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Distortion Behaviour and Mechanical Properties of Age Hardening Aluminium Alloys after High-Pressure Gas Quenching in Comparison to Liquid Quenching

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Abstract

The quenching process after solution annealing of age hardenable aluminium alloys is necessary for an improvement of the mechanical properties, but also tends to result in distortion, especially in thin or complex shaped parts, and requires a costly reworking. High-pressure gas quenching can reduce distortion compared to liquid quenching, because of the better temperature uniformity during quenching. A determination of the distortion behaviour of different serial parts of the aluminium wrought alloy 2024cl (AlCu4Mg1,clad) points out, that high-pressure gas quenching offers predominantly excellent values regarding the dimensional accuracy after quenching compared to liquid quenchants. In comparison to the conventional heat treatment similar values in strength, hardness and electrical conductivity have been determined after gas quenching and aging of different aluminium alloys (2024, 6013, and 7075).

1. Introduction

A supersaturated solution of alloying elements in the aluminium matrix is a necessary requirement for the formation of fine intermetallic precipitates during aging, which improve the mechanical properties of age hardenable aluminium alloys. Many of these alloys require high quenching rates (predominantly realised in water or water-glycol quenchants) to avoid a premature precipitation of coarse particles at the grain boundaries. During liquid quenching the Leidenfrost Phenomenon occurs: the formation and collapse of a vapour blanket around the part [1]. This non-uniform cooling can cause strong distortion, especially in thin or complex shaped parts (sheet, castings or forgings), and makes a costly reworking necessary [2].

During high-pressure gas quenching, the parts are passed by a cooling gas instead of a liquid medium. The better temperature uniformity provides an opportunity to manufacture parts with only slight distortion, because the Leidenfrost Phenomenon is not present. This could reduce the costs for reworking or scrap. Furthermore, by variation of the gas pressure, gas velocity or the gas itself, a well directed manipulation of the cooling rate is possible [3]. In this way, the cooling rate can be influenced to produce on hand the desired microstructure and mechanical properties. On the other hand, cooling should be as slow as possible to reduce distortion and residual stresses of the part. In consideration of both requirements a potential to reduce distortion exists by using high-pressure gas quenching.

The determination of mechanical properties of the aluminium alloys 2024-T4, 6013-T6 and 7075-T73 has already confirmed, that it is possible to obtain a sufficient strength up to a thickness of several millimetres after gas quenching with helium at 16 bar. For thin sheets (3 mm) nearly similar mechanical properties could be achieved irrespective of gas quenching and aging or water quenching and aging [4-6]. Further, a comparison of the distortion behaviour after gas quenching and after a conventional water-glycol quenching should indicate whether or not high-pressure gas quenching results in less distortion.

2. Experimental procedure

According to Figure 1 and Figure 2, two different types of formed parts made of 2024cl sheet material have been used for the determination of the distortion. To determine the permanent deformation caused by the solution heat treatment and the following quenching step, certain characteristics of the parts have been measured with the help of a coordinate measuring system before and after the heat treatment processes. From defined line-scans as shown in Figure 1 and Figure 2, it was possible to calculate certain angles of the parts (e.g. angle 2/8 of part 1). The grouping of multiple line-scans which lay in one plane, has enabled to calculate a form value (flatness) for the relevant planes, (e.g. lines 1,2,3,10,11 and 14 for plane “a” of part 1 and lines 1,2,3,7 and 8 for plane “b” of part 2). The distortion originated from the heat treatment could be calculated from the differences of these values before and after the heat treatments. To obtain a statistical average of the distortion behaviour, the parts were subjected to different heat treating methods in batches. The quantity of these batches is listed in Table 1.

Table 1: Number of treated parts for statistical coverage.

	Quantity of parts	
	Water-Glycol	Nitrogen 10 bar
Part 1	5	5
Part 2	7	8

The forming process of the parts was carried out in the soft annealed state, because a direct forming in the T4 state is not possible. After press forming the solution heat treatment with water-glycol quenching or high-pressure gas quenching and aging at room temperature followed.

