Heat treatments of EN AW 6082 aluminum forging alloy: effect on microstructure and mechanical properties

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Aluminum components for structural applications, such as some automotive suspension parts, are usually made by forging. In this context, the use of aluminum EN AW 6082 alloy application for highly demanding structural components is increasing due to lightweighting needs. Anyway, its response to age hardening is still not well investigated and the information about the time-temperature parameters and the relative mechanical properties are generally scarcer. In order to extend the knowledge in this field, during the present research a Design Of Experiment methodology was applied and T6 and T5 heat treatment were analysed. Microstructural and mechanical behaviour were studied. The output of these experiments constitutes a useful database of the properties of EN AW 6082 alloy in the considered range of data. This information can be used for the designing of different structural components where either an optimization of the elongation or a maximum yield strength could be required depending on the specific application. The results also suggest that for many applications a T5 heat treatment, with high mechanical properties, a lower thickness of recrystalized area and a reduced cost, could be a good option.

PAROLE CHIAVE: ALUMINUM ALLOYS, MECHANICAL CHARACTERIZATION, AUTOMOTIVE, FORGING, MICROSTRUCTURE, 6XXX SERIES.

INTRODUCTION

Usually, aluminum components for structural applications, such as some automotive suspension parts, where reliability and human safety are critical are made by forging. This process offers higher tensile, yield, fatigue strength and ductility respect to castings, thanks to an improved soundness and chemical uniformity [1]. Indeed, deformation processes refine the microstructure of alloys and reduce defects typical of castings, such as voids and porosity (gas and shrinkage), oxide films and inclusions, non-uniform microstructure, and coarse intermetallic phases [2]. Aluminium forging guarantees near net shape parts, high mechanical properties, a good surface finishing and are thus suitable for highly stressed parts [3]. The aluminium forging use is an increasingly need of the last years also for highly demanding structural products [3] mainly to further extend the automotive lightweighting at these challenging applications. Indeed, one of the major current trends of the

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automotive industry is the need of lighter components to reduce the vehicle emissions [4-9].

In this context one of the most widely employed alloy forging stock is aluminium EN AW 6082, extruded from a Direct Chill (DC) billet [10], due to its good corrosion resistance and mechanical properties. This is an age-hardenable alloy usually subjected to T6 heat treatment to improve the as-forged properties.

Although the application of this material is increasing in the field of structural automotive components, its response to age hardening is still not well investigated. Indeed, the information about the time-temperature parameters and the relative mechanical properties is generally scarcer. In particular, some exception can be found in Y. Birol et al. [1, 11-13] that studied the relation between some heat treatment parameters and the mechanical properties of EN AW 6082 alloy. As regards T6 treatment, temperatures between 510°C and 530°C and 170°C and 190°C were investigated for solubilization and age hardening respectively. In general, a detailed microstructural investigation was performed, but few data about the mechanical properties achieved after any heat treatment condition are available.

G. Mrówka-Nowotnik et al. [14] deepened the tensile properties of EN AW 6082 -T6 forging samples, after a solubilization at 575°C followed by agings between 130°C and 170°C. Anyway, the solubilization temperature is very closed to the eutectic transition (577°C [15]) this treatment takes a chance to induce a partial melting of the eutectic into the aluminum matrix. Indeed, further investigation about the mechanical properties at lower solubilization temperatures are required.

Another relevant aspect to be taken into account is that the extruded billet used for the forging process as a recrystallized surface, due to the high temperature and high strains of the process. Consequently, the elevate solubilization temperatures generate inevitably a grain growth [11-13]. Thus, the potential benefit of a T5 heat treatment on the microstructural behaviour and mechanical properties could be an interesting topic for the present application. Again, very few investigations can be found about the properties on EN AW 6082 -T5 forging [11-13].

To better understand all these aspects and to analyse the opportunity to extend the use of this alloy at even further stressed applications, the general knowledge about the effect of the heat treatments on EN AW 6082 aluminum forging need to be improved. At this purpose, during the present research a Design Of Experiment methodology was applied in order to analyse a wide range of heat treatment parameters applied at an actual EN AW 6082 aluminum forged components. T6 and T5 heat treatment were studied. T5 heat treatments are expected to reduce the typical surface recrystallization induced by the high solubilization temperature, while the use of real automotive parts is a fundamental aspect of the research aimed to be as reliable as possible in the perspective of a final industrial application. Microstructural and mechanical behaviour of these different heat treatments were examined and compared.

