

Warm-stamping mechanical behavior and microstructural characterization of Al-Si metal sheets using water refrigerated tooling

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Abstract—The use of water refrigerated tooling in a laboratory scale was used to simulate conditions of warm (500°C) stamping of aluminum plates with 0.8 mm in thickness. The work presents load-displacement curves of room temperature and heat treated samples during stamping at 120 and 240 mm/min, effect of the treatment in the anisotropic characteristics of the rolled sheet plate and electron microscopy analysis along with element detection, as this alloy contains small amounts of silicon. The processes resembles a solution treatment and, thus, also an aging treatment at 120°C for 12 h was carried out in order to understand the application possibilities of the manufacturing process in the automotive or aero-space industry.

I. INTRODUCTION

Aluminum-silicon (Al-Si) alloys are widely used in the automotive and aerospace industries due to their high strength-to-weight ratio, low thermal expansion, and good formability, among other advantageous characteristics [1]. Due to this, and their use in components like pistons and cylinder heads, researchers have been motivated to investigate the mechanical and microstructural behavior of aluminum alloys after thermal treatments. Previous studies, like those by Gutierrez and Requena [1], and Azadi et al. [2], have demonstrated that heat treatments significantly influence the hardness and microstructure of Al-Si alloys, resulting in the dissolution of intermetallic compounds and variations in precipitation. The precipitation of Si particles can be observed through microscopic studies, which was also confirmed in the work of Farokhpour et al. [3]. Additionally, Ozturk et al. [4] studied the influence of various ageing effects on the mechanical properties of aluminum alloys, identifying that peak ageing conditions in AA6061 were reached after 2 hours of heat treatment at 200°C. This study seeks to add to the results obtained in these and other similar studies by exploring the warm-stamping behavior of Al-Si metal sheets using a water-cooled die setup, focusing on how rapid cooling and different strain rates influence the resulting microstructure and mechanical properties.

In the case of steel sheets, the use of hot or warm stamping using water cooled press tools, is attractive because of the capacity of the steel to form martensite (or at least bainite) during forming. The process uses either a roller hearth furnace, induction heating or conduction heating to increase

temperature of the raw material (usually thin steel plates) and stamp the form or preform as quickly as possible (a few seconds) [5]. Yet, Al-alloys are much more interesting when designing structural parts, as the strength-weight ratio is similar to steel and forming stamped automotive or aerospace parts are easier to produce from a load capacity of the equipment point of view: a small increase in temperature drastically reduces resistance too plastic deformation. The use of solution and aging treatments during forming of al-alloys has also been investigated [6], as structural parts will benefit from modified anisotropic rolled microstructures [7]. The formability of Al-Mg-Si alloys has been reported to increase from 25 to 100% when temperature is increased from 25 to 500°C [8]. In the case of the 7075 alloy sheet, hot stamping has been performed by maintaining 480°C for 30 min, stamping with cooled tooling and aging at 120°C for 24 h, resulting in a material with a resistance of 650 MPa [9]. This last study also shows that, though the heat treatment modifies the anisotropic behavior of the original rolled microstructure, it is very hard to completely eliminate the anisotropy, specially in the case of the fracture toughness stress. Advanced techniques, such as digital image correlation, have proven extremely efficient in understanding plastic deformation during complex stamping of Al alloys [10]. Even though the present work is focused in Al-Si sheets, these Al alloys are of interest as coatings in 22MNB5 steels in order to prevent corrosion while producing composite arrangements for automotive parts [11].

The stamping process is extremely versatile when using Al alloys, as plasticity at high temperatures allows very complex geometries and even welding of dissimilar materials. Liu et al [12] have used fast light alloy stamping (very high strain rates) to weld 6XXX and 7XXX parts.

II. EXPERIMENTAL PROCEDURES

Rectangular samples of an Al-Si alloy of the 4000 series type in the form of metal sheet with 0.8 mm thickness ($t = 0.8$ mm) were cut with dimensions of 150 x 50 mm, with the rolling direction perpendicular to the length of 150 ($b = 50$ mm, $h = 150$ mm and h perpendicular to the rolling dimension). The samples were then stamped at room temperature or heated in a furnace (preheated for an hour at 500-520°C) for 10 min, taken out of the furnace and stamped in a water-cooled tooling mounted on a Shimadzu AGS-X 100 kN tension and compression machine (Figure 1a). As warm stamping may be performed and simulated at crosshead speed of 30 mm/min for warm [13] and hot