The electrical conductivity and the Webster hardness testing are common measuring methods of the quality control in the aircraft industry. Therefore, these values have been determined after the different quenching methods according to the standards ASTM-B647-84 for the electrical conductivity and ASTM-E1004-02 for the Webster hardness and were compared with the required values.

2.1 High-Pressure Gas Quenching

Solution annealing and high-pressure gas quenching were realized in a double-chamber vacuum furnace type IPSEN RVTC-600x400x400 (Figure 3). The system is equipped with a heating chamber (1) and a separated “cold” cooling chamber (2). Compared to single-chamber systems, higher cooling rates are possible, because quenching takes place in a chamber with ambient temperature. Thus, it is not necessary to cool the chamber together with the batch.

After solution annealing at 495°C for 25 minutes and opening of the doors between the chambers (3), the batch is transported into the cold chamber. The chamber is filled with the cooling gas (Nitrogen / 10 bar) and the gas is continuously recirculating through the chamber and a heat exchanger (4) by a fan (5). Both, parts 1 and parts 2 were hung-up inside the furnace. This means for parts 1, that the gas flow was parallel to its three planes. For parts 2, the gas flow was parallel to two planes, but perpendicular to the third plane (lines 9,10; Figure 2)

3. Results and Discussion

Former investigations regarding the mechanical properties have already shown, that it is possible to achieve the required minimum values for different aluminium alloys after high-pressure gas quenching with helium at 16 bar. Nitrogen does not offer the same quenching capabilities as helium at the same pressure, but it is considerably cheaper. A comparison of the mechanical properties of the wrought alloys 2024cl-T42, 6013-T6 and 7075-T73 according to Table 2 shows, that the mechanical properties after high-pressure gas quenching with nitrogen at 10 bar also exceed the specified minimum values [7-9].

Table 2: Mechanical properties after water- resp. gas quenching with nitrogen 10 bar for different wrought alloys in comparison with specified minimum values [7-9]

	Thickness [mm]	Water			Nitrogen 10 bar			Minimum values		
		$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]
2024cl-T42	1,6	305±5	449±4	16±0,7	294±2	452±2	16±0,5	262	420	15
6013-T6	3,0	389±2	412±1	14±1,5	370±2	406±1	14±0,4	317	359	8
7075-T73	3,0	450±2	528±2	13±1,3	421±3	497±3	11±0,5	386	462	8

In comparison with conventional water quenching, no significant differences can be observed for the alloys 2024cl-T42 (thickness 1,6 mm) and 6013-T6 (thickness 3 mm) . Solely for 7075-T73 (thickness 3 mm) the mechanical properties after gas quenching are approximately 30 MPa below the comparable values after water quenching, but still higher than the required values.

The Webster hardness and the electrical conductivity were measured after water-glycol or gas quenching at three parts of each batch according to Tab. 3.

Table 3: Webster hardness and electrical conductivity after water-glycol resp. gas quenching

	Webster Hardness		Electrical Conductivity [MS/m]	
	Water-Glycol	Nitrogen 10 bar	Water-Glycol	Nitrogen 10 bar
Part 1	13,8 ±0,3	14,3 ±0,6	19,81 ±0,05	19,92 ±0,07
Part 2	15,3 ±0,6	16,0 ±0,0	19,19 ±0,05	19,20 ±0,03
Required	14,5-18,0		16,5-21,5	

After gas resp. liquid quenching and naturally aging, the Webster hardness of 2024cl in the T42 temper is slightly below (part 1) or inside (part 2) the specification. The electrical conductivity of both batches is also situated inside the specification.

Therefore both gas quenched batches would pass the quality control regarding the values for Webster hardness and electrical conductivity.