MATERIALS AND METHODS

Samples description

About 50 hot forged suspension automotive components made of aluminum EN AW 6082 alloy were used for the current investigation. The chemical composition of this alloy is reported in Tab. 1.

Tab.1 - Chemical composition of the EN AW 6082 components.

	Si	Fe	Cu	Mn	Mg	Ni	Zn	Sn	V	Cr	Ti
EN AW 6082	1.108	0.207	0.067	0.926	0.891	0.009	0.019	0.003	0.014	0.185	0.032

After the forging process, the parts were heat treated in a preheated oven with different T6 and T5 time and temperature parameters reported in Tab. 2. The solubilization time was fixed at 4 hours. As it can be noted, a Design Of Experiment (DOE) methodology was applied to assess the influence of the time and temperature

of heat treatment conditions on the final alloy's mechanical properties.
Tab. 2 also reports the samples nomenclature that will be used hereafter. At least three components for each condition were tested.

Tab.2 - Time-temperature factors for each heat treatment conditions.

	$T_{solubilization}$	Taging	taging	Samples
T6	550	160	2	A
	550	160	6	B
	550	190	2	C
	550	190	6	D
	520	160	2	E
	520	160	6	F
	520	190	2	G
	520	190	6	H
T5	0	180	4	I
	0	180	8	L
	0	200	4	M
	0	200	8	N

For the tensile test, according to UNI EN ISO 6892-1:2009 standard, cylindrical samples with a total length of 120 mm and a gauge diameter of 10 mm were machined from the same section of the automotive components studied.
For the metallographic observations, samples before and after heat treatment were sectioned orthogonally to the forging direction and, also for this analysis, in the same area of the parts. The sample sections have average dimensions of about 25x60 mm.

Microstructural observation

The samples surfaces were prepared with standard metallographic techniques (ground with SiC papers and polished with 1 μm diamond paste) and were etched with SAPA solution. The microstructure was examined using a Leica DMI 5000M Optical Microscope (OM) and a Leica G.26 Stereo Microscope (SM).

Hardness and tensile test

Vickers microhardness tests were carried out under 0.3 Kg_f load applied for 15 s on the etched traverse surface, by means of a Mitutoyo HM-200 instrument according to ASTM E92-16. At least six measurements were taken and averaged for each heat treatment condition.
The tensile tests were carried out on three samples for each heat treatment condition, following UNI EN ISO 6892-1:2009. An electromechanical testing machine Instron 3369 at a strain rate of 2 mm/min was used.

RESULTS AND DISCUSSION

Microstructural observation

The grain structure of transversal sections of the forged suspension components analysed are reported in Fig. 1 for the as forged, T5 and two T6 conditions. The as-forged sample has a very fine structure in the middle and a very thin (about 0.5 mm) area at the surface boundary characterized by recrystallized grain, due to the high temperatures reached during the process. After the heat treatments, the extension of the coarse-grains area increases with the temperature and reach elevate thickness after T6 heat treatment (up to about 3.5 mm). The effect of T5 heat treatment is very similar, with only a slight less extension of the grain growth in comparison with T6 heat treatment (3 mm).

