Thixoforming Wrought Aluminium Alloys

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ABSTRACT

Thixoforming is a processing route based on the thixotropic behaviour of alloys with non-dendritic microstructure in the semi-solid state.
Commercially, thixoforming systems have multiple heating stations and millions of components are now made annually, most made from the conventional casting alloys A356 and A357. These alloys have silicon content of around 7wt%, which provides fluidity and good 'castability' because of the relatively high volumes of Al-Si eutectic. However, these alloys do not give as high mechanical properties as conventionally wrought alloys such as 2014, 6082 and 7075.
This paper examines the difficulties involved in thixoforming such alloys and investigates whether these difficulties could be overcome. Issues such as alloy compositions for thixoforming, appropriate solidus-liquidus interval, suitable fraction solid versus temperature, reheatability of feedstock material, optimum morphology of structure and rheological properties in the semi-solid state are reviewed. Finally, recent data on mechanical properties of thixoformed are presented.

KEYWORDS
Thixoforming, Wrought Alloys, Microstructures, Mechanical Properties

INTRODUCTION

Thixoforming - or semi-solid processing – is the shaping of metal components in the semi-solid state. As a relatively new process, thixoforming has had to exploit alloys that were already available. Conventional aluminium casting alloys have additions of silicon, which provide high fluidity. Such alloys have high corrosion resistance, combined with low coefficient of thermal expansion and good weldability. Hypoeutectic alloys of the AlSi7Mg type (A356 and 357) were used for the initial industrialisation of the thixoforming process. The use of such alloys was necessary during the period in which thixoforming was gaining credibility as a commercial process.

This phase of development is now over and millions of thixoformed automotive parts are now in every day use in the cars we drive. However, one of the challenges for thixoforming is to process alloys which would otherwise be wrought and have higher performance than the casting alloys. These alloys include 2014 (AlCuSiMn, normally used as sheet, plate, extrusions and forgings, aerospace applications), 6082 (AlSiMgMn, normally used for rolled products, extruded and forged shapes, automotive applications), 7010 (AlZnMgCu, normally used for sheet, plate, extruded and forged shapes for aerospace applications) and 7075 (AlZnMgCu, sheet, plate, extruded and forged shapes for aerospace applications), the subject of this paper. Successful thixoforming of these alloys would serve to strengthen the market potential of semi-solid processing and would address the urgent need in the aerospace industry for near net shape, high

strength, aluminium products.
From the mechanical properties so far published [1], it is clear that thixoforming is capable of manufacturing near net complex shapes in high strength aluminium alloys. This paper outlines experiments on microstructural development in the semi-solid state, measurements of mechanical properties of thixoformed products produced after optimising thixoforming temperatures, injection speeds and soaking times prior to thixoforming and the effects of varying heat treatments. The results are encouraging on 2014, 201, 6082 and 7075.

EXPERIMENTAL WORK

Microstructural development during heating in the semi-solid state

The key to Thixoforming of alloys is in their spheroidal microstructures, as opposed to the dendritic microstructures typical of castings. Such microstructures give alloys thixotropic properties, allowing them to be near net-shaped whilst in the semi-solid state. The feedstock used in this work consisted of extruded wrought bar material. The spheroidal microstructure is therefore developing via the Recrystallisation And Partial melting (RAP) route [2]. In order to optimise the heating schedule that would generate the necessary microstructures, isothermal heating tests were used (Figure 1).

