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ADAPTATION OF ALUMINIUM FOAM PROPERTIES BY MEANS OF PRECIPITATION HARDENING

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Abstract – Aluminium foam samples based on four aluminium alloys were investigated with respect to their reaction to heat treatments, namely precipitation hardening treatments. Foam samples were produced according to the powder compact foaming or Fraunhofer process. 6XXX and 7XXX series alloys containing significant amounts of copper (6061, 7075) were compared to members of the same group with lower copper content (6082, 7020) as matrix alloys. Comparison was based on strength values and failure modes as reflected in the stress-strain curves obtained in quasi-static compression tests. Measurements were performed on samples without heat treatment and samples subjected to different precipitation hardening treatments. To evaluate the influence of quench sensitivity, the quench rate was varied for the alloys 6082 and 7020 by using air and water as quenchants.

Keywords - Aluminium; Foam; Heat treatment; Processing

1 INTRODUCTION

The unique combination of properties metal foams possess has generally been acknowledged in the past few years since these materials gained wide interest. It has led to a considerable number and variety of potential applications being evaluated [1,2]. Nevertheless, until today, metal foam technology has not been upscaled from laboratory to industrial production level. This is partly due to a lack of knowledge regarding the exact properties and potentials within the broad scope of materials designated as metal foams. Of these, aluminium foams produced according to the powder compact foaming or Fraunhofer process are at the focal point of this investigation. It has been shown before that much of the existing knowledge about the heat treatment of certain aluminium alloys can be transferred to such foams using the respective alloy as matrix material. Thus a powerful handle exists for adjusting aluminium foam properties to the requirements of a certain application. What is even more important, this approach is independent of the density, the use of which to control mechanical properties must necessarily counteract the need for even lighter structures.

Heat treatment of metal foams has already been covered in a number of publications. Most studies focus on AlMgSi type alloys, both as wrought (6XXX series) and as casting alloys. In some cases, wrought alloys of the AlZnMgCu (7XXX series) and the AlCu type (2XXX series) as well as casting alloys of the AlSiCu family have been investigated. Mechanical behaviour is usually evaluated on the basis of compression tests. Tension tests may add to the results gained from the former, and in some studies, fatigue tests have also been performed.

Of common interest in these investigations is the cellular structure's influence on all aspects of the heat treatment. Heat treatment in this case means precipitation hardening, a treatment including a solution heat treatment as a first step, followed by rapid quenching and natural (cold) or artificial (warm) ageing. A typical feature of this heat treatment type is the need to achieve a rapid change of temperature throughout a component, in this specific case during quenching from solution heat treatment temperature. It has been suggested that the heterogeneity of the structure, typical aspects like the nearly pore-free outer skin and the much lower density in the central region etc. may cause a certain variation of material conditions achieved over a part's cross section. Hardness measurements along the radius of cylindrical samples could not confirm this assumption in an earlier study [3]. However, rapid

quenching does cause other problems, some of them associated to the need to use quenchants other than air. This practice carries the risk of introducing e.g. water into the pore structure of the component or sample. Therefore it is the aim of the current study, to investigate the suitability of certain alloys with lower quench sensitivity for foaming as well as for the subsequent heat treatment. The focus is on wrought alloys, and two groups of these have been selected, namely the 6XXX (AlMgSi) and the 7XXX (AlZnMg) series.

6XXX alloys are chosen whenever heat-treatable alloys combining medium strength with good corrosion resistance, reasonable weldability and moderate cost are required. The 7XXX series comprises alloys characterised by the highest strength levels to be found in aluminium alloys. These are alloys of the AlZnMgCu group commonly used in aerospace applications. In contrast, those of the AlZnMg type combine lower strength with improved corrosion resistance and weldability. Their applications lie in more down-to-earth fields like the automotive [4].

Within both groups, some alloys derive extra strength from an increased copper content. Examples are AlMg1SiCu (6061) and AlZn5,5MgCu (7075). In both alloys, the higher Cu level serves to increase strength in T6 or T7 states, but raises quench sensitivity in parallel. This effect together with consideration of e.g. corrosion resistance has led to the development of alloys with reduced copper content. Of these, AlSi1MgMn (6082) and AlZn4.5Mg1 (7020) have been chosen for a comparison with 6061 and 7075. The assumed lower quench sensitivity of the latter two alloys is evaluated by comparison of strength levels achieved using air and water as quenchants. An indication of the two alloys general potential with respect to heat treatment is derived from the assessment of these strength values in contrast to those determined for 6061 and 7075 foam. Furthermore, failure modes and energy absorption capability are considered.

