7 (b). The showing surfaces must be as parallel as possible.

After this, the samples are now treated by sanding, which provides a clear surface, without impurities. This is done with a series of rotating plates, each one of them with a smaller grain abrasive paper. All the samples are exposed to contact with all the papers, progressively. The sanding papers used are, in order: P80, P180, P320, P800, P1200 and P2000 (graded in accordance with the European FEPA standard). A smaller paper number means bigger grains and removes more material but leaves more noticeable scratches, while a larger paper number (smaller gains) removes less material, leaving a smoother surface with finer scratches. As AA7075 is a soft material, this is a quick process, but precaution must be taken concerning surface flatness. This process is assisted with a weak stream of water as lubricant.

Finally, a polishing step is applied to create a smooth and shiny surface. This is done with another rotating plate but with a smooth cloth instead of sanding paper. After cleaning the sample with alcohol, a diamond suspension liquid is applied, and rubbing the sample with it creates the needed surface. This liquid is a water-based carrier with synthetic diamond suspension on it. Of all the different grades, the one used is the 3 µm diamond size. Lastly the sample is cleaned again with alcohol and carefully taken to the hardness testing.

(a) (b) (c)

Figure 8. (a) Mold with resin curing. (b) Cured resin with slices showing. (c) Sanding rotating plates with papers of different grain sizes.

3.4. Hardness testing.

After polishing, the samples are ready to proceed to the hardness testing. Vickers hardness measurement is the one used. It is a very accurate method and requires less load applied than other methods. The Vickers Hardness value represents the stress level needed to cause a permanent indentation.

The measurement consists on applying a certain load (5 kp in this case) with a small diamond indenter with a square cross-section on the polished surface. It is made with an automatic hardness tester, which performs the indentation and provides an amplified picture of the square-shaped indent. This is done by the electronic microscope that the tester has on it.

The remaining indents are typically small (less than 0,2 mm) and are considered non-destructive. This provides the information needed without scarifying the product.

For this report, an average hardness value is calculated from 9 different measurements on each one of the samples (3 on each slice). It is important that the indentations on the same slice are separated at least 3 times the value of the diagonal of the indents made (around 1 mm: 3mm separation). This ensures that the value is not affected by the hardening that the indenter makes around the area of the previous indentations.

The microscope shows the amplified image and it automatically marks the distance between the corners of the square, although it also allows the user to adjust it manually. With this, the tester calculates the Vickers Hardness value, dividing the load applied by the section, calculated with both diagonal lengths.

(a) (b)

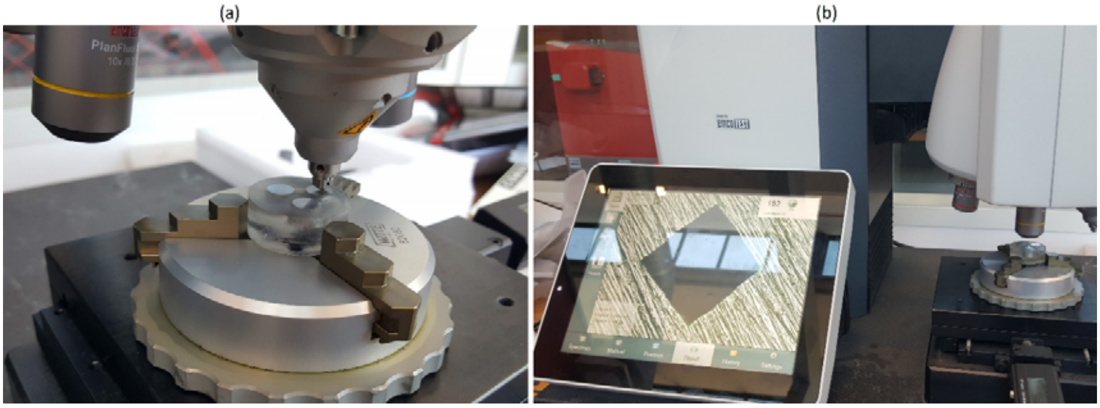


Figure 9. (a) Tester performing indentation. (b) Microscope showing measurement.

3.5. Tensile testing.

This test is performed in an electromechanical tester with the help of two extensometers. This is a destructive test so every specimen can only be tested once.

Firstly, the specimen is placed in the machine, being held by two clamps that allow rotating movement. This ensures that no other efforts rather than tensile are being applied. When it is perfectly attached, two extensometers are placed on the central area of the specimen, one on each side. The average between these extensometers values at every point (every 0,01 s) represents the true strain that the specimen is suffering.

The machine is programmed with a strain rate of 0,015 mm/s, which gives the value of the engineering strain (every 0,01 s).

As the strain grows, the load applied does too, and with the diameter of each specimen, the value of engineering stress is calculated, dividing the load by the initial section of the specimen's neck: $S = \pi * \left(\frac{D}{2}\right)^2$. The diameter of every specimen is not exactly the same, as it is reported in the machining point (3.2.) there is an error of $\pm$0,17 mm between the real values of the diameters.

Due to the fact that, when the necking phenomenon starts, the neck's diameter at every point can't be known, the true stress can't be calculated (its value is the load at every point divided by the neck's section at every point). But, although it is impossible to obtain the true stress-true strain plot, the specimen always reaches its Yield Stress before the necking phenomenon begins (and the diameter starts to change) so theoretically, the engineering stress-true strain plot must be the same and it is valid for this report's purpose.

(a) (b)

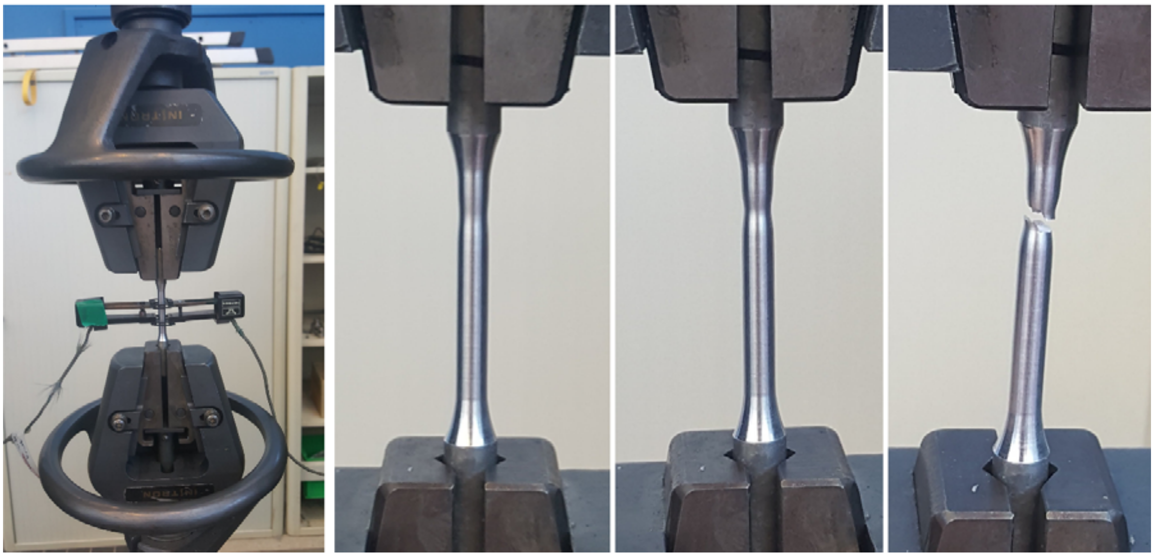


Figure 10. (a) Rotating clamps and extensometers setup. (b) Necking sequence detail.