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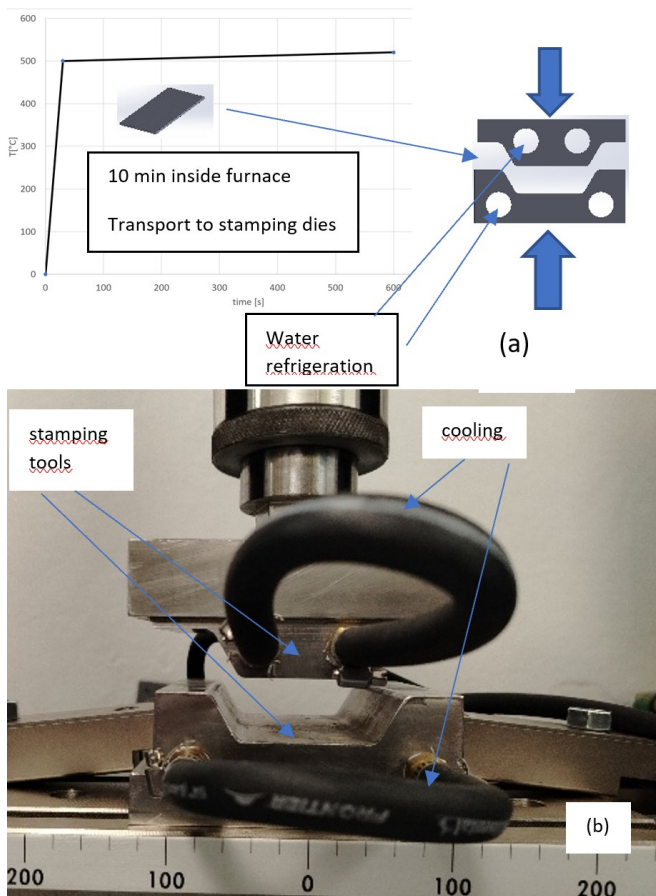


Fig. 1. Heat treatment of 10 min and stamping of sample in water-cooled tooling (a), and stainless-steel tooling mounted in a tension-compression machine to produce warm stamping (b).

stamping as high as 2000 mm/min [14], two intermediate speeds of 120 and 240 mm/min were used. The procedure of taking out the samples from the furnace and stamping at rates of 120 or 240 mm/min until a 3000 N load was reached, took approximately 10 s.

High speed punching machines may reach 5,000 N [14] though the 3,000 N maximum force was checked to be enough to completely deform the Al sheet without compromising surface quality. The process of taking the samples out of the furnace with tweezers (Fig. 1a) and placing them on the stamping dies (Fig 1b), and also activating the testing machine to lower the die while both tools were refrigerated, took 10 s (+/- 1). Microstructural and mechanical properties changes indicate that this time is short enough to produce the effects expected from warm stamping (industrial processes time periods depend on part size and stamping equipment arrangements).

XRD patterns were obtained placing the samples with the rolling direction parallel to the XRD beam in a Rigaku Mini Flex 600 equipment and using a minimum of 0.1 degree step and 0.5 degrees per minute rate, with Cu K alpha wavelength of 0.1542 nm.

Also, in order to analyze tension properties of the as-delivered metal sheet, the Shimadzu equipment was used

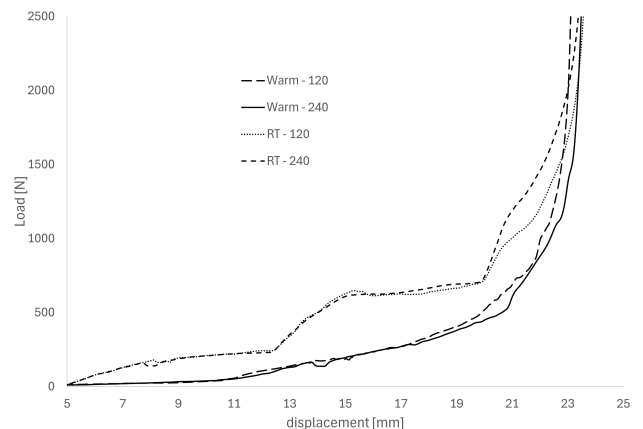


Fig. 2. Load-displacement curves for samples stamped at 500 °C and at room temperature, using displacement speeds of 120 and 240 mm/min.

cutting samples 150 mm long and approx. 25 mm in width in both the parallel and perpendicular directions of rolling and tension testing was performed at 120 and 240 mm/min displacement rate using a 50 mm extensometer (4e-2 or 8e-2 1/s). Stress strain curves were traced even though this is not a standard tension test.