2 HEAT TREATMENT OF 6XXX AND 7XXX SERIES ALLOYS AND FOAMS

2.1 General considerations

In 6XXX alloys, Si and Mg serve as main alloying elements, whereas 7XXX alloys contain Zn and Mg. Among the secondary alloying elements, if present, it is Cu that takes a prominent role as described above. During precipitation hardening, solution heat treatment (SHT) and quenching lead to a supersaturated solid solution

of the alloying elements. During ageing, precipitates are formed in fine dispersion within the supersaturated regions. Depending on the alloy, these are mainly of Mg_2Si or $MgZn_2$ type respectively [4,5]. In a critical temperature range between 400 and 290°C, the cooling rate needed to suppress premature formation of such precipitates and achieve maximum strength is said to be in an order of magnitude 100 K/s for 6061. For 7075, it is even higher at approximately 300 K/s [4]. To achieve such rates, water quenching is obligatory. Lower rates tend to result in a higher fraction of grain boundary precipitates having detrimental effects on toughness, though not in all cases on strength [6].

Some typical problems which may be encountered during heat treatment of aluminium foams have been mentioned above. More are listed in [3], and as far as they are concerned with effects caused by the use of water as medium for quenching, it is the aim of this study to show ways to overcome them. Not covered in former examinations was the question whether the specific microstructure of a foam allows the direct transfer of heat treatment parameters from solid material to foam. For this reason, samples of the two alloys 6082 and 7020 without blowing agent have been produced which reflect the microstructure of the precursor material and, after having been melted, the foam itself. These were used to analyse the influence of ageing time on the strength of the matrix.

3 SAMPLE PREPARATION AND CHARACTERISATION

Two kinds of samples were manufactured: Unfoamed reference samples for studying heat treatment procedures without having to deal with the specific difficulties associated with foams and, as the actual subject of the study, foams.

3.1 Preparation of unfoamed reference samples

3.1.1 Selection of starting materials

From the alloys 6082 and 7020, powder compacts were produced without blowing agent in order to establish heat treatment parameters for the corresponding foam samples. Dimensions of the compacts were 30 diameter and approximately 15 mm height, resulting in a weight between 28 and 30g. The composition of these samples and the powders used are exactly the same as those for the foam samples. Combinations of elementary and pre-alloyed powders were used. The Al content was

partly based on the use of Al99.7 powder (Eckart), partly on the appropriate amount of pre-alloyed AlMg5 powder supplied by Mepura, which was used to adjust the Mg content. Other alloying elements were added as elementary powders, including Si (Oelschläger), Zn (Heraeus), Cu (Chempur), Fe (Johnson Mattey) and Mn (Chempur). Consolidation to a compact material with more than 99 % of the theoretical density was achieved by means of uniaxial hot pressing. Two powder compacts were produced from each alloy. One of these was melted and solidified to create a microstructure similar to that of a foam.

3.1.2 Heat treatment

To evaluate suitable heat treatment parameters for the alloys 6082 and 7020, the powder compacts without blowing agent were subjected to a precipitation hardening treatment. Two quench methods were compared for 6082, namely air and water quenching, while for 7020, only air quenching was examined. Solution heat treatment was done at 530°C for alloy 6082 and 473°C for alloy 7020, in both cases for 100 minutes. 6082 compacts were subjected to a one-step ageing treatment at 165°C. For 7020 compacts, a two-step ageing treatment was chosen: The first step with a duration of 10 hours at 95°C, the second step at 150°C. The ageing treatment was interrupted in regular intervals to carry out hardness measurements. When longer interruptions became necessary, the specimens were stored at a temperature of –20°C. Heat treatments were stopped after 27,5 hours for water-quenched 6082, 48,5 hours for air-quenched 6082 and 44,7 hours altogether for 7020. The latter value includes both ageing steps.

3.2 Preparation of aluminium foams

3.2.1 Selection of starting materials

For all the foamable precursor material used in the course of this study, 0.6 wt.% titanium hydride powder (Chemetall, Hanau [8]) where chosen as a blowing agent. Preparation of the precursor material of alloy 6061 was based on pre-alloyed powder (<160 μm) purchased from Mepura (Ranshofen, Austria). The powder mix was first consolidated by cold isostatic pressing, followed by hot extrusion[8][9] to long rectangular rods.