4. Results and discussion.

4.1. Results from experimental methods and calculations.

•0,2% offset Yield Stress (from tensile test).

In order to obtain the 0,2% offset Yield Stress, a tensile test is applied on every specimen until it reaches the fracture. The test is done at room temperature (25 °C) and at a constant strain rate of 0,015 mm/s.

From this tests, the stress-strain curves are obtained for each one of them, along with the matrix with all the points recorded (stress and strain every 0,01 s). Alongside with this data, the Young's Modulus is automatically calculated for every specimen.

Table 2. Young's Modulus and 0,2% obtained from tensile tests for each specimen, depending on the heat treatment..

Heat treatment		Ø (mm)	E (MPa)	0,2% YS (Mpa)
Temp. (°C)	Time (h)			
70	6	4,83	70449,04	449,5
	24	4,87	68481,69	459,2
	96	4,89	70007,61	483,0
120	6	4,88	68935,65	490,6
	24	4,98	69225,13	568,7
	93	5,04	70153,99	583,9
170	6	4,92	69521,36	467,6
	24	4,89	70017,88	425,9
	96	4,88	69746,71	352,2

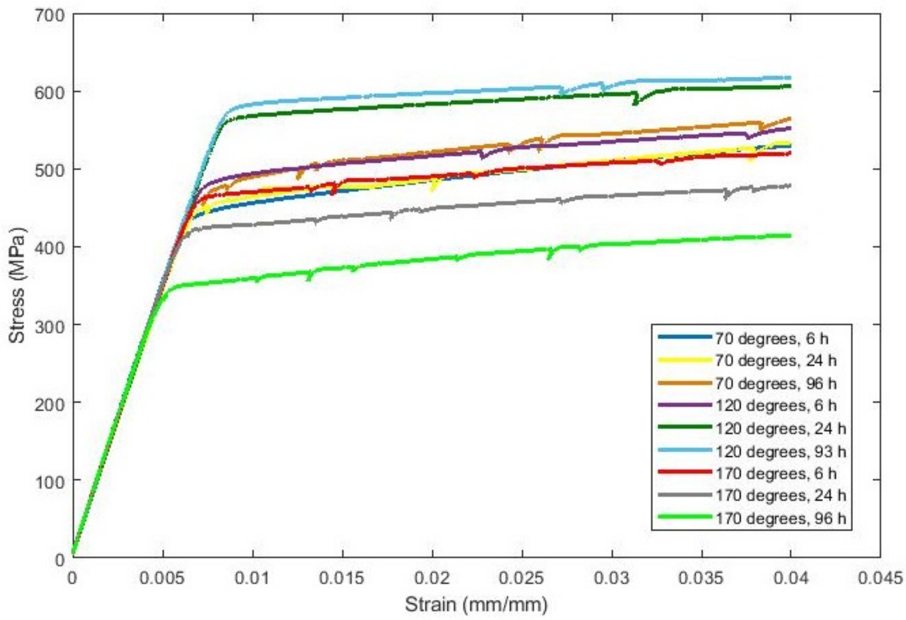


Figure 11. All stress-strain curves together.

It can be appreciated that the initial slope is almost the same for every plot, meaning that the Young's Modulus has not varied significantly due to the different heat treatments.

As the 0,2% offset slope is the same for every plot, the superposition of all the curves provides a clear visualisation of the hardening scale made by every heat treatment, being the 120 °C during 93 hours the highest of them and the 170 °C during 96 hours the lowest of them. This scale gives a good explanation of why the reference heat treatment for AA7075 is the 120 °C during 24 hours, since the hardening effect is almost the same as the highest one (568,7 vs. 583,9 MPa) and the time needed (24 h) is almost a quarter of it (93 h).

Thus, the so called AA7075-T6 is the resulting alloy that corresponds to the heat treatment at 120 °C during 24 h, being this considered the most efficient heat treatment for this material.

The stress-strain curves for every specimen with the 0,2% offset slope and estimated yield point are represented individually in the point 6: Graphs.

•Yield Stress from physical yield criterion.

With the tensile test data (stress and strain for every specimen) the Kocks-Mecking plot can be obtained. The hardening rate, as said before, is the derivative of the stress with the strain: $\theta = \frac{d\sigma}{d\epsilon}$ so with the help of a matlab code it can be obtained with the input of the right vectors ("sig_eng" for stress and "eps" for strain).

```
function [sigma,theta,epsilon] = KMPlot(sig_eng,eps,h)

% Differentiate for Kocks-Mecking (theta) Data
for i=(h+1):(length(sig_eng)-(h+1))
ds= (sig_eng(i+h)-sig_eng(i-h));
de= (abs(eps(i)-eps(i-h))+abs(eps(i)-eps(i+h)));
theta(i-h)=ds/de;
end
clear i

% Correct size of sigma for plot
sigma=sig_eng(h+1:end-(h+1))';
epsilon=eps(h+1:end-(h+1))';

%Plot
plot(sigma,theta);
hold on
xlabel('Stress (MPa)');
ylabel('Work-hardening rate (MPa)');
hold off
```

Figure 12. Matlab code used to obtain the Kocks-Mecking plot.

Another input variable "h" is needed for this process, as it represents the difference between points for the derivation. The derivation is done for every point as the difference of stress divided by the difference of strain (this is the slope) but it can be done between the previous and the next point (h = 1) or several points before and after (h = 10; 100; 500…). In order to obtain neat plots “h” must be high, since the values taken by the tensile testing machine are not continuous and between every point the slope can vary sharply:

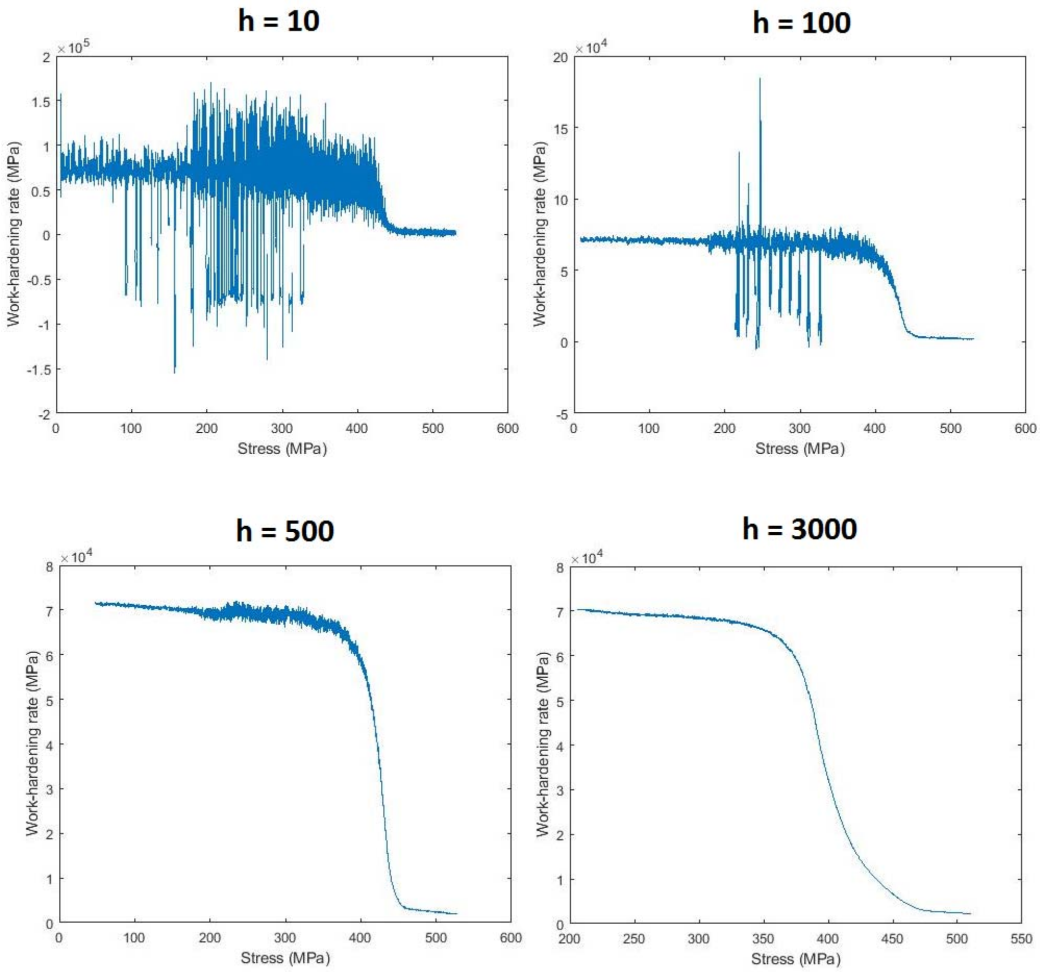


Figure 13. Example: different Kocks-Mecking plots for the same specimen (treated at 70 ℃ during 6 hours) depending on the “h” value.

A magnitude of hundreds is enough to clearly distinguish the slope change that marks the yield point, while a magnitude of thousands smoothens too much the curve. The value taken for this report is h = 500.

With this, the graph for every specimen is obtained (they are displayed individually in the point 6: Graphs.) and from they, the Yield Stress is determined.

Table 3. Yield Stress and hardening rate at yield point for every specimen.

Heat treatment		YS (MPa)	Hardening rate (MPa)
Temp. (°C)	Time (h)		
70	6	457,5	3673
	24	467,8	2724
	96	514,8	3462
120	6	501,7	2468
	24	576,6	1533
	93	591,1	1485
170	6	474,6	2651
	24	433,2	1910
	96	358,0	3058

All the Kocks-Mecking plots can be displayed together to get a visual comparison of the obtained values.

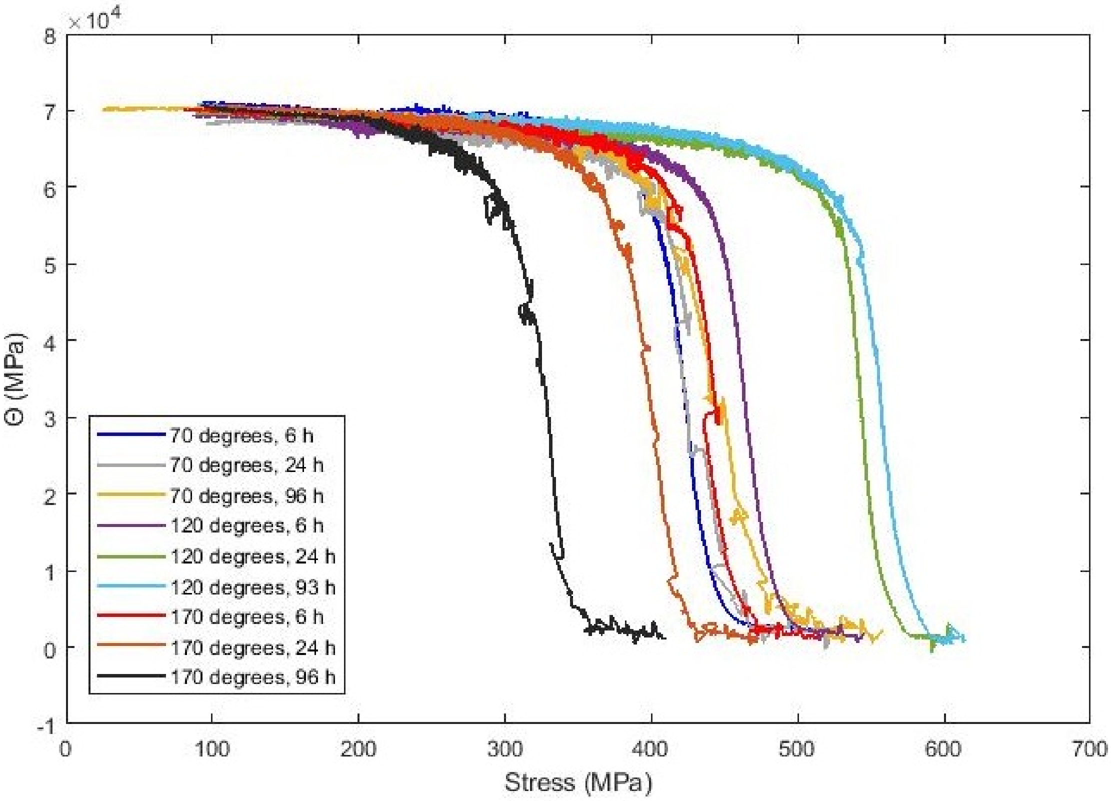


Figure 15. All Kocks-Mecking plots together.

The Young's Modulus uniformity can be appreciated in the coincidence of the initial horizontal section, at 70 GPa, meaning the slope of the elastic region of the stress-strain curves.

As in the tensile test graphs, this ones also show how 120 °C during 93 hours is the temper that provides a higher stress at yield, closely followed by 120 °C during 24 hours. It is again proved that

120 °C during 24 hours is the ideal heat treatment for AA7075 with almost a quarter the time of the highest results.

•Vickers hardness.

For each sample, 9 hardness measures are directly obtained. These values are ranked (from low to high) and the highest and the lowest are discarded, in order to remove possible measuring mistakes.

Table 4. Vickers hardness measurements and average value for every sample.

Heat treatment		Tests									Average HV		
T (°C)	Time (h)	Hv1	Hv2	Hv3	Hv4	Hv5	Hv6	Hv7	Hv8	Hv9	Value	Error+	Error-
70	6	147	148	149	150	151	151	152	152	155	150,43	1,57	2,43
	24	141	142	143	149	149	152	153	154	154	148,86	5,14	6,86
	96	155	155	157	157	157	157	158	158	159	157,00	1,00	2,00
120	6	149	152	152	156	156	156	156	158	161	155,14	2,86	3,14
	24	172	174	174	174	176	176	179	180	182	176,14	3,86	2,14
	93	179	180	184	184	185	185	186	187	189	184,43	2,57	4,43
170	6	154	155	156	157	157	157	157	158	160	156,71	1,29	1,71
	24	142	143	143	143	146	146	147	149	151	145,29	3,71	2,29
	96	127	129	129	130	131	131	131	131	133	130,29	0,71	1,29

•Yield Stress from hardening test.