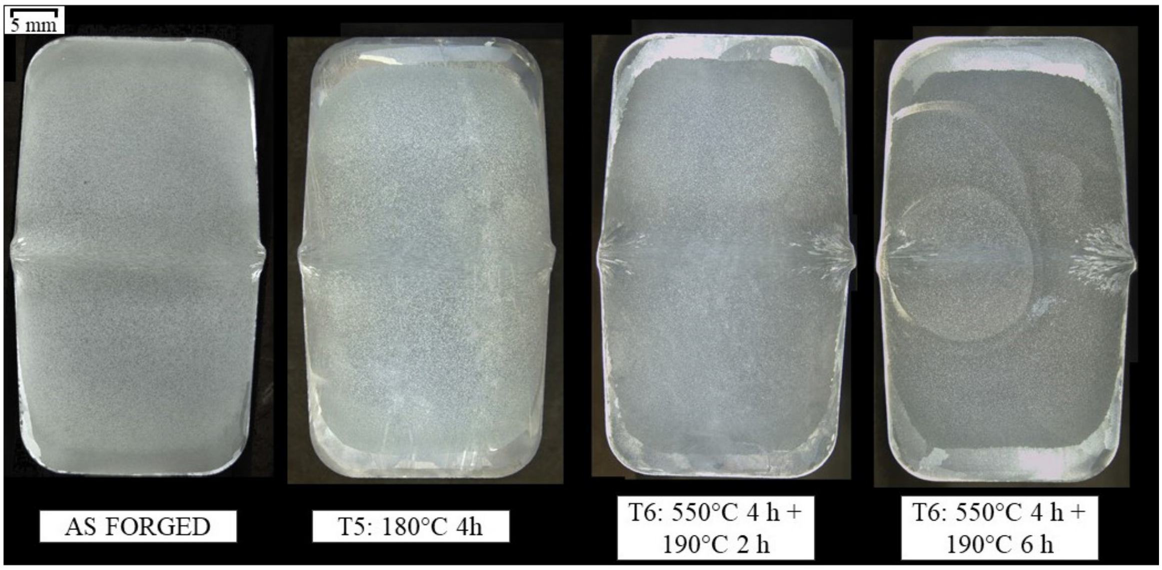


Fig.1 - Grain structure across section of samples in the as forged and heat-treated conditions.

The microstructures of as forged condition, "D" T6 and "I" T5 heat treatment are reported Fig. 2 a, b, c respectively.
In general, it can be noted a fine dispersion of Mg_2Si [1] and plate-like particles, probably cubic α-AlFeMnSi [16], at the grain boundaries. These particles are mainly aligned in the forging direction especially for the as-forged condition. The presence of precipitate-free zones (white areas at the grain boundaries) can be attributed to the bounding of silicon in the α-AlFeMnSi compounds. After the heat treatment a more uniform distribution of finer particles than the as-forged condition can be observed. Similar consideration can be advanced for both the heat treatment, with only a slightly more pronounced effect for T6 heat treatment.

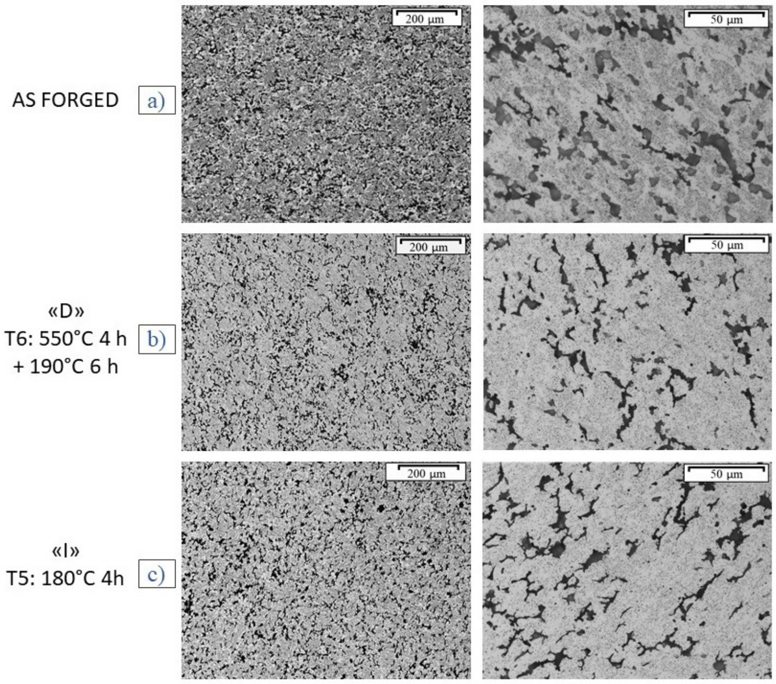


Fig.2 - Microstructure of as forged condition (a), "D" T6 heat treatment (b) and "I" heat treatment (c).

Hardness

Fig. 3 reports the microhardness profile along a transversal section for As Forged (AF), "D" T6 heat treatment and "I" T5 heat treatment. The average hardness in the As Forged (AF) condition is 87±6 HV. Peaks of hardness are observed at the sample edges and could be related to the high strain ratio of the surface. After T6 and T5 heat treatment the hardness increases up to 115±3 HV and 114±5 HV respectively, as it can be gathered from "D" and "I" heat treatment reported as example in Fig. 3. In these cases, the hardness is more uniform across the section without any peaks at the sample edges in comparison with the as-forged condition ("AF" sample).

