Investigating the quench sensitivity of high strength AA6082 aluminium alloy during the new FAST forming process

Qunli Zhang*, Xi Luan*, Saksham Dhawan*, Denis J. Politis*, Zhaoheng Cai* and Liliang Wang*

* Department of Mechanical Engineering, Imperial College London, London, SW7 2AZ, UK

Abstract. Optimised manufacturing rates offer enormous cost saving benefits to industry. FAST (Fast light Alloys Stamping Technology) has been recently developed to rapidly and economically manufacture high-strength panel components from sheet metal alloys. For heat treatable aluminium alloys, artificial ageing is subsequently employed to strengthen the formed components. The diffusion-controlled precipitation response is dependent on the cooling rate. The temperature evolution during FAST quenching significantly affects the final strength. In the present research, the AA6082 specimens were heated to the target temperature at an ultra-fast rate and cooled by either air (providing different quenching rates) or water, followed by artificial ageing at 180°C. Hardness measurements were conducted to track the strength evolution of the specimens during thermal cycles. Transmission electron microscopy was also performed to characterise the microstructures under different cooling conditions. Based on the experimental results, quench sensitivity during FAST has been analysed in depth and modelled. This detailed quenching sub-model was incorporated in the post-form strength prediction model, for simulating strength of the components. A great agreement between experimental data and modelled results has been achieved with the deviation less than 7%. By identifying undesirable quenching methods, optimisation of the forming process is thus possible, improving the final strength of the formed parts.

Keywords: FAST, AA6082, Quench sensitivity, Precipitation response, Post-form strength

1. Introduction

The strength of Al-Mg-Si alloys can be altered by employing various heat treatment procedures during and after forming. The traditional approach to manufacture and strengthen heat treatable sheet 6xxx series aluminium alloys usually consists of solution heat treatment, forming, quenching and artificial ageing. For the common commercial 6xxx series aluminium alloys, strengthening is a combined effect of solid solution hardening, work hardening and precipitation hardening with precipitation hardening as the dominant mechanism [1]. Recently, the precipitation response of the 6xxx series aluminium alloys has been frequently investigated and the generally accepted sequence can be simplified as follows: SSSS (supersaturated solid solution) -> co-clusters -> pre-β” precipitates -> β” precipitates -> β’ precipitates [2]. It is important to note that the exact precipitation sequence is dependent on the initial microstructure and chemical composition of the raw material.
By undergoing the regular precipitation sequence, the material can retain its full strength. The formation of precipitates during quenching ought to be suppressed as much as possible, and this is achieved when the alloys are rapidly cooled to room temperature at a rate faster than the critical quenching rate (CQR). This critical rate increases with increasing amounts of alloying elements, namely Mg and Si [3]. If the alloy is cooled any slower, the precipitates formed during quenching will have a detrimental effect on the obtained peak strength. The induced particles are presumed as equilibrium β precipitates, that coarse rapidly and lower the peak strength accordingly. Furthermore, these precipitates break down the SSSS state by consuming solute atoms as well as quenched-in vacancies, thus limiting the potential for the formation of new hardening precipitates in the artificial ageing process [4]. Therefore, it is crucial to select an appropriate quenching rate and optimize subsequent thermal cycles with detailed scientific knowledge of quench sensitivity, especially for the newly developed forming techniques.

The recently established FAST (Fast light Alloys Stamping Technology) forming procedure has proposed a novel approach towards producing panel components from sheet metals, such as aluminium alloys [5] [6]. The blank is heated to the target temperature at an ultra-fast rate and immediately formed and quenched in the cold dies. Compared with conventional stamping technology of aluminium alloys, lengthy solute heat treatment (SHT) is eliminated, leading to a significantly decreased cycle time. Despite the elimination of solution heat treatment, quenching rate still remains an extremely important factor towards accomplishing the ideal post-form strength after artificial ageing. Thus, it is of fundamental importance to develop a dedicated model to characterize quenching sensitivity for the new FAST forming technique. With the goal of incorporating this into a unified post-form strength prediction model, the full potential of precipitation hardening can be exploited.