For the alloys 6082 and 7020, the procedures for production of the precursor material are the same as for the unfoamed powder compacts (see 3.1.1), the only exception being the addition of the blowing agent. Similar combinations of

elementary and pre-alloyed powders as for 6082 and 7020 were used for alloy 7075. Mg was again added as pre-alloyed AlMg5 powder, supplemented by Cu (Chempur) and Zn (Heraeus) as elementary powders. Consolidation to a foamable precursor material was achieved by means of uniaxial hot pressing.

Table 2 gives the composition of the different precursor materials. For 6082, 7020, 7075, the data is derived from the nominal compositions given by the powder manufacturer, for 6061, it was actually measured using atomic emission spectroscopy (AES).

3.2.2 Foaming

For producing foam specimens a piece of foamable precursor material was inserted into a cylindrical steel mould. Foaming was carried out in a batch furnace with indirect conductive heating and atmosphere circulation at temperatures between 730°C and 750°C. During foaming the mould stood upright as shown in Figure 1 to reduce the influence of transverse drainage. To stabilise the porous structure after foaming, cooling with pressurised air was used.

After removal from the mould cylindrical foam specimens were obtained with approximately 44,2 mm diameter, 60 mm height, and an overall foam density of 0.60 ± 0.05 g/cm^3 for the alloys 6061 and 7075. For the alloys 6082 and 7020, a slightly smaller mould was used giving samples of 50 mm height and densities of 0.58 ± 0.05 g/cm^3. Of these, top and bottom faces were cut off prior to mechanical testing to give a height of 40 mm. As a consequence, sample density changed considerably to 0.51 ± 0.06 g/cm^3.

Except for 6082 and 7020 top and bottom faces, all samples retained the closed outer skin formed during foaming, as this feature will be present in future components, too. Due to drainage effects during foaming, specimens exhibit a slight vertical density gradient.

3.2.3 Heat treatment

An overview of all heat treatments performed and the resulting sample types is given in **Table 2**. After solution heat treatment warm ageing was generally retarded for 3 days to simulate similar delays common in many industrial processes. Heat treatment was carried out in a furnace of the same type as the one used for foaming. The adherence to the required temperatures was tested by measuring sample

temperatures with two thermocouples inserted into two small holes drilled into the specimen.

Solution heat treatment parameters as well as ageing temperatures for all samples were selected from the relevant literature. Also based on literature values are the ageing times for the alloys 6061 and 7075. In contrast to this, the duration of the second ageing step for 7020 and the total ageing time for 6082 were determined according to the results of hardness measurements on the powder compacts (see 3.3 and 4).

The various possible combinations of matrix alloy and heat treatment procedures (including the possibility of omitting the solution heat treatment to test direct ageing) gave rise to a total of thirteen distinct temperature cycles.

3.3 Characterisation programme

3.3.1 Hardness measurements

Vickers hardness with a load of 300 g and a loading time of 20 seconds (HV 0.3) was measured at various locations on the powder compacts, in an as pressed as well as a melted and solidified state. The measurements were aimed at establishing heat treatment parameters for the alloys 6082 and 7020 as described above. The variable during the measurements was warm ageing time. For each time, 7 hardness values were measured. In order to achieve a satisfactory time resolution even over longer ageing times, treatments were interrupted overnight and the samples stored at –20°C.

3.3.2 Compression tests

Quasi-static compression tests were carried out on Zwick testing machines, models 1474 and 1476, at room temperature and at a constant strain rate of 5 mm/min. For each heat treatment state 4 different specimens were tested. Compression was stopped whenever either 80% strain or 95 kN force (equivalent to 61.9 MPa) were reached.

4 RESULTS AND DISCUSSION

4.1 Hardness Mesurement

The results of the hardness measurements on 6082 and 7020 powder compacts are displayed in Figure 2. All alloys have in common that the melted and solidified specimens are characterised by higher hardness. An incomplete compaction and

sintering, which is healed during melting and solidifying the material is a possible explanation. However, since density measurements of the compacts show that theoretical density is almost reached, such effects must be considered to be of secondary importance. Dominating is the fact that in both cases, except for the AlMg5 powder giving the Mg content, all powders used are of elementary type. Thus the main effect of the melting is the actual formation of an alloy. For the further discussion, only the melted and solidified powder compacts will be considered as they reflect the metallurgical state of the foams.

The curves for air- and water-quenched 6082 show a notable difference in hardness levels. A reduced quench-sensitivity is not visible in these measurements. The increase in hardness is approximately 59.2 % for air-quenched 6082, but 84.4 % for water-quenched 6082 compacts. In air quenched 7020, hardness increases by 82.0 %. All values are based on comparison with values describing the material's condition prior to the solution heat treatment.