The average hardness values are the variable H used for the calculation of the Yield Stress following Tabor's equation: $\sigma y = \frac{H}{3} * 0{,}1^{m-2}$. The Meyer's coefficient is obtained from the relation: $m = n + 2$; where n is the index of the potential approximation of the plastic deformation part of the stress-strain curve: $\sigma = K * \epsilon^n$. The value of "n" is, then, the slope of the linear approximation of the equivalent equation: $\ln(\sigma) = \ln(K) + n * \ln(\epsilon)$.

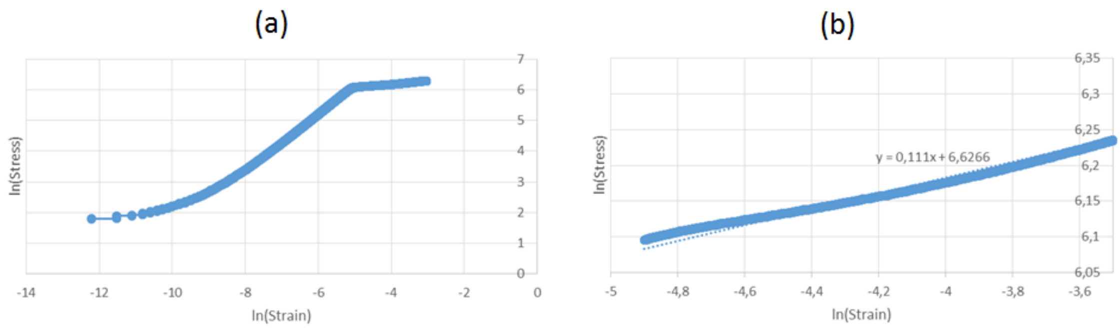


Figure 16. Example plot: (a) ln(Stress)-ln(Strain) for 70 ℃ during 6 hours tempered specimen. (b) Isolation of the plastic behavior zone and linear approximation of it.

As it can be seen in Figure 16 (b), with a linear approximation of the plot, removing the elastic behaviour part, the value of "n" is the slope: $n = 0{,}111$. Now: $m = n + 2 = 2{,}111$.

With the Meyer's coefficient and the hardness value, the Yield Stress is calculated for every specimen.

Being Tabor's equation not completely reliable for Al-ZN-Mg alloys, as it has been explained, Chang's correction: $\sigma y = \left(\frac{\mathrm{H}}{2,9}\right)^{\frac{1}{3-m}} * \left(\frac{12,5}{E}\right)^{\frac{m-2}{3-m}} + 25 * (m-2)$ is also used and their values are expected to be more accurate than Tabor's.

Table 5. Yield Stress values for every specimen calculated with the 2 different equations.

Heat treatment		n	Meyer Coef.	Tabor	Correction
T (°C)	Time (h)			YS (MPa)	YS (MPa)
70	6	0,1110	2,1110	380,8	403,9
	24	0,0831	2,0831	401,9	425,8
	96	0,1038	2,1038	404,1	429,6
120	6	0,0798	2,0798	422,0	447,4
	24	0,0495	2,0495	513,8	542,5
	93	0,0435	2,0435	545,4	575,0
170	6	0,0773	2,0773	428,8	454,2
	24	0,0755	2,0755	399,1	421,3
	96	0,1027	2,1027	336,2	354,7

The values are similar but the corrected ones seem are always higher than Tabor's.

4.2. Comparisons.

•3 Yield Stress values.

After all the process, different values for the same Yield Stress are now calculated for every specimen.

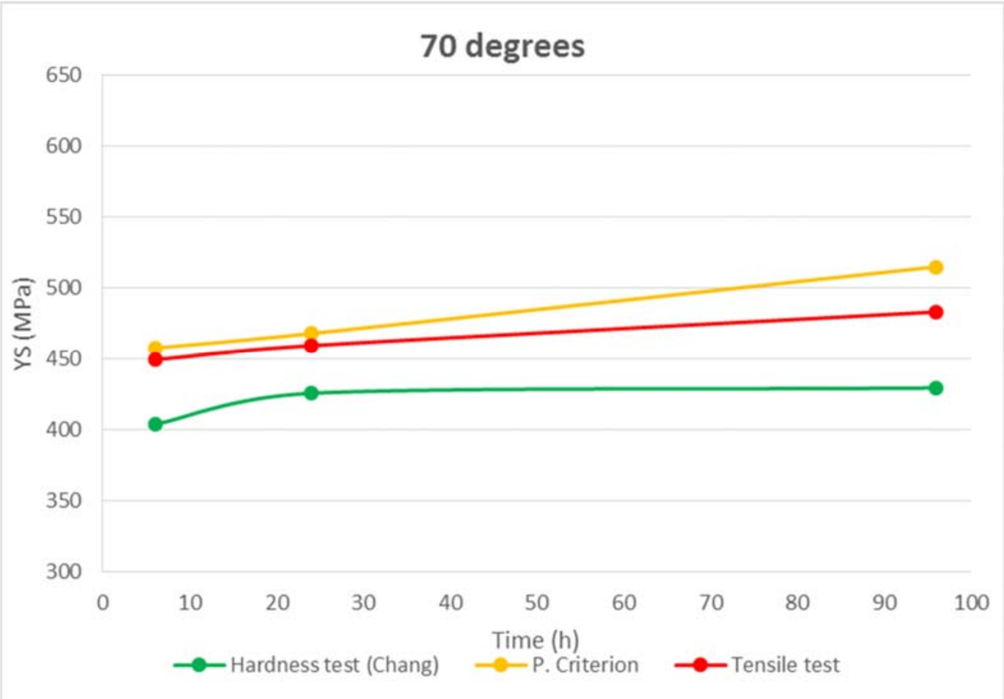
Table 6. All Yield Stress value for every heat treated specimen.