In the present research, quench sensitivity of AA6082 during FAST was investigated by conducting heating and quenching (H&Q) tests, Transmission electron microscope (TEM) tests and hardness measurements. Accordingly, the continuous cooling precipitation diagram (CCP) for AA6082 during FAST was implemented in the post-form strength (PFS) prediction model. As a consequence, the extended PFS model also calculates the strength evolution for the insufficiently quenched components and can be further embedded into FE simulation software.

2. Experimental methodology

The commercial AA6082-T4 alloy was used, with the chemical composition shown in Table 1. Workpieces were cut along the rolling direction from the blank sheets. K-type thermocouples were welded at the centre of the samples to measure and control the temperature evolutions during tests. The thermo-mechanical simulator Gleeble 3800 was used to conduct the H&Q tests. The prepared workpieces were heated to an elevated temperature at an ultra-fast heating rate (over 50°C/s) in order to simulate the FAST process, and subsequently quenched to ambient temperature by either water (WQ) or air (AQ) with varying cooling rates and detailed information is shown in Table 2.

| Alloy  | Al   | Mg  | Si  | Mn  | Fe  | Cu  | Cr  | Zn  | Ti  |
|--------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| AA6082 | 97.37| 0.7 | 0.9 | 0.42| 0.38| 0.08| 0.02| 0.05| 0.03|

Table 2. Quenching information for each workpiece

| Workpiece Number | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
|------------------|------|------|------|------|------|------|------|
| Quenching method | AQ   | AQ   | AQ   | AQ   | AQ   | AQ   | WQ   |
| Quenching rate in 1st second (°C/s) | 168.0| 194.4| 200.8| 205.7| 210.2| 230.5| 1632.9|
| Average quenching rate (°C/s)      | 67.9 | 72.3 | 73   | 75.2 | 76.1 | 77.9 | 1632.9|
Artificial ageing tests were performed to strengthen the as-quenched workpieces to investigate the effect of quenching on the precipitation response. Workpieces under different cooling conditions were aged at 180°C for a range of times until signs of over-ageing were observed. Zwick hardness tester was used to measure the hardness of each workpiece. 30N load (HV3) was applied with a 10 second dwell time for each test. After at least three indentations, the representative average hardness values were recorded.

Disc-shaped samples were polished, thinned and punched from the aged workpieces for microstructure investigations conducted on an FEI Technai F20 TEM. All the TEM images were taken along <100> Aluminium axis where precipitates can be easily observed.

3. Results and discussion
This section presents the experimental results from the various testing procedures and discusses key findings for determining the quench sensitivity. All the workpieces were aged at 180°C for 5 hours after quenching to room temperature with different quenching rates or quenching methods. The temperature evolution during AQ and WQ for each workpiece can be seen in Figure 1, the experimental hardness evolution and corresponding obtained peak hardness for each workpiece are illustrated in Figure 2 and Table 3.

![Temperature evolutions for the workpieces during quenching (AQ & WQ)](image1)

![The experimental hardness evolutions for the workpieces aged at 180°C with different quenching conditions](image2)

Table 3. Peak hardness obtained for each workpiece after artificial ageing at 180°C

| Workpiece Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|------------------|-----|-----|-----|-----|-----|-----|-----|
| Peak hardness (HV) | 63.6 | 95.5 | 97.6 | 103.0 | 112.7 | 121.7 | 121.8 |