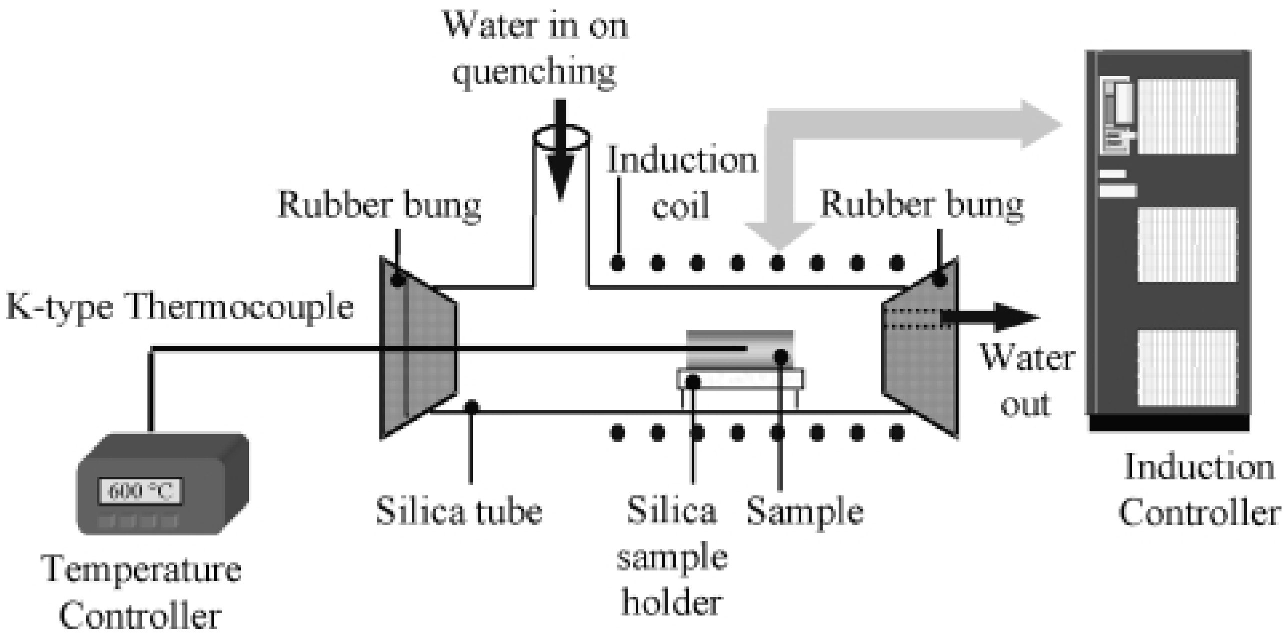


Figure 1. Schematic of the experimental arrangement for isothermal partial heating of small wrought alloy slugs into their semi-solid range.

In the case of the 2014 alloy, unrecrystallised grains remained after heat treatment in the semi-solid range, as shown in Figure 2, even when multi-step heating regimes are used, unlike the nearly completely spheroidal microstructures that evolved in the case of the 7075 (Figure 3) and 6082 alloys.

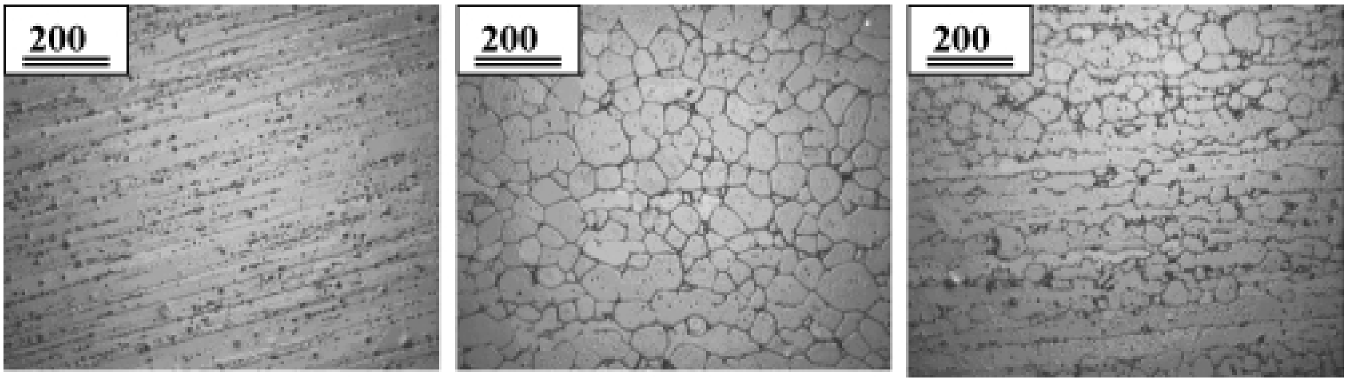


Figure 2. 2014 alloy: as extruded, 3 step heating (6000C 1min, 6300C 2min, 6430C 1 min, soaking times), and 3 step heating (6000C 2min, 6300C 1min, 6430C 0 min, soaking times).