In order to observe microstructural characteristics, the stamped samples were cut in a metallographic saw, mounted and polished to 0.05 micron diamond particles finish. Most important zones were considered as the bending curve during stamping as strain in the material is the highest at that zone. The sections (0.8 mm in thickness) were analyzed using a Hitachi TM 3030 SEM and also an EM CRAFTS CUBE II SEM equipped with a EDX detector using AZtec analysis software.

The stamped samples were cooled from 500°C using the refrigerated tools and this procedure may be considered a solution treatment. Therefore, samples were also treated at 120°C for 12 h in order to simulate an aging treatment on the material.

Hardness was measured in the HRB and 30T Rockwell scales, and also in the microVickers 300 g scale.

III. RESULTS

A. Warm and room temperature stamping

Figure 2 shows the load-displacement curves during stamping of samples heat-treated at 500°C (warm) and stamped until a 3000 N load was reached, comparing this behavior with room temperature stamping of the as-delivered material. It is evident that the warm samples, independently of the 120 or 240 mm/min deformation rate, have a lower resistance to deformation as Al, at that temperature, will completely dissolve Si precipitation and an industrial press will use much lower amounts of energy during the manufacturing-stamping process. On the other hand, room-temperature deformation is not characterized by a soft curve, and at least two distinct angles in the curve are evidence of the resistance of the metal sheet when vending at high angles is produced.

B. X-ray diffraction

Two X-ray diffraction patterns were obtained from aluminum samples: Figure 3a in its as-received state (cold-rolled sheet), and Figure 3b after undergoing heat treatment. The cold stamped XDR suggests larger grain size and fewer internal defects. Surprisingly, the cold-stamped sample shows higher peak difference between one to another and sharper peaks, indicating better crystalline coherence. The hot stamped XDR indicates lower crystallinity and higher defect density. Although the temperature is elevated, the material undergoes dynamic recovery and recrystallization, but also significant deformation. The difference between peaks shows a more random orientation of grains. X-ray diffraction patterns for all samples only indicate the Al crystals, as Si and other alloys exist in an amount too low to distinguish diffraction peaks. The data base for Al specifies that peaks at 65° and 78° degrees should have the same height. If Figure 3 is observed the material in its delivered as-state has an evident grain orientation due to rolling deformation and the peak at 65° is twice as high as the one at 78° . Once the sample is heat treated at 500°C and stamped using water refrigeration the difference between the height of these 2 peaks is considerably reduced, though not completely erased from the orientation point of view.

C. Mechanical testing

The tensile test in its as-delivered state as presented in figure 4, for the four samples, shows both the rolling direction parallel (at 120 and 240 mm/min), and both with the rolling direction perpendicular (also at 120 and 240 mm/min). All samples show similar behavior with a maximum stress of approximately 140 MPa. However both the perpendicularly tested samples sustain a higher stress with the one deformed at 240 mm/min being slightly more resistant and suffering a smaller deformation before fracture. This means that the rolling direction and the pressing speed are capable of withstanding fracture propagation in a more efficient fashion, though the perpendicular direction is more resistant, most probably due to the hardening effect of Si precipitation.

D. Microscopy

Figure 5a shows a linear defect in the sample, possibly from the polishing action to obtain the sample. In both figures a slight indication of the Si particles rolling orientation is observed.

This is confirmed in Figure 6, where the lines of Si deposits are clearly visible. Both samples show a different concentration of Si, product of the heat treatment.

The heat treated samples show lamination orientation in figures 7a and 7b. The impossibility to distinguish the Si particles in Figure 7a means that it did not precipitate and therefore it does not contribute to the hardness of the material.