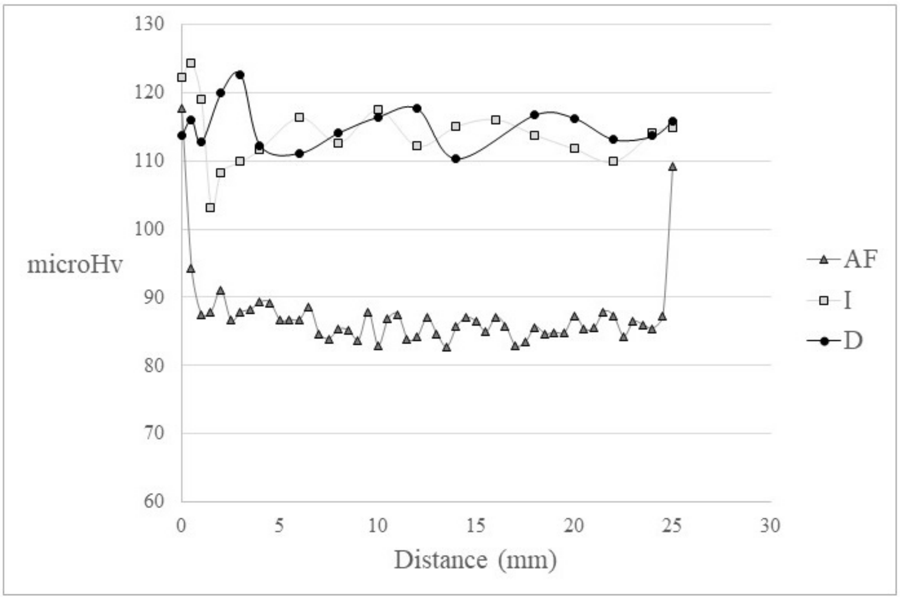


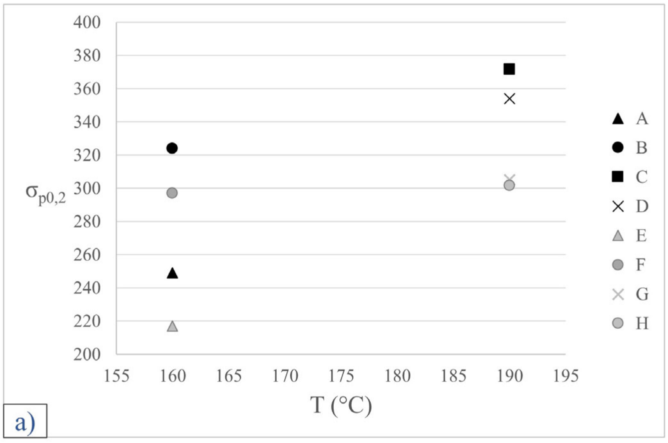
Fig.3 - Microhardness profile of As Forged (AF) condition, "D" T6 heat treatment and "I" heat treatment.

Tensile test

The tensile properties (yield strength, stress at break, Young modulus and elongation%) of EN AW 6082 alloy after solubilization and artificial aging (samples from A to H) and artificial aging only (sample I to N) at various time and temperatures are summarized in Tab. 3. For a better understanding of the data, the effect of temperature on yield strength and elongation of EN AW6082 T6 Al alloy is schematized in Fig. 4. In particular, the grey and black points represent 520°C and 550°C solubilization temperatures respectively. From the analysis of T6 results it can be clearly noted the effect of the aging: the yield strength increases while the elongation percentage decreases with the time; an opposite trend is observed with the aging temperature. Keeping constant the aging parameters, the yield strength increases and the elongation percentage slightly decreases with the solubilization temperature (from 520°C to 550°C). Only in the case of 190°C of aging temperature, a slight over-aging is observed after 6 hours of heat treatment (reduction of both yield strength and elongation%). It is worthwhile to note that these considerations can be useful for the setup of the heat treatment parameters also for all the condition comprised within the range of time-temperatures considered for the present activity. Good mechanical properties are observed also after T5 heat treatments. In this case, higher aging temperature and time lead to a decrease of the mechanical properties, probably due to an overaging. The results suggest that for many applications a T5 heat treatment, with high mechanical properties, a lower thickness of recrystalized area, could be a good option. It should be noted that thermal treatment T5 would also lead to cost savings.