Maxima of the curves are detected after approximately 10 hours for 6082 and 18 hours of the second ageing step (28 hours including the first at 95°C) for 7020. They are rather shallow, which leads to the conclusion that the danger of over-ageing is reasonably small. When comparing air- and water-quenched 6082, it is noteworthy that the time at which the maximum is reached is the same in both instances.

4.2 Compression behaviour

4.2.1 Stress-strain curves

Figure 3 displays average stress-strain curves for all specimen types tested, each of them based on 4 compression tests. At a first glance, it is obvious that the great majority of samples fails according to what is generally known as the brittle failure mode. Typical for this behaviour are the occurrence of a stress peak if specimens are strained beyond the elastic regime, followed by a corresponding drop in stress. The plateau region identifiable in such foams tends to decline until a certain level of compaction is reached and the pores have collapsed. Such deformation modes are usually associated with casting alloys. Among wrought alloys, they are commonly known only in precipitation hardened states, whereas untreated foams normally exhibit a ductile deformation mode characterised by a smooth and constantly rising stress-strain curve [10-12]. Failure is controlled by bending rather than breaking of cell walls and struts. As strength is density-dependent, a specimen with slightly

inhomogeneous density distribution will first be deformed in the section with lowest density ("weakest link") [11]. With this region being simultaneously compressed to higher densities and strain-hardened, a new deformation band will soon develop and take its place [13]. In contrast to this, brittle failure does not necessarily start at a weakest link. Cracks created by thermal stresses induced during production of the foam or heat treatment may become starting points for failure of the structure as a whole. Strain-hardening effects will not occur. The 6061 specimens in the untreated condition and to a slightly lesser degree the 6082 specimens in the same state are the only ones within this study which clearly react in a ductile manner to the load they are subjected to. All other specimens, even states "as foamed" of the alloys 7075 and 7020, fail according to a brittle mode. The reason for this phenomenon has to be sought in further investigations of the samples and especially their microstructure. At this stage of the investigation, a certain division between the two groups of alloys, 6XXX series on the one hand and 7XXX series on the other hand may be noted. Whether this is caused by the altogether higher content of alloying elements in the 7XXX series or else the effect of specific alloying elements on matrix properties or foaming behaviour can not yet be decided.

4.2.2 Strength

Figure 4 depicts the strength levels achieved with the various heat treatments and matrix alloys. From the different strength definition commonly used to describe metal foams, two have been selected in this case. Initial peak stress values (UYS) have been used for all curves where such peaks can be distinguished. If this was not possible, as in the case of 6061, the strength level at 5 % total deformation has been chosen. A direct comparison of strength values should be performed only having in mind that sample geometry and initial density was slightly different. The latter would account for a strength variation with an order of magnitude of 7 % in favour of 6061 and 7075. The effect of the former is more difficult to judge: It is to be expected that cutting off the top and bottom surfaces will have a weakening effect on 6082 and 7020 specimen, although one could argue that if a "weakest link" as introduced above has the central role in failure, this effect may be limited - at least with respect to strength values. However, if cutting off top and bottom surface means that what is thus isolated and actually tested is the region of preferred deformation of the original sample, there may also be an influence on the shape of stress-strain curves: In the

non-cut sample, both top and bottom surfaces may act as solid layers of metal with certain but unknown thickness, between which a weaker foam is compressed. While being compressed to a lesser degree themselves, they would still contribute to the calculated total deformation of the sample. The effect would be a shift of the measured stress levels to lower apparent deformation levels than did actually occur between the surface layers. Any such effect is most probably in favour of the 6061 and 7075 specimens and thus magnifies the consequences of the density variation.

In all cases examined, the highest increase in strength is achieved by precipitation hardening treatments including water quenching. The highest susceptibility to precipitation hardening is thus found for 6061, with an increase in strength from 11.72 MPa to 20.42 MPa , equivalent to +74.2 %. Following are 7075 (+63.3 %), 6082 (+51.4 %) and 7020 (+26.3 %). This finding is supported by the shape of the stress strain curves as displayed in Figure 3. The decreasing tendency of the plateau stress level is nowhere else as strong as in the water-quenched 6061 specimen. This is another hint towards a very brittle failure. A similar tendency is visible for the same condition of alloy 7075.