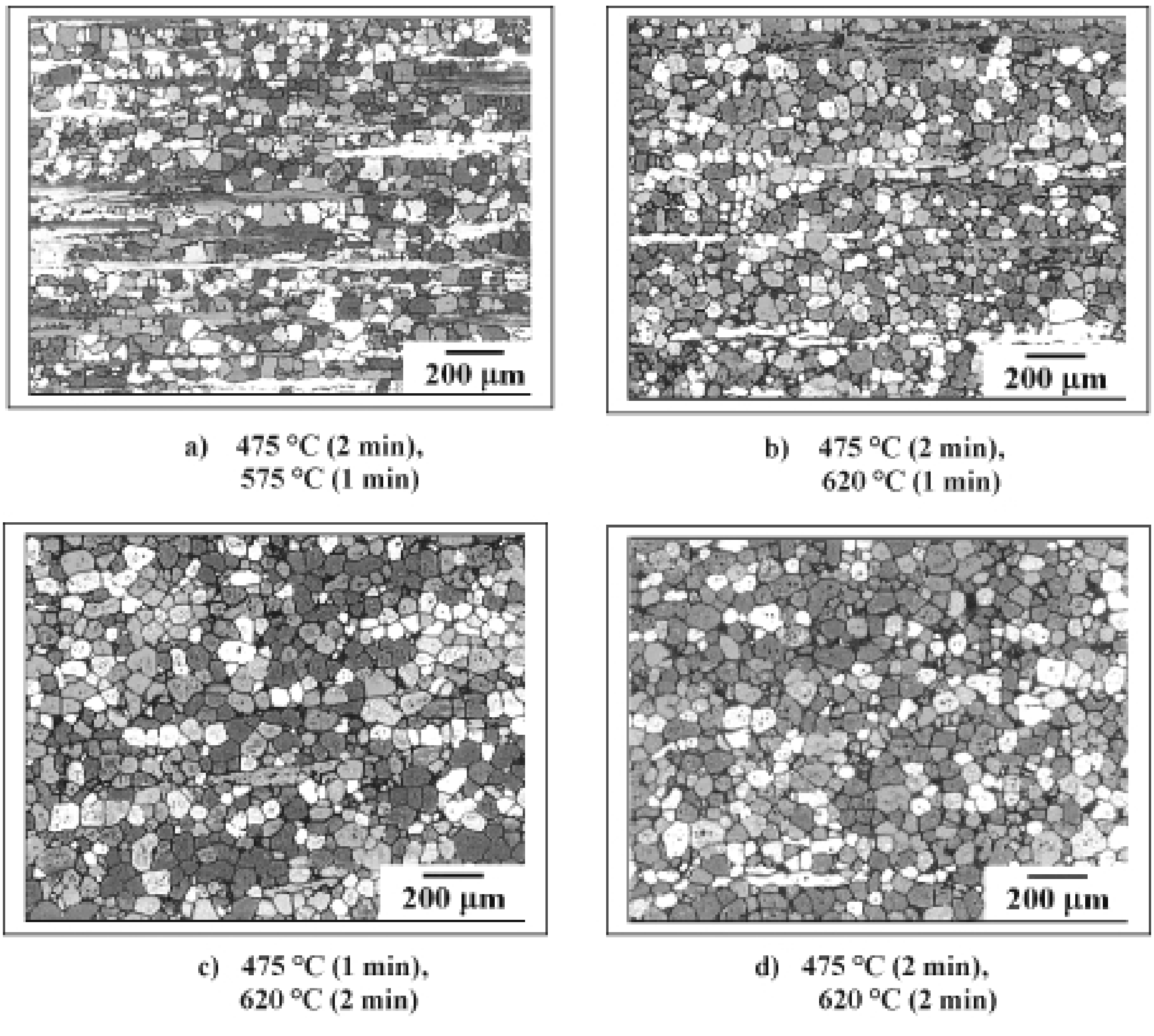


Figure 3. Optical micrographs in longitudinal section of 7075 heated by 2-step heating at different temperatures and holding times (in brackets), viewed under cross-polarised light. (Barker's etch). Very few elongated grains survive in Fig.3d.