The changes in flatness of plane “a” (Part 1) are shown in Figure 4. The parts after water-glycol quenching show flatness changes of 0,05 ±0,15 mm. After gas quenching with nitrogen at 10 bar flatness changes of –0,05 ±0,05 mm occurred. This indicates, that a more homogenous distortion of the gas quenched batch can be achieved, because the determined scatter band is lower. A lower scattering of distortion is more important than a lower average of distortion. A certain average of distortion can be compensated by suitable process steps before or after the heat treatment, if the scattering is low, whereas a high scattering of distortion complicates the compensation.

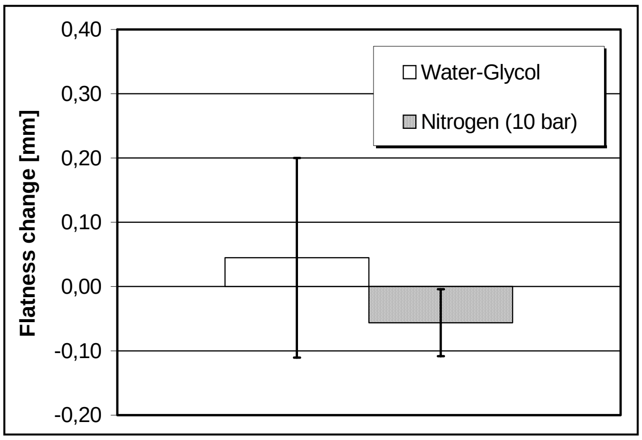

Figure 4: Flatness change of plane “a” after quenching (Part 1).

The change in bending angles of part 1 is shown in Figure 5. The standard deviation for the different measured angles is significantly higher for the water-glycol quenched batch, than for the gas quenched batch. For the changes in bending angles of the gas quenched parts almost negligible deviations of ±0,04° can be observed. In case of water-glycol quenching especially the angles which are spanned by the line scans 1/4, 2/5 and 3/6 feature high scattering. Under the assumption that close tolerance bands are required for the bending angles, reworking operations for the water-glycol quenched parts would be necessary. The narrow scatter bands after gas quenching allow a prediction of the change in bending angles during heat treatment. This would offer the possibility of an aimed control of the bending angles especially for serial parts, by an adaptation of the bending angles in the corresponding forming tool.

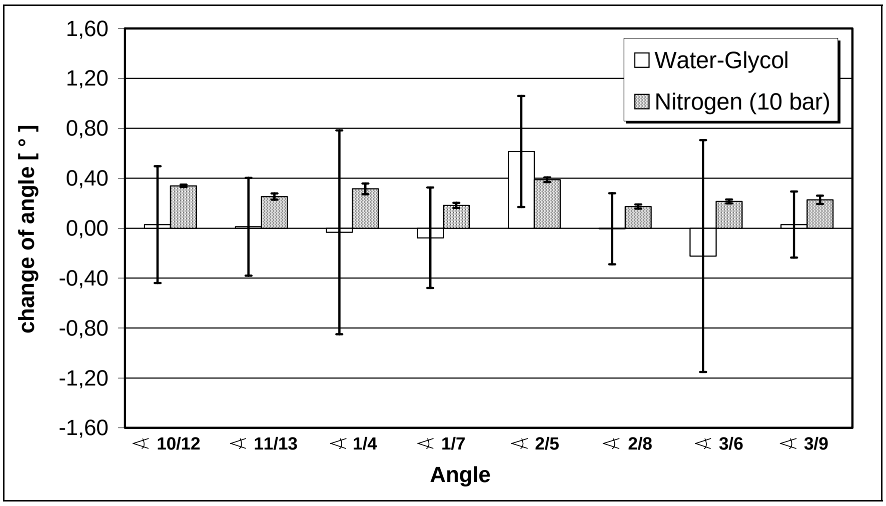

Figure 5: Change of angles of part 1 after quenching.

The change in bending angles of part 2 are pictured in Figure 6. The angles of the long leg (angles 1/4, 2/5 and 3/6) show lower scatter bands for gas quenching compared to liquid quenching.