It is noteworthy that the increase in compressive strength achieved via heat treatments does not always reflect the increase in hardness exactly as discussed in chapter 3 and **Figure 2**: For air quenched 6082, the increase in hardness is approximately +59.2 %, compared to +49.3 % when looking at the compressive strength. For water quenched 6082 and air quenched 7020, hardness changes by +84.4 % and +51.4 % as opposed to +82.0 % and +20.8 %. The agreement is good for 6082, whereas 7020 does not seem to show a direct correlation between the increase in hardness and strength. This shows once more that it is problematic to derive foam properties from the properties of the matrix alloy. Processing of foams is such a complex process that mechanisms changing the metallurgical state of the material cannot be ruled out.

Recalling that one of the reasons for testing 6082 and 7020 alloys was to reduce quench sensitivity we have to conclude that this point has not become clear. While the 6082 reference samples unexpectedly showed a large difference between water and air quenching, this effect is absent in 6082 foams. In contrast, the 7020 foams quench sensitivity even when the standard deviations associated with the measurement are taken into account.

4.2.3 Energy Absorption

In addition to strength values, Figure 4 gives values for the energy absorption efficieny of the different specimen types. The property is defined by the following expression:

$$\eta(\varepsilon) = \frac{\int_0^{\varepsilon} \sigma(\varepsilon') \cdot d\varepsilon'}{\max \sigma(\varepsilon)\big|_0^{\varepsilon} \cdot \varepsilon}. \qquad (1)$$

From this definition it is obvious that both brittle and ductile failure modes have certain deficiencies regarding optimum energy absorption properties – the ideal would be a horizontal plateau region, and neither the rising one of the ductile foams nor the declining one of the brittle ones conforms to this description. The conclusion must be that under these very specific load conditions, an intermediate state showing aspects of both types is preferable, a state which may often be achieved by means of direct ageing without prior solution heat treatment.

As characteristic values taken from the curves depicting energy absorption efficiency, the maximum efficiency and the efficiency at 50 % strain have been selected. For three of the alloys compared here, namely 6061, 6082 and 7020, direct ageing treatments have been included in the test series, omitting the solution heat treatment step. For all of these alloys, it is this treatment which results in greatest values both of the maximum energy absorption and the energy absorption at 50 %. The worst performance with respect to energy absorption is associated with the material's conditions combining highest strength with brittle failure modes, 7075 and 6061 in the precipitation hardened and water-quenched state.

5 SUMMARY

The experiments have documented the potential of heat treatments for customising the properties of aluminium foams. In all cases investigated, precipitation hardening treatments lead to a considerable rise in strength. This rise was most pronounced in the alloys 6061 and 7075, with the latter showing the highest strength levels of all alloys in the study. Strength was lower in 6082 and 7020 foams, which conforms well with the general observation that the former alloys, but especially 7075 in comparison to 7020, gain extra strength from their Cu contents. Quench sensitivity is not eliminated for the copper-free alloys. However, the results obtained for 6082 clearly hint at a possibility to avoid water quenching,

which might have deteriorating effects on the cell structure. With respect to adapting a foam for energy absorption requirements, the study has confirmed the promise of direct ageing for this purpose.

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FIGURE CAPTIONS

Figure 1. Precursor material AlMg1SiCu (6061), mould and aluminium foam cylinder.

Figure 2. Hardness measurements performed on hot pressed samples, comparison between as pressed and melted material for a) air quenched 6082, b) water quenched 6082 and c) air quenched 7020.

Figure 3. Stress-strain-curves obtained in compression tests for a) 6061 (density 0.6 g/cm^3), b) 6082 (density 0.58 g/cm^3), c) 7075 (density 0.6 g/cm^3) and d) 7020 samples (density 0.58 g/cm^3).

Figure 4. Strength values and efficiency of energy absorption achieved for the different alloys and heat treatment conditions, namely a) 6061 (density 0.6 g/cm^3) and 6082 (density 0.58 g/cm^3), b) 7075 (density 0.6 g/cm^3) and 7020 (density 0.58 g/cm^3).

TABLES

Element		Mg	Si	Cu	Fe	Mn	Cr	Ni	Zn	V	Ti
6061	[wt.%]	0.85	0.58	0.20	0.18	0.002	0.001	0.001	0.011	0.017	0.69
6082	[wt.%]	1.0	1.1	0.1	0.5	0.8	-	-	0.2	-	0.6 TiH_2
7075	[wt.%]	2.25	-	1.55	-	-	-	-	5.5	-	0.6 TiH_2
7020	[wt.%]	1.3	0.35	0.2	0.4	0.35	-	-	4.5	-	0.6 TiH2

Table 1. Composition of foamable precursor materials: Measured by AES for alloy 6061, nominal composition according to manufacturer specification for alloys 6082, 7020 and 7075.