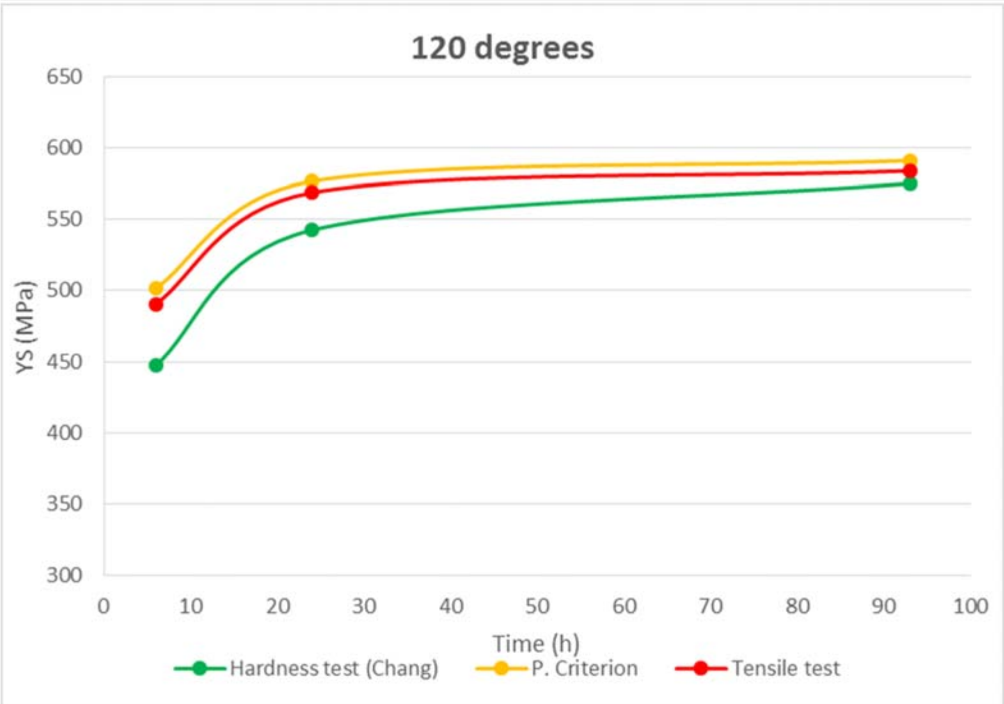
Heat treatment		P. Criterion	Tensile test		Hardness test (Chang)		Hardnes test (Tabor)	
Temp. (°C)	Time (h)	YS (MPa)	YS (MPa)	Error (%)	YS (MPa)	Error (%)	YS (MPa)	Error (%)
70	6	457,5	449,5	1,7	403,9	11,7	380,8	16,8
	24	467,8	459,2	1,8	425,8	9,0	401,9	14,1
	96	514,8	483,0	6,2	429,6	16,6	404,1	21,5
120	6	501,7	490,6	2,2	447,4	10,8	422,0	15,9
	24	576,6	568,7	1,4	542,5	5,9	513,8	10,9
	93	591,1	583,9	1,2	575,0	2,7	545,4	7,7
170	6	474,6	467,6	1,5	454,2	4,3	428,8	9,7
	24	433,2	425,9	1,7	421,3	2,8	399,1	7,9
	96	358,0	352,2	1,6	354,7	0,9	336,2	6,1

The errors % shown are referred to the physically based criterion, due to the fact that it is the one with a physical meaning, rather than an approximation as the other ones are. Once again, these approximations are acceptable, but not as accurate.

Concerning to the hardness test Yield Stress, it should be noticed that the average error in Tabor's equation calculation is 12,3 %, while in Chang's correction is 7,2 %. Individually, every specimen's Yield Stress error is also smaller when it is calculated by the corrected equation. Given this facts, it can be affirmed that Chang's correction is more accurate than Tabor's method.

Maintaining the colour code (physical criterion; 0,2% offset; hardness) already used, the 3 Yield Stress values can be represented in a graph (for every temperature of heat treatment) as follows.





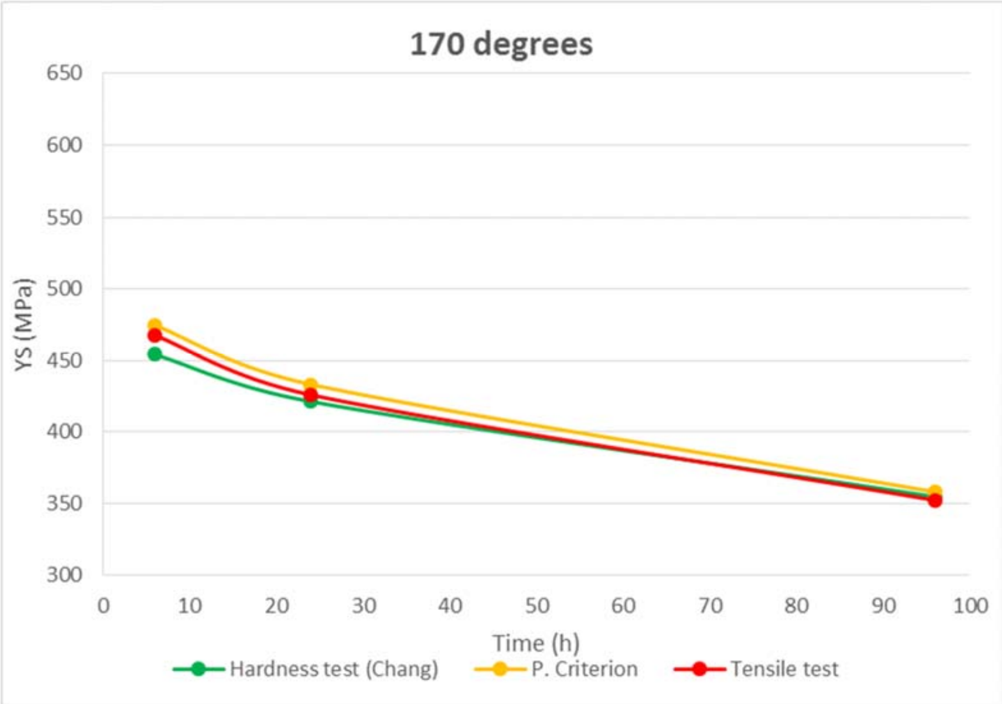


Figure 17. Evolution of the Yield Stress depending on the time of tempering for the 3 methods, separated by the different heat treatment temperatures.

For the 3 methods it must be highlighted that the Yield Stress from the physically based yield criterion is in every case the highest value, meaning that the 0,2% offset and the hardness test methods are more conservative. This makes sense, considering that when an approximation like these is made, it is interesting that the final value is not higher than the real value, which could cause a lack of safety in, for instance, a piece of the engine of a car, making possible that it breaks unexpectedly.

Also, the 0,2% offset Yield Stress is higher than the hardness Yield Stress in every case except for the last section of the 170 °C, meaning that generally the hardness Yield Stress value is more conservative, although it has been calculated by an equation (it has even been corrected for this kind of alloys) and the 0,2% offset value is an arbitrary value empirically determined for a broad spectrum of different materials.

•Yield stress - heat treatment.

The different heat treatments are expected to harden the treated specimen, but it can also soften it if the temper is not the adequate for the material.

As it can be appreciated in Figure 18, independently of the method used, the 70 °C and the 120 °C heat treatment harden the AA7075 specimens (specially the second one), while the 170 °C worsens the Yield Stress more and more with the time.

In the case of the 70 and 120 °C the Yield Stress would seem to tend to a value where it stabilizes, but in the 70 °C physical yield criterion after a long time it shows how it starts to lower the Yield Stress. This confirms that an excessive heat treatment can be harmful for the material.

The 170 °C heat treatment is always prejudicial for the AA7075 alloy. It means this temperature is too high to be used in AA7075 precipitation hardening.

With all this information, it is confirmed that the ideal heat treatment for AA7075 is 120 °C (highest hardening rate) during 24 hours (more hours do not make great improvements).

This has already been set, as the AA7075-T6 is the reference for heat treated AA7075 alloy.