OPTIMISATION OF THIXOFORMING CONDITIONS THROUGH MECHANICAL PROPERTIES

In order to obtain the best conditions possible, a number of tensile specimens, as those shown in Figure 4, were thixoformed at different temperatures. Round tensile specimens were machined out of the 'fingers' and tested. Having obtained the optimum temperature range for each alloy from the results of mechanical tests, more components were thixoformed at the chosen temperatures, using different injection speeds. Once again the results were correlated with the resulting mechanical properties.

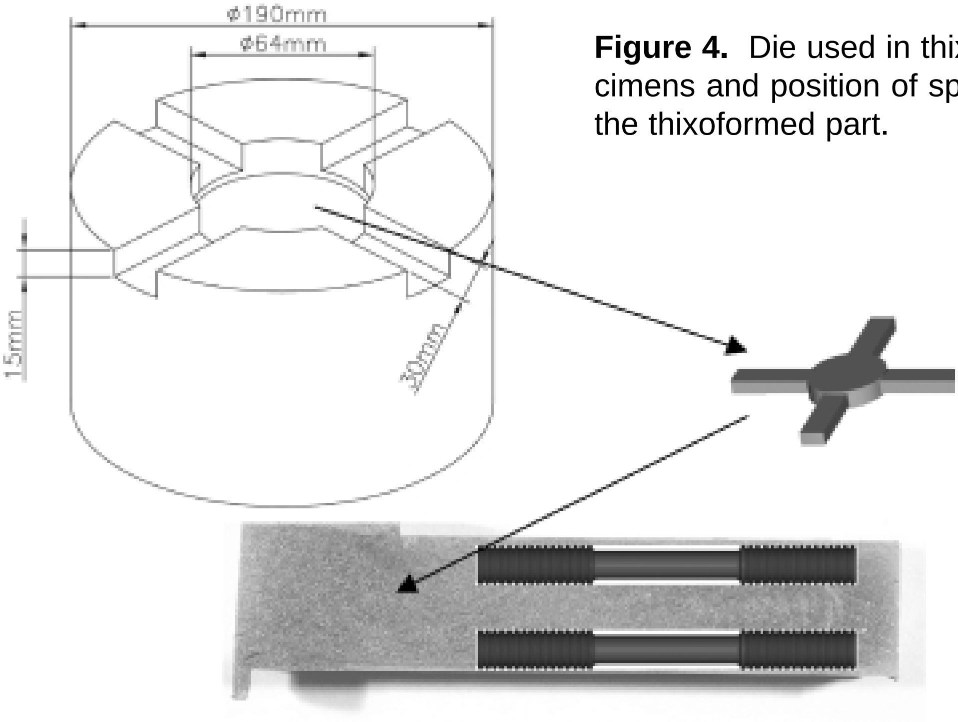


Figure 4. Die used in thixoforming tensile specimens and position of specimens in relation to the thixoformed part.

Another variable used was soaking time at the thixoforming temperature, and the correlation of the resulting mechanical properties is shown in Figure 5 below.