	Solution heat treatment			Warm ageing		Sample designation
	T_s [°C]	t_s [min]	quench medium	T_a [°C]	t_a [h]	
6061	-	-	-	-	-	**6061-1** / 6061 as foamed
	-	-	-	165	10	**6061-2** / 6061 direct ageing
	530	100	water	165	10	**6061-4** / 6061 water quench
6082	-	-	-	-	-	**6082-1** / 6082 as foamed
	-	-	-	165	10	**6082-2** / 6082 direct ageing
	530	100	air	165	10	**6082-3** / 6082 air quench
	530	100	water	165	10	**6082-4** / 6082 water quench
7075	-	-	-	-	-	**7075-1** / 7075 as foamed
	480	100	water	120	24	**7075-4** / 7075 water quench
7020	-	-	-	-	-	**7020-1** / 7020 as foamed
	-	-	-	95/150	10/18	**7020-2** / 7020 direct ageing
	473	100	air	95/150	10/18	**7020-3** / 7020 air quench
	473	100	water	95/150	10/18	**7020-4** / 7020 water quench

Table 2. Overview showing the different sample types and parameters used for their heat treatment, including solution heat treatment and age-hardening of 6061, 6082, 7075 and 7020 alloys.

FIGURES

Figure 1

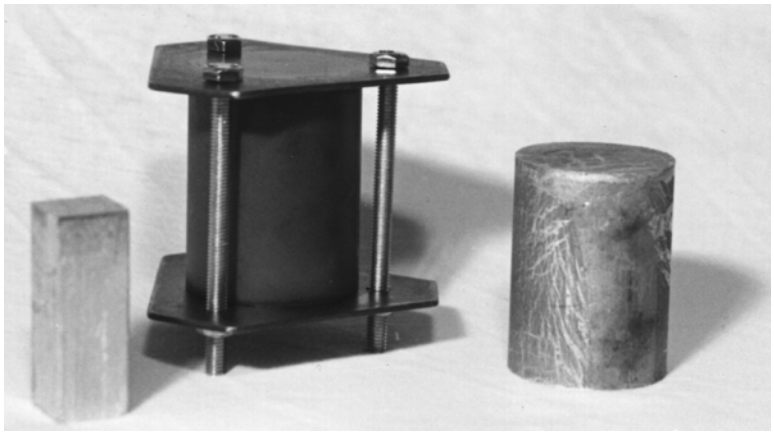


Figure 2

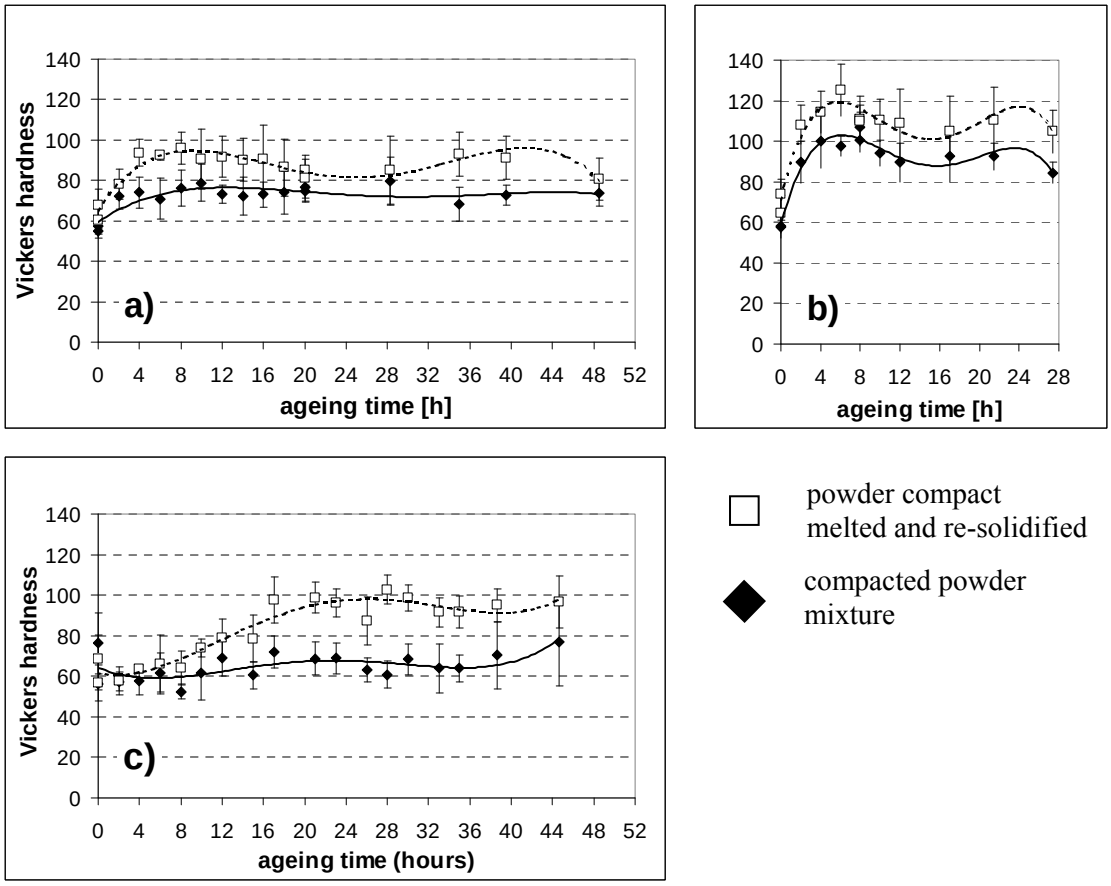

Vickers hardness
a)
ageing time [h]
b)
ageing time [h]
c)
ageing time (hours)
powder compact melted and re-solidified
compacted powder mixture