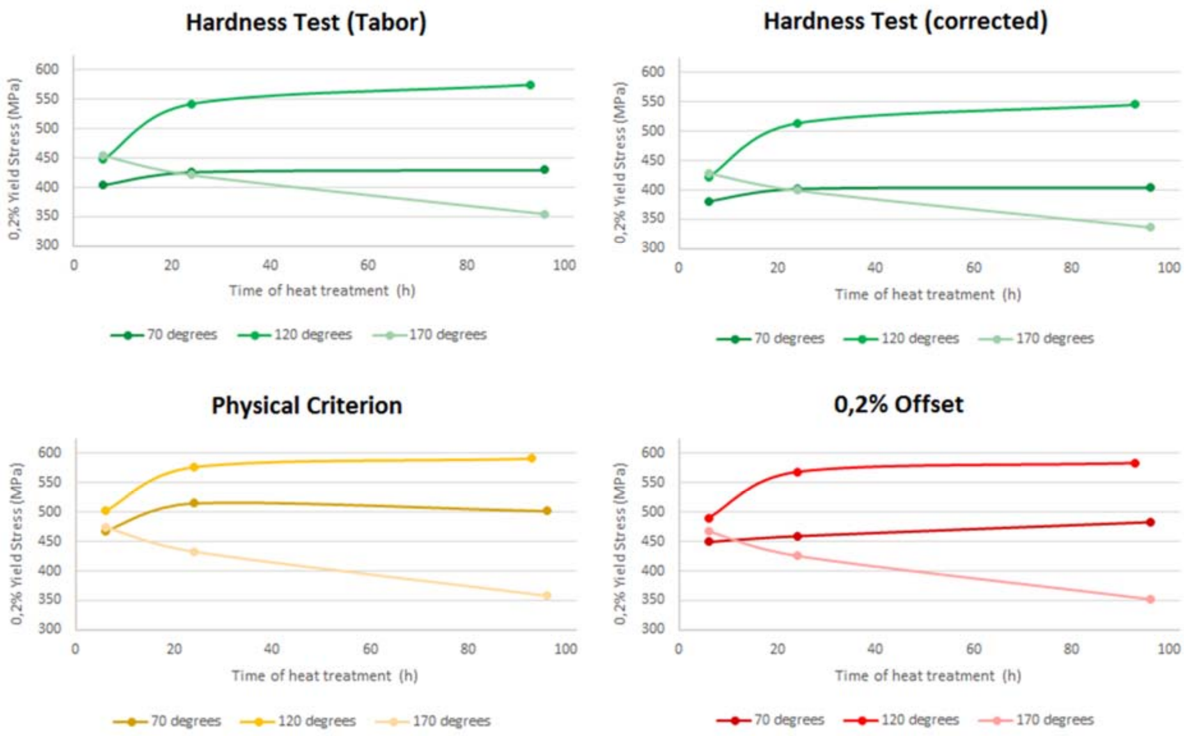


Figure 18. Evolution of the Yield Stress depending on the time of tempering for the different temperatures, separated by the 3 different methods.

•Yield Stress from hardness test - hardness.

The value of the Yield Stress can be represented in a graph versus the Vickers Hardness value used to calculate it in every case.

From the graph in Figure 19, it is noticeable that the curve is not the same for the different heat treatments. Comparing the values obtained at the 3 temperatures it is clear that 120 °C tempering strengthens the material and hardens it at the same ratio during time, being both raises more significant during the first 24 hours. The 170 °C tempering reduces both the Yield Stress and the Vickers Hardness value at the same ratio, but this time the drop is more considerable from the 24th hour onwards.

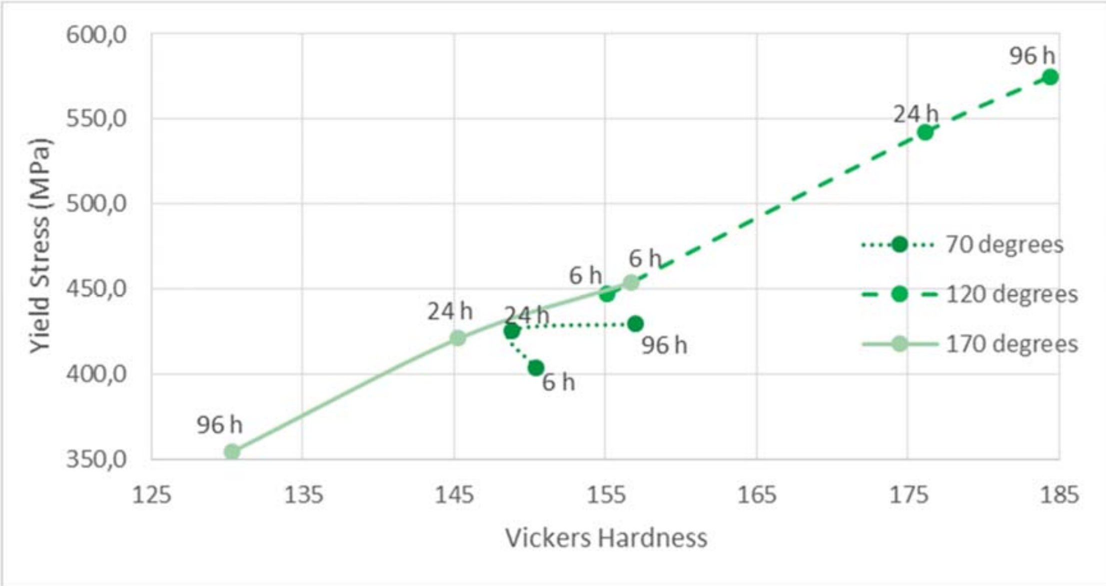


Figure 19. Yield Stress from hardness test vs. Vickers Hardness for every heat treatment.

This duality after 24 hours is due to the fact that the heat treatment generally starts losing improvement effect with time after several hours, so when it is actually improving the mechanical properties (120 °C) it lowers its effect, but when it is already damaging the material (170 °C) the time helps to worsen the properties.

The 70 °C tempering, distinctly, seems to enhance the stress resistance at the expense of reducing the hardness at the beginning and, after the initial 24 hours, the Yield Stress increases very slightly, while the hardness does increase considerably.

This behaviour of AA7075 alloy states that not all the heat treatments are beneficial for the materials, thus the adequate heat treatment must be done for a certain material with a certain purpose.

5. Conclusions.

After all the facts are displayed, it is clear that the Yield Stress obtained by the yield criterion developed by Peter van Liempt and Jilt Sietsma is less conservative than the traditional 0,2% offset Yield Stress and the Yield Stress calculated from the Vickers hardness test. It is also more accurate, since it has a physical meaning regarding the analysis of pre-yield dislocation behaviour, while the other methods are approximations based on empirical evidence.

Both two methods serve well for the main purposes of materials like AA7075 alloy, but when more accuracy is needed, the physically based yield criterion is a good asset to obtain more reliable information.

Age hardening is a simple way of strengthen metals and the experimental results show that there is an efficient way to do it. For AA7075, too high temperature treatments (like 170 °C) do not enhance the mechanical properties. The same happens when AA7075 alloy is exposed too much time to the heat treatment, there is a point where the mechanical properties improvement do not worth the time. The ideal treatment for the AA7075 alloy is 120 °C during 24 hours, what is commonly known as AA7075-T6.