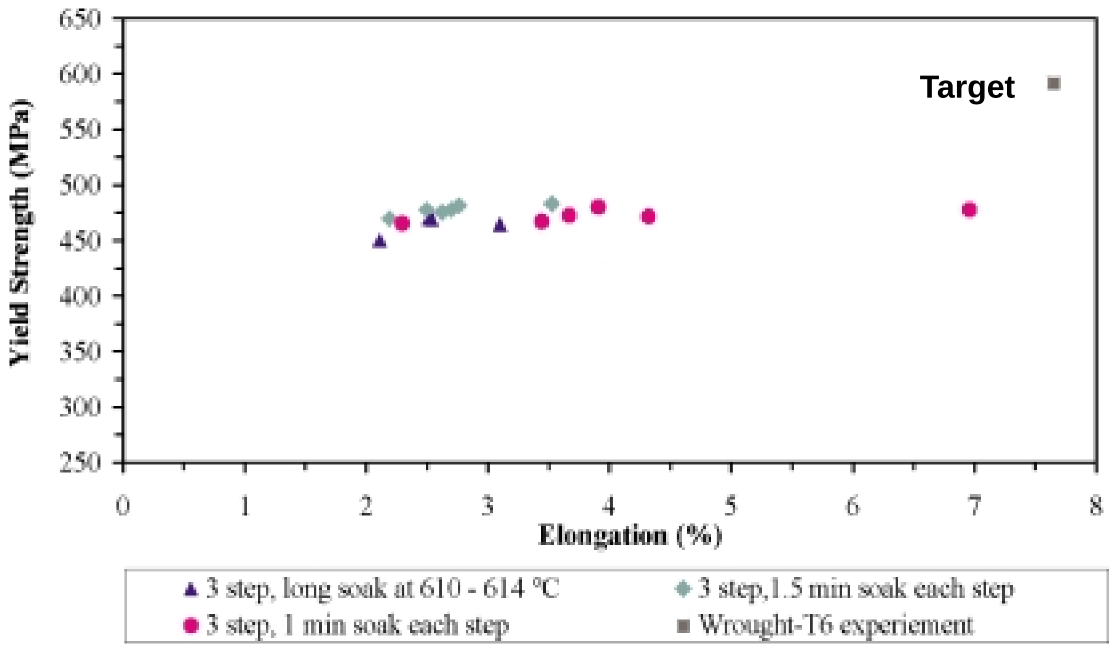


Figure 5. Tensile properties in the T6 condition of 7075 thixoformed samples with 3-step heating and with different soaking times as compared with 7075 in the as-wrought-T6 condition (Solution treated at 465 °C for 16h, quenched and aged at 125 °C for 24h).

The results of their tensile strength and elongation to failure of these CS and RAP samples are shown in Figure 6. The ultimate tensile strength of T6- thixoformed CS 7075, and T6-thixoformed extruded 7075 alloys are slightly different, but the elongation percent of T6-thixoformed CS 7075 are lower than that of T6-thixoformed extruded 7075 alloys. This could be because of oxides forming during CS casting process. The application of atmospheric protection, such as casting in argon gas chamber, might reduce this oxide formation, and increase the application of CS casting as feedstock preparation route for semisolid forming in the future. Moreover, in comparison between T6-thixoformed CS 7075, and T6-thixoformed CS modified 7075 alloys, the ultimate strength of T6-thixoformed modified 7075 are much higher than that of T6-thixoformed CS 7075 alloys, at the expense of elongation. This could be the result of higher magnesium and copper elements in this modified 7075 alloy.