Figure 3

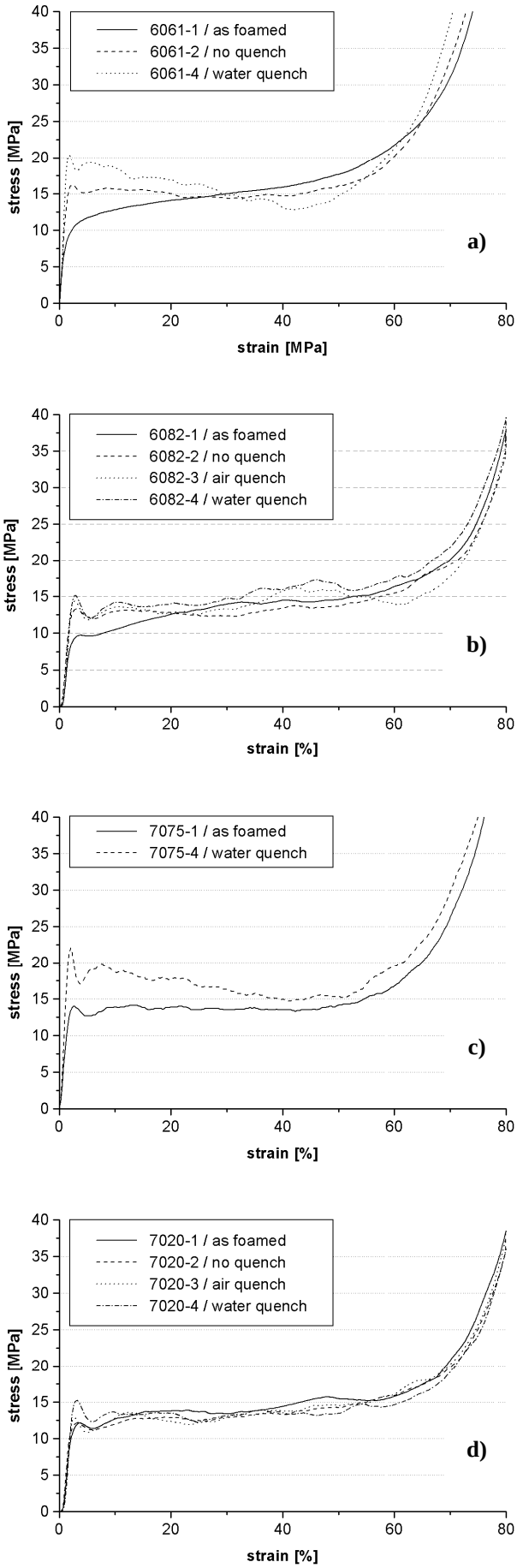
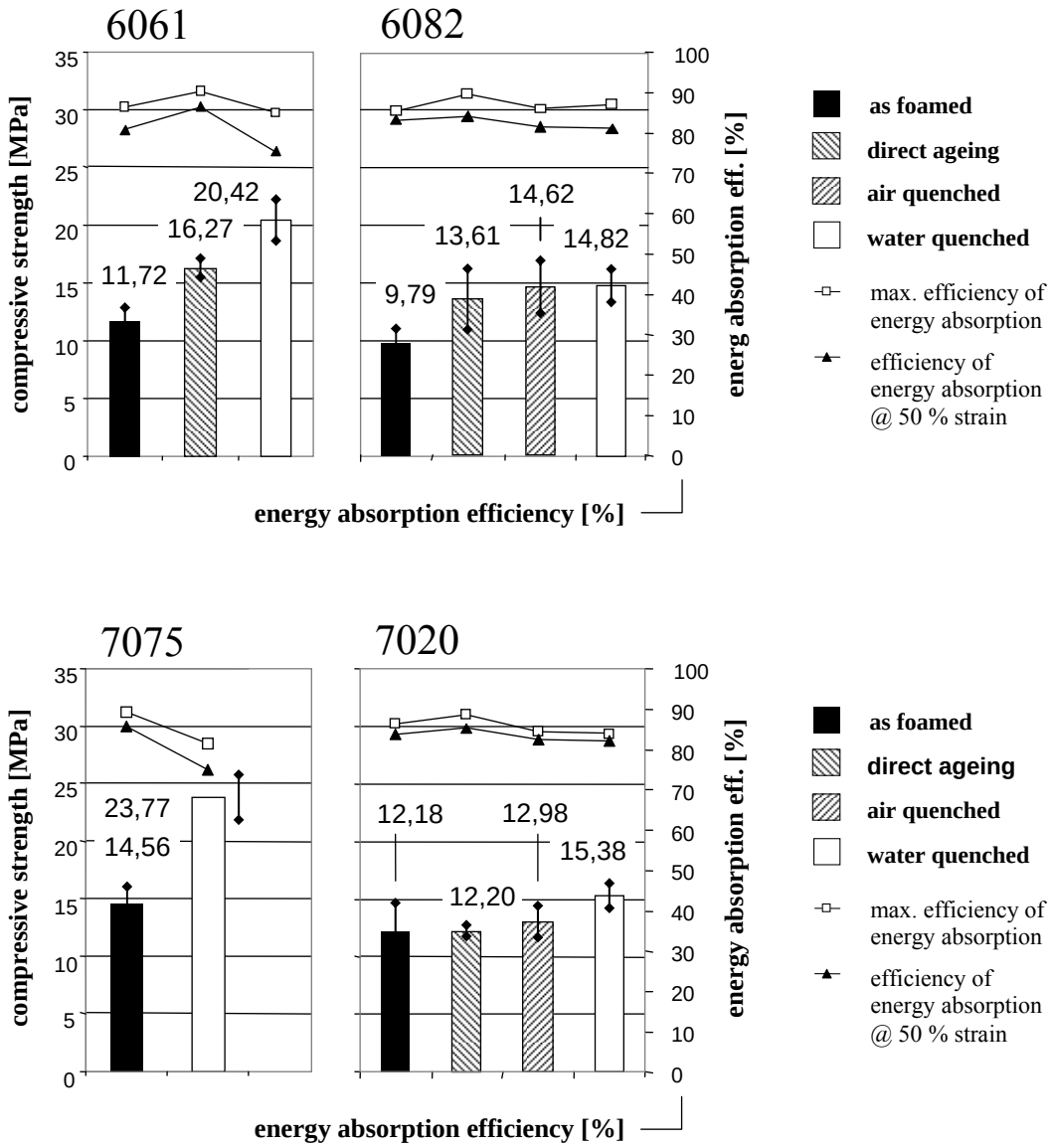

6061-1 / as foamed
6061-2 / no quench
6061-4 / water quench
stress [MPa]
strain [MPa]
a)
6082-1 / as foamed
6082-2 / no quench
6082-3 / air quench
6082-4 / water quench
stress [MPa]
strain [%]
b)
7075-1 / as foamed
7075-4 / water quench
stress [MPa]
strain [%]
c)
7020-1 / as foamed
7020-2 / no quench
7020-3 / air quench
7020-4 / water quench
stress [MPa]
strain [%]
d)

Figure 4


6061
6082
7075
7020
compressive strength [MPa]
energ absorption eff. [%]
energy absorption efficiency [%]
11,72
16,27
20,42
9,79
13,61
14,62
14,82
23,77
14,56
12,18
12,98
15,38
12,20
as foamed
direct ageing
air quenched
water quenched
max. efficiency of energy absorption
efficiency of energy absorption @ 50 % strain