Using a 25 kV beam, SEM shows in a clear fashion the distribution of Si, and Fig. 7a (heat treated and stamped) has clusters of Si an a smaller amount of precipitation than the aged sample (Fig.7b). The rolling direction (horizontal) is

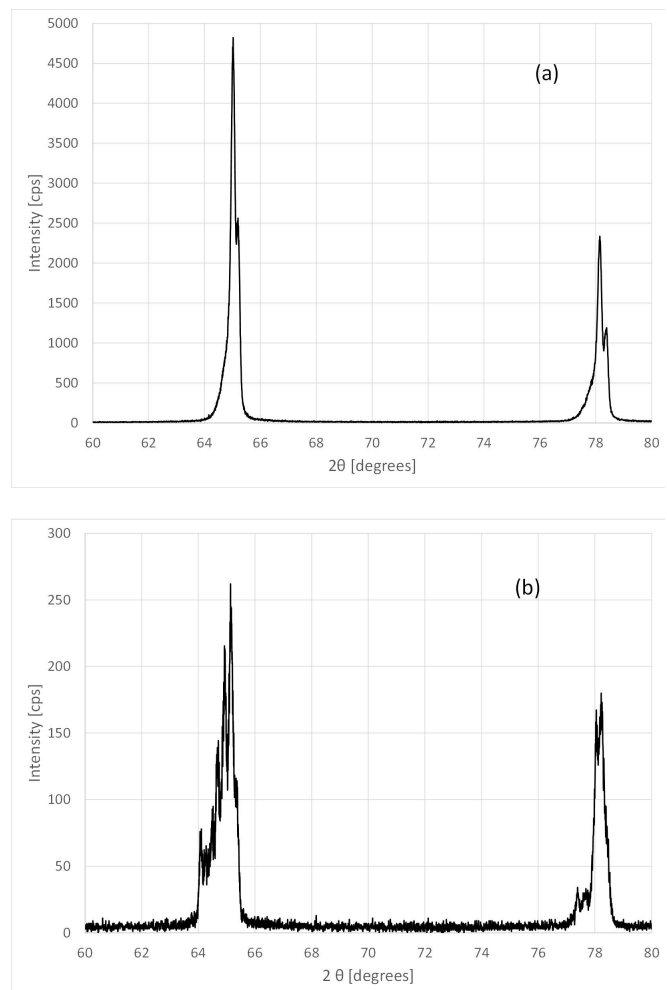


Fig. 3. XRD for (220) and (311) planes of room temperature (a) and heat-treated at 500°C (b) stamped samples.

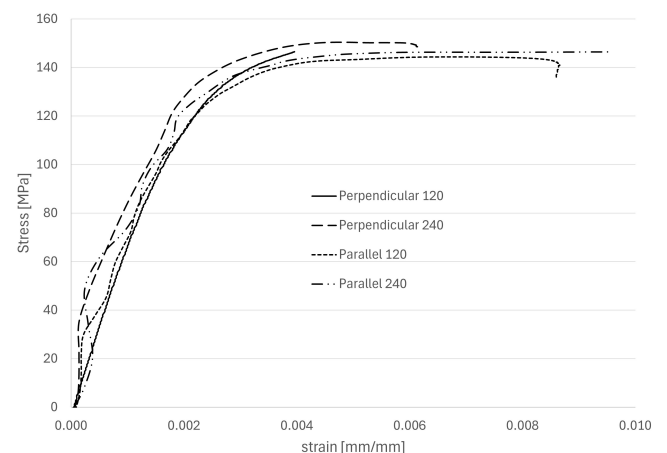
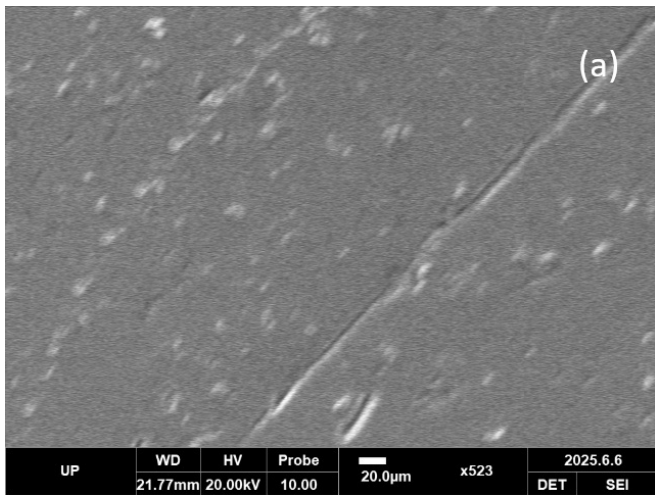
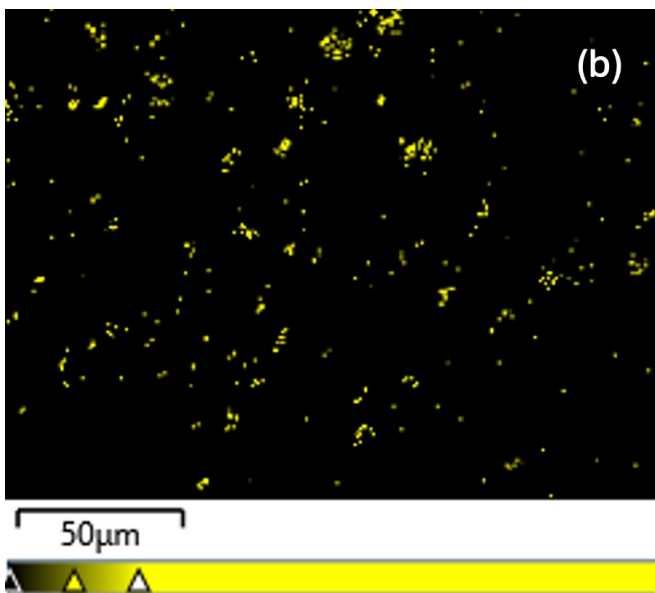