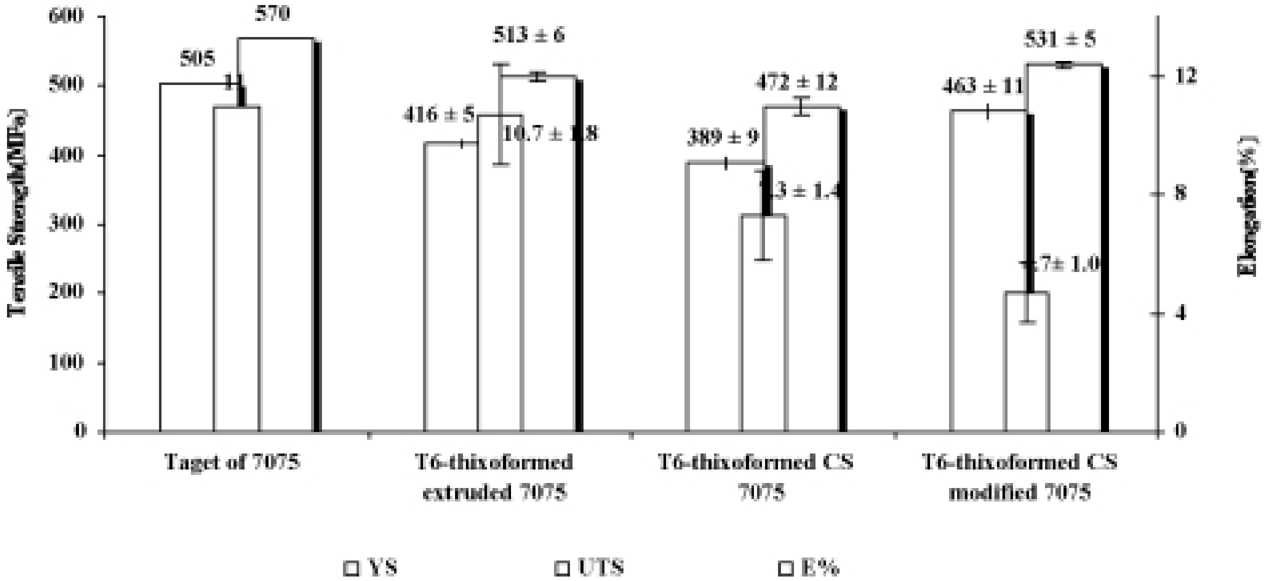


Figure 6. Tensile strength and elongation to fracture of thixoformed extruded 7075, CS 7075, CS modified 7075 alloys in the T6 condition.

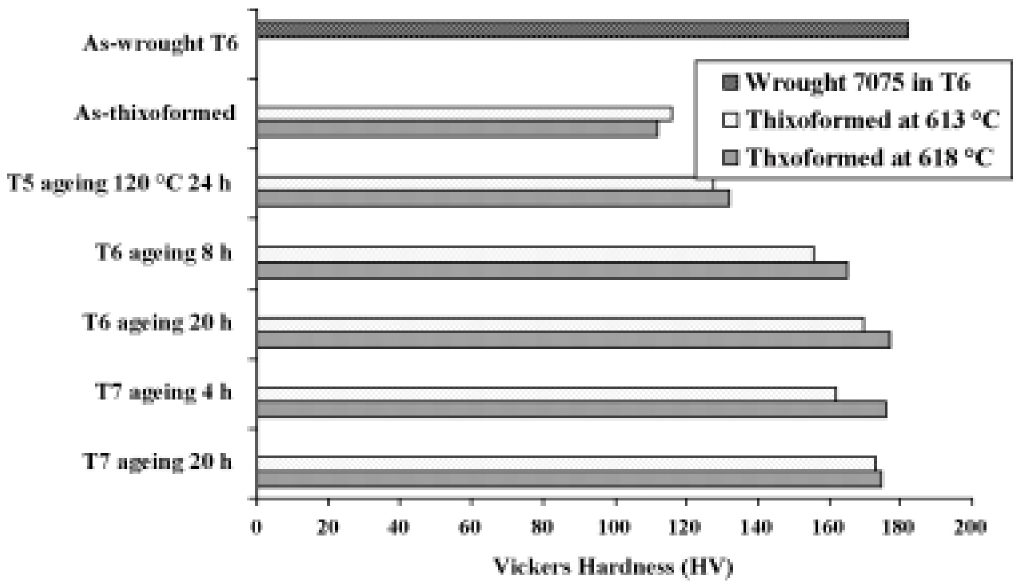


Figure 7. Recovery of hardness in thixoformed through heat treatment 7075 parts.

A number of standard heat treatments were used (T5, T6, T7), as well as variations around them in that they might be more appropriate to the thixoformed products. An example of hardness recovery after thixoforming back close to the as-wrought T6 value for a 7075 alloy is shown in Figure 7.

Four alloys were thixoformed and mechanically tested, 2014, 6082, 7010 and 7075. Figure 8 shows graphically the results for the 6082 series, whilst Table 1 gives a summary of the average and maximum values of UTS, YS & Elongation obtained for all the alloys thixoformed, as compared with the as-wrought target values.

Alloy	Average UTS (MPa)	Maximum UTS (MPa)	Av. YS (MPa)	Max. YS (MPa)	Av. (%) Elong	Max. E (%)	Wrought UTS (MPa)	Wro. YS (MPa)	Wrought E (%)
2014		360				4	508	445	12
6082	330	340	293	306	9	12	370	340	11
7075	490	510			5	7	560		10
7010	470	480				4	485		12

Table 1. Summary of properties of thixoformed wrought alloys and wrought target values.