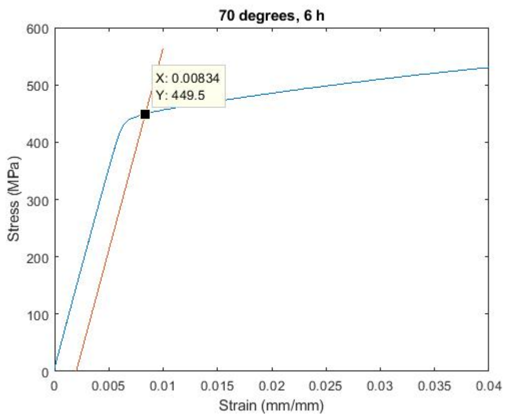
In regard to hardness characterisation, Chang's correction to Tabor's Yield Stress equation for Al-Zn-Mg alloys has proven to be more accurate in comparison with the physical Yield Stress, while both of them are still less precise than the classic 0,2% offset method from tensile test.

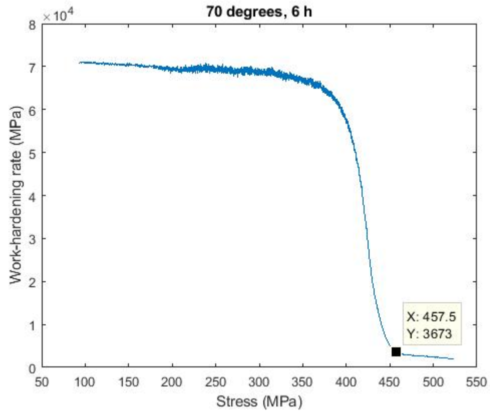
6. Graphs.

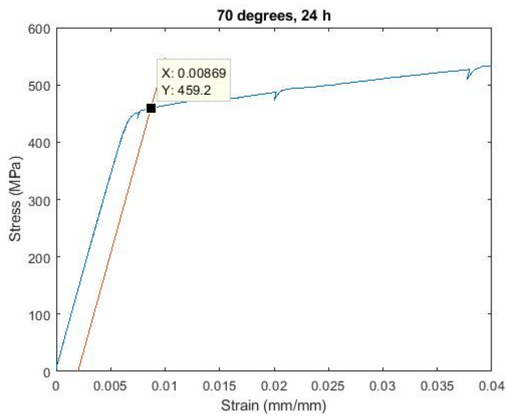
The stress-strain curves for each one of the heat treated specimens is individually represented, alongside with the Kocks-Mecking plot relative to that heat treatment.

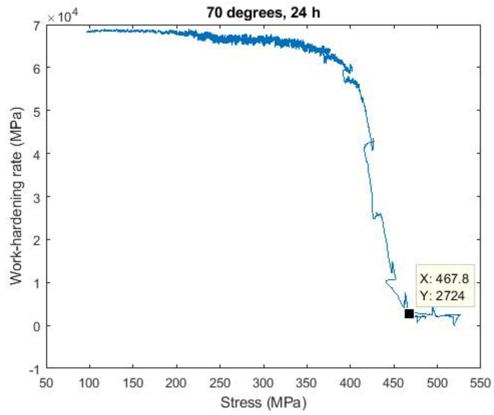
The yield point in every S-S graph is estimated with the intersection of the curve with the red 0,2% offset slope.

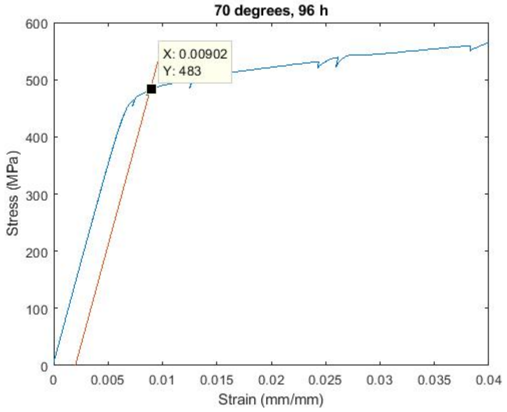
The yield point in every K-M plot is determined where a sharp change of slope is produced in the region where the anelastic behaviour ends and the plastic deformation starts.

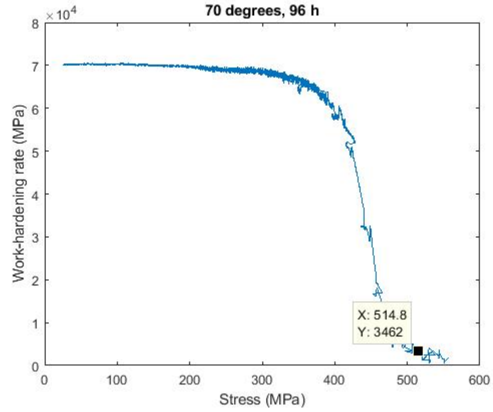


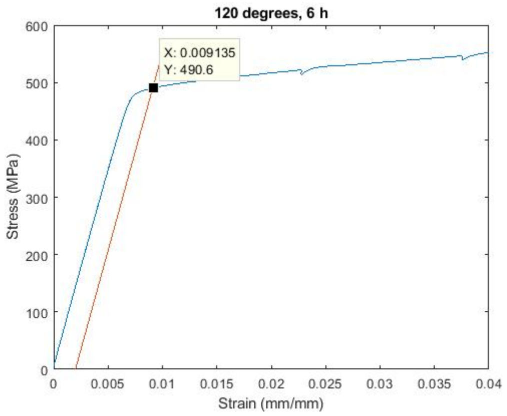


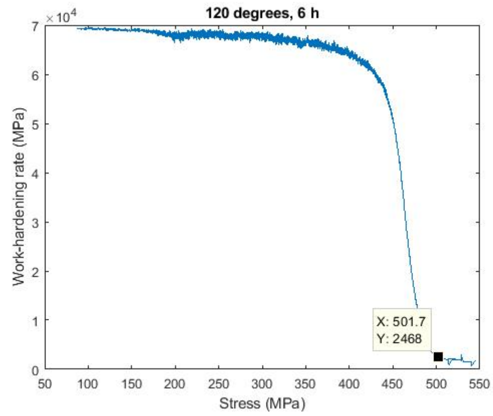


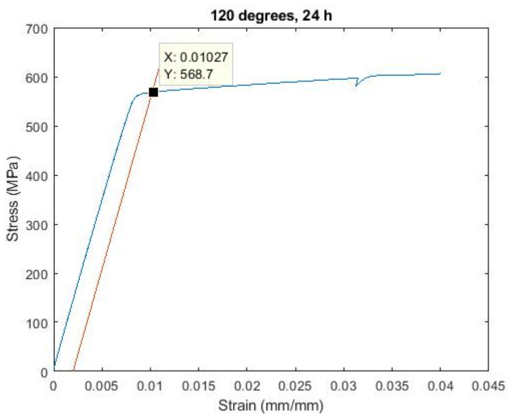


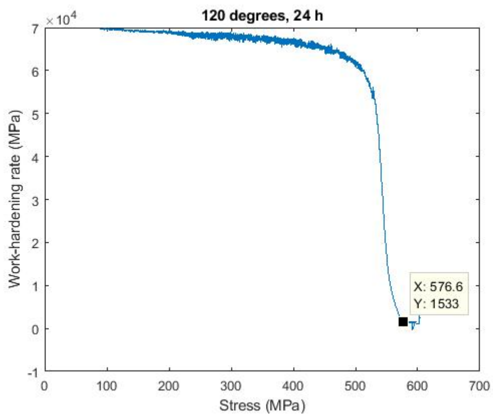

70 degrees, 96 h
X: 0.00902
Y: 483
Stress (MPa)
Strain (mm/mm)