Fig. 4. Stress–strain curves for tension samples parallel and perpendicular to the rolling direction and at displacement rates of 120 and 240 mm/min.

evident in the aged sample yet no so clear in the stamped one. This means that deformed orientation remains part of the structure after the 120°C and 12 h heat treatment, producing



(a)



(b)

Fig. 5. (a) SEM of deformed bending zone in sample heated at 500°C and stamped at 120 mm/min; (b) EDS detection of Si zones.

small precipitates and an more resistant and hard material.

IV. DISCUSSION

The load measurement during stamping (Fig. 2) shows for the RT samples a distinct angle when the plates are bent against the tooling curves, indicating a high friction coefficient. The disappearance of this feature in the curve when the sample is heated at 500°C may be explained as superficial oxidation in the Al plate, allowing sliding and a more uniform deformation of a material which is, already, less resistant to plastic stain. This behavior may explain the interest in using more Al-alloy bulk or coating materials in the automotive industry. As expected from the as-received material, there is an evident anisotropy of the plate with plastic deformation of preferred crystals in the rolling direction. The XRD analysis (Fig. 3), which shows the comparison of the (220) and (311) peaks in the original rolled

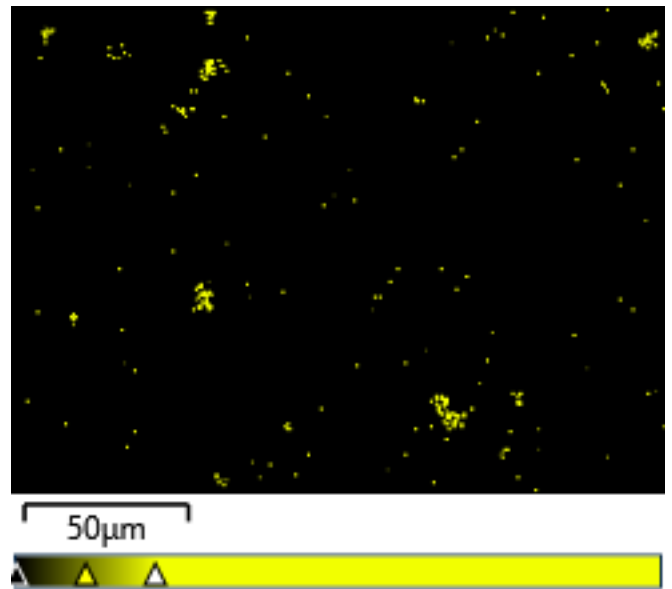


Fig. 6. EDS detection of Si zones in sample heated at 500°C and stamped at 120 mm/min, and aged at 120°C for 24 h.