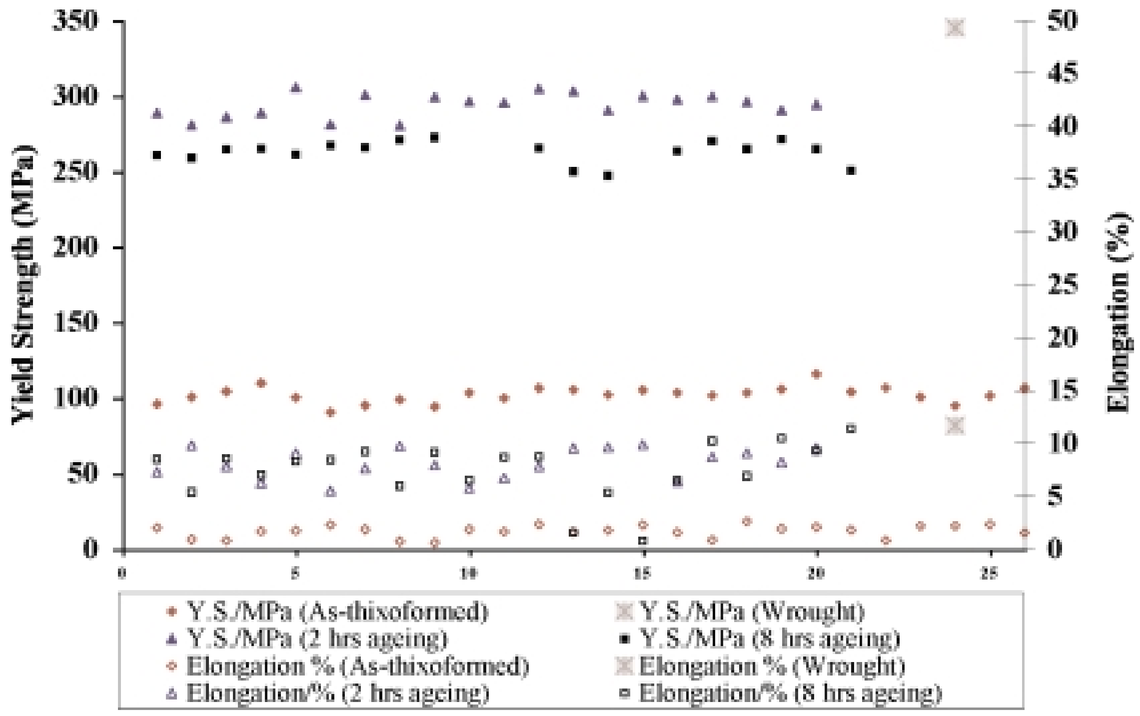


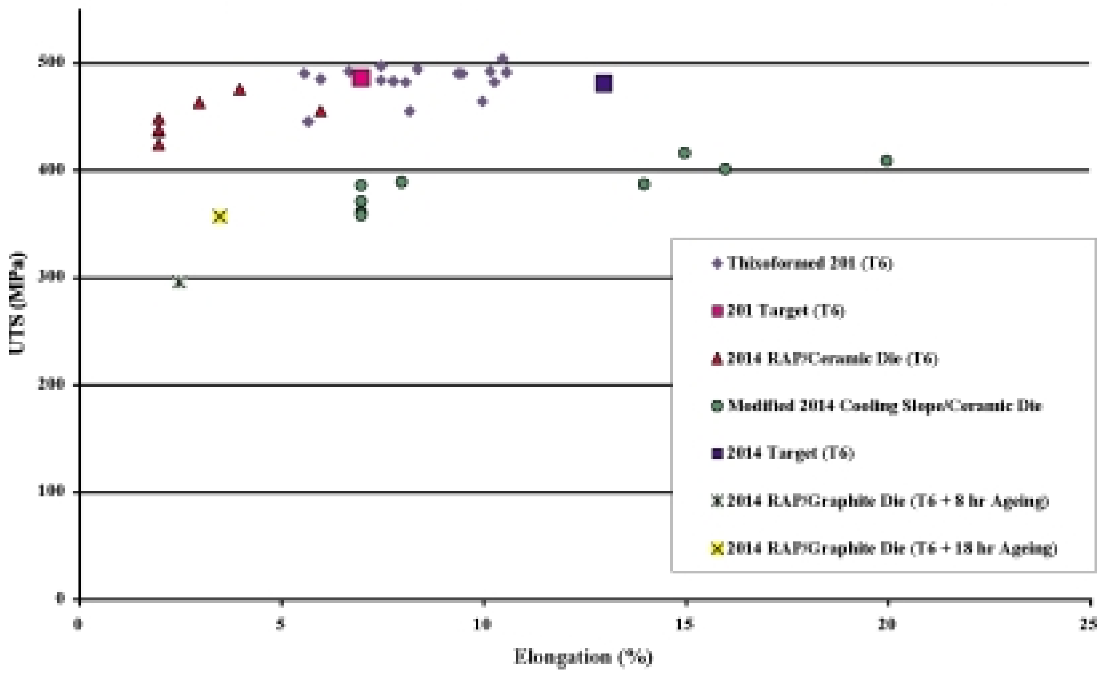
Figure 8. Mechanical properties of thixoformed 6082 (various heat treatments) compared with as wrought values.