Tab.3 - Mechanical properties of EN AW 6082 alloy after T5 and T6 heat treatment

			σ_{p02} [MPa]		σ_m [MPa]		E [GPa]		A(%)	
			Avg.	±	Avg.	±	Avg.	±	Avg.	±
A	550°C 4h	160°C 2h	249	11	352	6	72	2	15	1
B	550°C 4h	160°C 6h	324	3	383	4	73	2	12	1
C	550°C 4h	190°C 2h	372	9	386	8	73	2	9	1
D	550°C 4h	190°C 6h	354	9	367	8	72	3	8	1
E	520°C 4h	160°C 2h	217	5	311	2	74	2	16	0
F	520°C 4h	160°C 6h	297	11	344	12	73	2	13	1
G	520°C 4h	190°C 2h	305	7	332	5	73	1	11	0
H	520°C 4h	190°C 6h	302	2	323	1	73	0	10	0
I	180°C 4h		326	7	349	6	72	3	11	0
L	180°C 8h		321	4	340	3	73	1	9	1
M	200°C 4h		295	5	317	3	72	3	11	0
N	200°C 8h		272	4	303	4	72	3	11	1



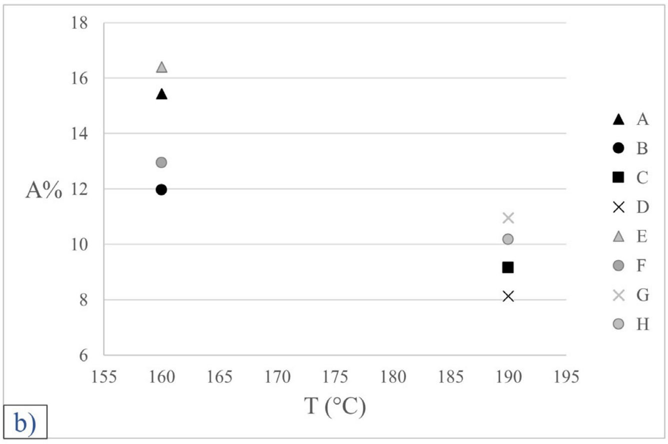


Fig.4 - Effect of temperature on yield strength and elongation of EN AW6082 T6 Al alloy.

CONCLUSIONS

The use of aluminum EN AW 6082 alloy application for highly demanding structural components is increasing due to lightweighting needs. Thus, further investigation about the most proper heat treatment parameters for different application are required. At this purpose, during the present research a Design Of Experiment methodology was applied and T6 and T5 heat treatment were analysed. Microstructural and mechanical behaviour were studied and the following conclusions can be retrieved.

- The microstructural investigation revealed that:
  - o From a macrostructural point of view, the as-forged sample has a very fine structure in the middle and a very thin (about 0.5 mm) area at the surface boundary characterized by recrystallized grain. After the heat treatments, the extension of the coarse-grains area increases with the temperature having elevate thickness both after T5 (3 mm) and T6 (up to about 3.5 mm) heat treatments. Indeed, T5 heat treatment led only to a slight reduction of the grain growth in comparison

with T6 heat treatment, probably due to the high reduction ratio adopted in the area considered for the microstructural investigation.
 - o The microstructure is composed of a fine dispersion of Mg2Si and plate-like particles, probably cubic α-AlFeMnSi, at the grain boundaries. After the heat treatment a more uniform distribution of finer particles than the as-forged condition can be observed for both T5 and T6 heat treatments.
- The hardness analysis revealed that:
  - o Values of 87±6 HV, 115±3 HV and 114±5 HV were measured in the AF, D-T6 and I-T5 conditions respectively.
- The tensile properties revealed that:
  - o For T6 the yield strength increases while the elongation percentage decreases with the aging time, while an opposite trend is observed with the aging temperature. Keeping constant the aging parameters, the yield strength increases and the elongation percentage slightly decreases with the solubilization temperature (from 520°C to 550°C). An over aging is observed after 6 hours of aging at 190°C.
  - o After T5 heat treatments good mechanical properties are reached, similar to many T6 conditions. In this case, higher aging temperature and time lead to a decrease of the mechanical properties, probably due to an overaging.
  - o The average values ranged from 271 MPa, 303 MPa and 8% to 372 MPa, 386 MPa and 16% for yield strength, stress at break and elongation percentage respectively.

Finally, it can be concluded that the output of these experiments constitutes a useful database of the properties of EN AW 6082 alloy in the considered range of data. This information can be used for the designing of different structural components where either an optimization of the elongation or a maximum yield strength could be required depending on the specific application. The results also suggest that for many applications a T5 heat treatment, with high mechanical properties, a lower thickness of recrystalized area and a reduced cost, could be a good option.

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