plate (Fig. 3a) and the one after heat treatment and stamping (Fig. 3b) clearly shows that these two peaks, which are supposed to be similar in size for a polycrystalline randomly oriented material [15], have a bigger difference before heat treatment. This means that the warm stamping diminishes the anisotropic structure though it does not eliminate it completely and the resulting part may loose resistance in the rolling direction while gaining overall resistance to combined stress configurations. Aging treatment at 120°C was also analyzed by XRD though no differences with the heat treated samples were found (the amount of Si nor its distribution appears in the diffractograms). Another aspect to be taken into account is the reflectiveness of the sample as the intensity of the detected X-rays is in counts per second (cps): the heat treated sample produces a much lower amount of diffracted X-rays, most probably because of an oxide layer formed during heating. EDS analysis in Fig. 5b indicates the presence of Si as large clusters after heat treatment and stamping, while Fig. 6 is evidence of much smaller particles after aging at 120°C for 12 h, and this is more clearly observed in Fig. 7. This last one also shows that preparing the polished surface on the heat treated and stamped sample (Fig. 7a) is easier than polishing the harder surface with well distributed Si precipitates (Fig. 7b). The hardness in HRB of the as-received sheet is 13, and the hardness for the heat treated and stamped material is even lower, evidence of the solution mechanism produced during stamping. If a more adequate hardness scale is used, the heat treated and stamped sample has 32 in the 30T Rockwell scale, while the material after a 12 h aging at 120°C has 38 in the same scale, thus indicating the capacity of aging to precipitate Si particles with small sizes. Aluminum materials with more alloying elements such as Mg, Cu or Mo may benefit from stamping at warm temperatures and total or partial aging

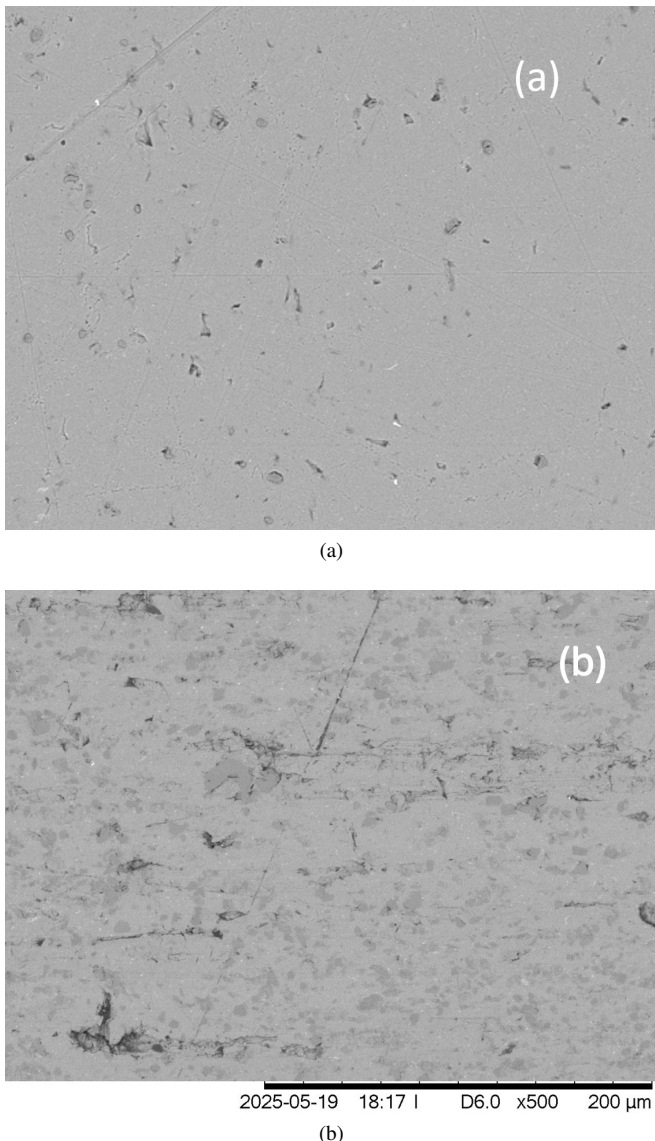


Fig. 7. (a) SEM of deformed bending zone in sample heated at 500 °C and stamped at 120 mm/min; (b) EDS detection of Si zones.

to obtain tailored properties in the rolling direction or in the perpendicular one, as the material is more difficult to deform in this last way at higher deformation rates (Fig. 4). It is worth noting that the SEM-EDS results (Figs. 5 and 6) indicate that heating at 500°C does not lead to a complete dissolution of the silicon phases in the aluminum matrix. Instead, large Si clusters remain after the heat treatment and stamping process, suggesting only partial fragmentation and redistribution of eutectic or primary silicon. During subsequent aging at 120°C, these clusters evolve into much finer and more uniformly distributed precipitates, as evidenced by the EDS maps. This microstructural refinement is consistent with the observed increase in hardness after aging, indicating that the heat treatment at 500°C primarily promotes partial solution and structural homogenization rather than full dissolution of silicon.

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