Figure 1 shows the transient nature of the cooling rate and demonstrates the need to calculate an average quenching rate (Table 2), in order to make quantifiable comparisons. As seen in Table 3, the hardness of workpiece 1 is the lowest among all other samples, settling to a value of approximately 63HV after 3-hour ageing. Moreover, hardness evolution curves for workpieces 2 to 5 (Figure 2) lie between workpiece 1 and workpiece 6, for which the peak hardness increases in ascending order. Hardness evolutions for workpiece 6 and 7 are very similar, with peak hardness 121.7HV and 121.8HV respectively. Comparing with the quenching rates displayed in Figure 1, it can be deduced that the peak hardness obtained during artificial ageing is positively correlated with quenching rate. It follows the generally accepted trend that rapid quenching leads to a higher peak value, with negligible difference after the critical quenching rate is achieved.
A lower peak hardness value for workpiece 3 suggests a suboptimal quenching rate was used when compared with the water quenched workpiece 7. Figure 3 shows the TEM microstructures in the <100> Al zone axis orientation for workpiece 3 and 7, respectively. Needle-shaped β” precipitates, observed as dots when considering their end-on views, have been observed along the <100> major axis in both TEM images. However, large size rod-shaped β’ precipitates can only be detected in workpiece 3 and the distribution of precipitates in the aluminium matrix in Figure 3 (b) is more uniform and finer than Figure 3 (a). Additionally, the number density of precipitates is notably greater and the average size of precipitates is smaller in Figure 3 (b) compared with microstructures in Figure 3 (a), 13.2 nm vs 30.6 nm in length respectively.

Summarizing the quenching details and peak hardness values shown in Table 2 and Table 3, it can be observed that the obtained peak hardness is particularly sensitive to the average quenching rate in the first second when compared to the overall average quenching rate, which suggests that the detrimental effect is mainly induced at relatively higher temperatures. The final peak hardness of the workpiece could be markedly lowered if the quenching rate is below 190°C/s in the first second. Conversely, full strength is attained as long as the quenching rate is over the required critical quenching rate (CQR), inferred as 230°C/s in the first second, in this case. It is also worth mentioning that if the quenching rate is greater than CQR, hardness evolutions during artificial ageing will not show a significant difference, even if the difference between the quenching rates is over 1000°C/s.

With the aid of well correlated TEM bright field micrographs, it was easy to observe that for well-quenched specimens, the number density of needle-shaped β” precipitates is larger and distribution is finer. From the aforementioned established precipitation sequence of heat treatable 6xxx series aluminium alloys during artificial ageing, the major hardening precipitates are the needle-shaped β” [2]. For workpieces with an insufficient quenching rate, the coarse β’ and β precipitates are most likely induced. These β’ and β precipitates consume lots of Si and Mg solute atoms, are unable to reverse transform to the preferred needle-shaped β”, and coarsen rapidly during artificial ageing. In comparison to β”, they contribute poorly to strength as they are readily bypassed by the dislocation movements.
Thus, with a blend of $\beta''$, $\beta'$ and $\beta$ precipitates, the volume fraction of precipitates is lower and average radius of precipitates is larger leading to a lower peak hardness, compared to the well-quenched workpiece with finely distributed needle-shaped $\beta''$ precipitates in the matrix.

4. Quenching sensitivity modelling

The development of a model for quenching sensitivity in the FAST process is essential for determining the precipitation order and hence vital in estimating the post-form strength. The model is embedded in a PFS prediction model and simulates the strength evolution of the workpieces during artificial ageing under different quenching conditions. The details of the PFS model have been recently established by the authors [7]. In the encompassing PFS model (Eq. (1)-(2)), the overall post-form strength is the sum of intrinsic aluminium strength $\sigma_i$, solid solution hardening $\sigma_{ss}$, dislocation hardening $\sigma_{dis}$ and precipitation hardening $\sigma_{ppt}$ (consisting of contributions from shearable precipitate $\sigma_{sh}$ and by-passing precipitate $\sigma_{by}$) [1][8]. Contribution of each term is computed via internal microstructural variables, where volume fraction of precipitates, average radius of the precipitates, dislocation density and solute concentration are correlated.