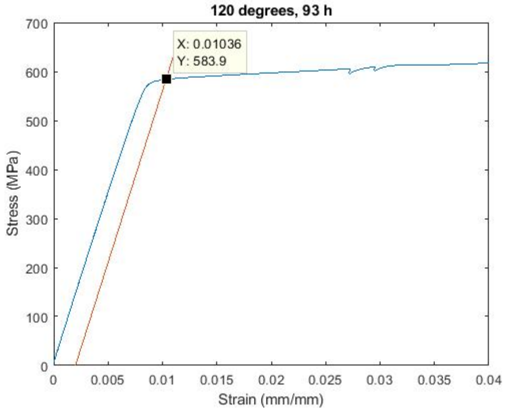

70 degrees, 96 h
×10^4
X: 514.8
Y: 3462
Work-hardening rate (MPa)
Stress (MPa)

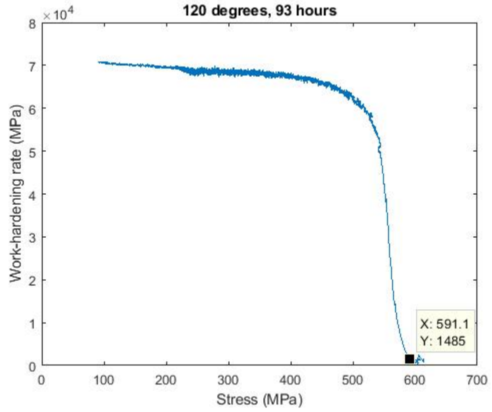

120 degrees, 6 h
X: 0.009135
Y: 490.6
Stress (MPa)
Strain (mm/mm)

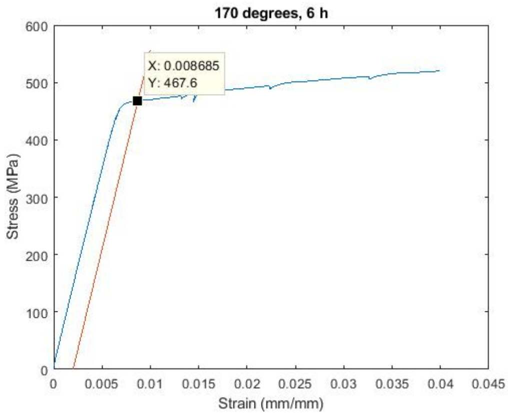

120 degrees, 6 h
×10^4
X: 501.7
Y: 2468
Work-hardening rate (MPa)
Stress (MPa)

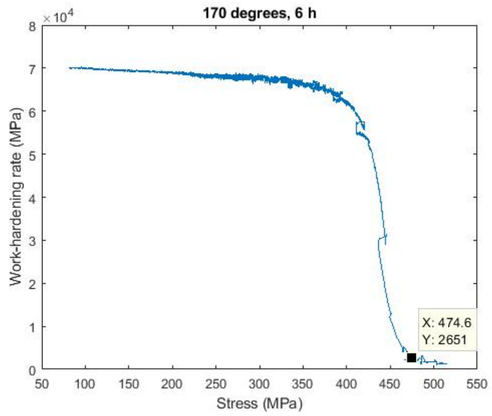

120 degrees, 24 h
X: 0.01027
Y: 568.7
Stress (MPa)
Strain (mm/mm)

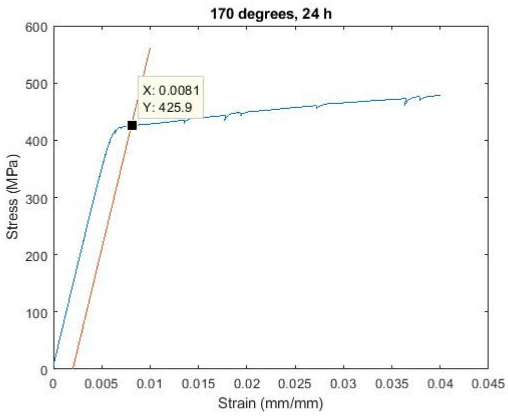

120 degrees, 24 h
×10^4
X: 576.6
Y: 1533
Work-hardening rate (MPa)
Stress (MPa)

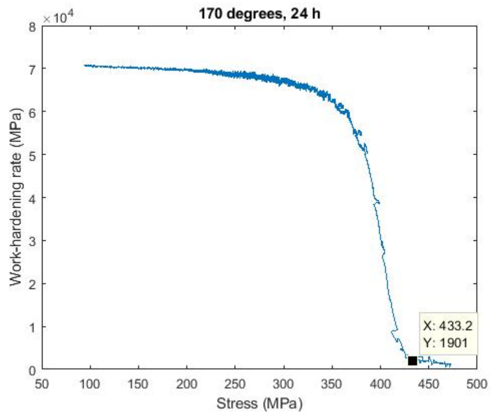

120 degrees, 93 h
X: 0.01036
Y: 583.9
Stress (MPa)
Strain (mm/mm)

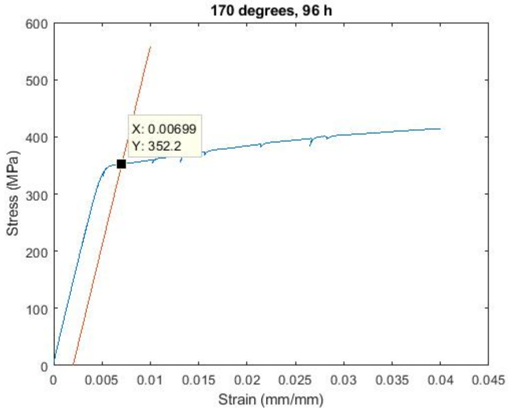

120 degrees, 93 hours
×10^4
X: 591.1
Y: 1485
Work-hardening rate (MPa)
Stress (MPa)

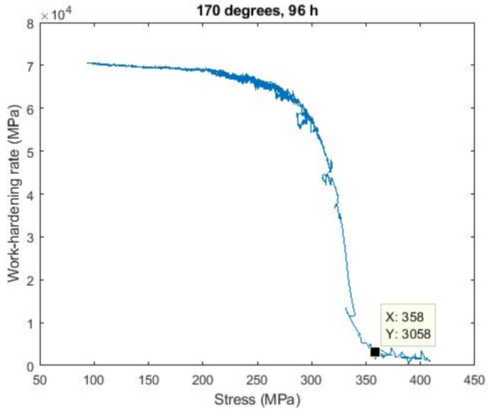

170 degrees, 6 h
X: 0.008685
Y: 467.6
Stress (MPa)
Strain (mm/mm)


170 degrees, 6 h
×10^4
X: 474.6
Y: 2651
Work-hardening rate (MPa)
Stress (MPa)


170 degrees, 24 h
X: 0.0081
Y: 425.9
Stress (MPa)
Strain (mm/mm)


170 degrees, 24 h
×10^4
X: 433.2
Y: 1901
Work-hardening rate (MPa)
Stress (MPa)





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