But in case of the angles 7/9 and 8/10, remarkably high scatter bands in the same magnitude as after water-glycol quenching were observed after high-pressure gas quenching. It is assumed, that this was caused by the gas flow direction regarding this leg.

The gas flow during quenching was directed perpendicular to this leg so that an unhindered flow was not given around the whole part. For this reason the leg can be considered as a flow resistance and the inevitable applied force of the gas flow may cause the higher scatter bands of these bending angles.

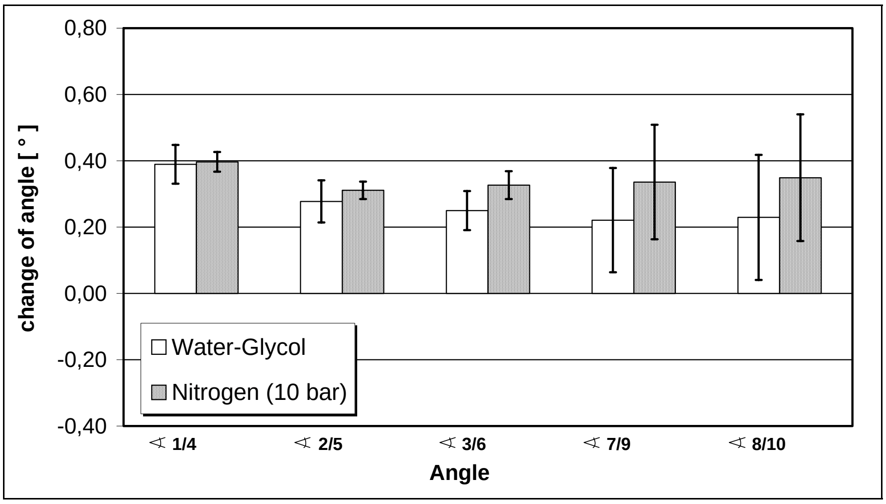

Figure 6: Change of angles of part 2 after quenching.

It has to be pointed out, that the heat treatment is not the sole reason for the appearance of distortion. The quenching process is certainly one important factor for distortion, especially in case of an inhomogeneous cooling of a part. In fact, it is necessary to consider all manufacturing steps prior to the heat treatment regarding the potential to cause distortion. The hardening process itself also releases the distortion potential which is accumulated in the workpiece along a series of operations building the overall manufacturing process. Therefore, the chemical composition, the microstructure, the component geometry and the residual stress distribution can be classified as a carrier of distortion potential [10-11].

In case of the investigated parts, residual stresses occur as a result of the forming process in the deformed regions of the parts. If the residual stresses exceed the low yield strength during solution annealing, distortion already occurs during solution annealing.

4. Summary

The determined tensile properties, Webster hardness and the electrical conductivity of the gas quenched parts (2024cl) are at the same level compared to a conventional age hardening with water-glycol quenching. This means, that it is possible to replace a conventional liquid quenching process by using high-pressure gas quenching with nitrogen at 10 bar.
The Leidenfrost Phenomenon during liquid quenching provokes an inhomogeneous cooling and causes an increased amount of distortion. The collapse of the vapour blanket, is different for each part in a liquid quenched batch and therefore leads to larger scattering of distortion after water-glycol quenching of the tested aluminium parts.

The more homogenous high-pressure gas quenching tends to result in closer tolerance bands especially for the determined changes in angles and changes in flatness of plane “a” of part 1.

The partial perpendicular approaching gas flow in case of part 2 causes higher scattering of distortion also after gas quenching. It is assumed, that the approaching flow applies a force and causes a further bending of the affected region of the part.

A lower scattering of distortion is more important than a lower average of distortion. A certain average of distortion can be compensated by suitable process steps before or after the heat treatment, if the scattering is low, whereas a high scattering of distortion complicates the compensation.

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