$$\sigma_y = f(f_t, r, \rho, C_t) = g(\sigma_{dis}, \sigma_{ss}, \sigma_i, \sigma_{ppt})$$

$$\sigma_y = \sigma_{dis} + \sigma_{ss} + \sigma_i + \sigma_{ppt} = \sigma_{dis} + \sigma_{ss} + \sigma_i + \frac{\sigma_{by}}{\sigma_{by} + \sigma_{sh}}$$

The quenching sub-model shown in Eq. (3) and (4) is a key supplement to the unified PFS model. It facilitates the complex strength prediction for insufficiently quenched components during the forming process. Using the model, the precipitation behaviour during quenching is simulated by FE software by tracking the temperature evolutions of all the elements. This is subsequently embedded into the PFS model to capture the effect of corresponding microstructural changes on the strength.

$$C_i = Q \cdot C_0$$

$$Q = Q_0 \cdot e^{\frac{Q_q}{RT_c}}$$

where $C_i$ is the solute concentration after quenching, $Q$ is the quenching factor, $C_0$ is the maximum solute concentration after quenching ($C_i$ of SSSS), $Q_0$ is the pre-exponential quenching factor, $Q_q$ is the activation energy for diffusion controlled precipitation behaviour during quenching, $R$ is universal gas constant, and $T_c$ is the start temperature when the quenching evolution curve intersects the CCP curve (equals to infinity if intersection point of two curves does not exist).

The comparison of hardness evolutions between experimental data and modelling results is shown in Figure 4. An excellent agreement between experimental data and model can be noted. The difference between the extended PFS prediction model and experimental results is less than 7%. While the experimental hardness for workpiece 6 lies slightly outside the error bars (in the initial stage of artificial ageing), this sample is quenched by air at a rate over the required CQR, which shows slight different artificial ageing response when using the quenching sub-model. In summary, the unified PFS model incorporated with quenching sub-model is capable of capturing the strength of insufficiently quenched components and hence optimize the forming process.
Figure 4. Comparison of hardness between experimental data and modelling results for the workpieces during 180°C artificial ageing.

5. Conclusions
In this work, quenching sensitivity of AA6082 during the newly established, advanced FAST forming technology has been investigated. It has been found that the diffusion-controlled precipitation response during artificial ageing is highly dependent on the quenching rate and is particularly sensitive to the average cooling rate in the first second, which suggests that the detrimental precipitation behaviour is mainly induced at relatively higher temperatures. It is worth mentioning that T6 strength can be completely obtained if the quenching rate is faster than the specific critical quenching rate while peak strength is adversely affected if the quenching rate is insufficient. Moreover, a quenching sensitivity model has been established to simulate the precipitation behaviour during quenching and is developed for smooth implementation into the unified PFS prediction model. Strength evolutions of manufactured components can be tracked and insufficient quenching rates can be accurately identified, with less than 7% deviation between measured and predicted values. Optimizing the forming process in such a way can assist in truly achieving the desired target strength.

References
[1] H R Shercliff and M F Ashby, *Acta Metall. Mater.*, 38 (1990), pp. 1789–1802.
[2] Q Du, K Tang, C D Marioara, S J Andersen, B Holmedal, and R Holmestad, *Acta Mater.*, 122 (2017), pp. 178–186.
[3] B Milkereit, N Wanderka, C Schick, and O Kessler, *Mater. Sci. Eng. A*, 550 (2012), pp. 87–96.
[4] M J Starink, B Milkereit, Y Zhang, and P A Rometsch, *Mater. Des.*, 88 (2015), pp. 958–971.
[5] X Luan, Q Zhang, O El Fakir, and L Wang, (2016), pp. 1–5.
[6] L Wang et al., (2017), 1713741.5.
[7] Q Zhang, X Luan, D Politis, Q Du, M Fu, and L Wang, under review.
[8] Y Mahmoodkhani, M Wells, N Parson, C Jowett and W Poole, *Materials.*, 7 (2014), pp. 3470-3480.