A recent study carried out at the University of Sheffield [3] has provided substantial amounts of data on mechanical properties of various wrought alloys as seen in Figures 9-11. As can be seen, the challenges in thixoforming these alloys are many but the ones that appear to be fundamental to the possible future commercial applications of these alloys are, feedstock preparation, and die design/materials.

With this in mind, a new programme of work has been initiated at the joint University of Sheffield/Boeing Advanced Manufacturing Research Centre [4] aiming to continue with the thixoforming of wrought aluminium alloys with three basic targets:

1) Generation of consistent mechanical property data that will include, fatigue, fracture toughness and stress corrosion testing,
2) Experimentation with ceramic and composite die materials, and
3) Thixoforming of complex shapes appropriate for the aerospace industry.

Figure 9. Mechanical Properties of Thixoformed 201 Casting & 2014 Wrought Alloys



Mechanical Properties of Thixoformed 2014 Wrought Alloy

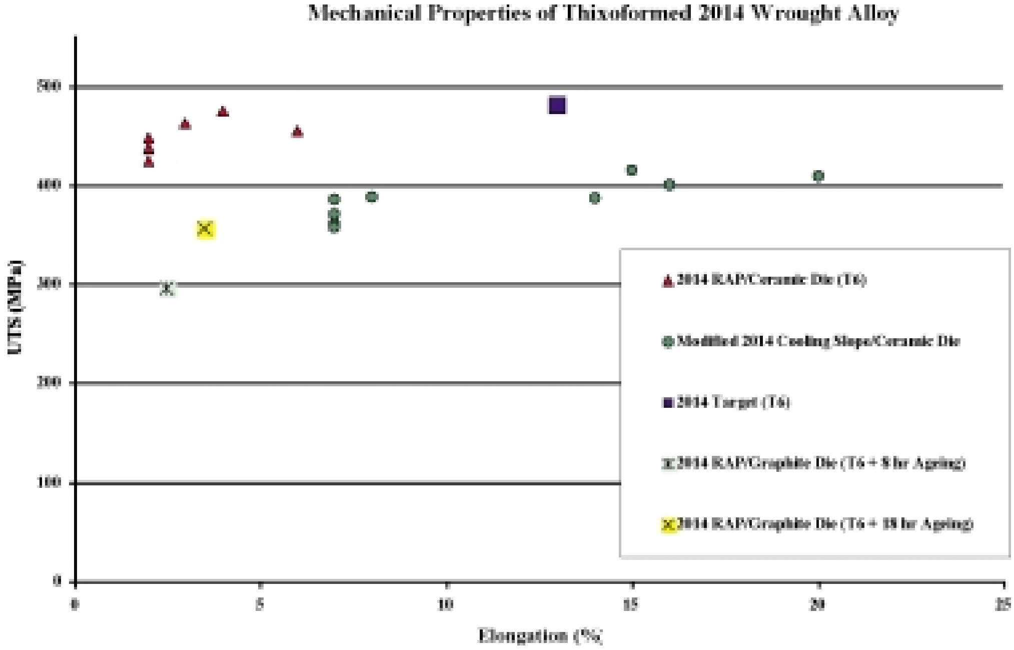
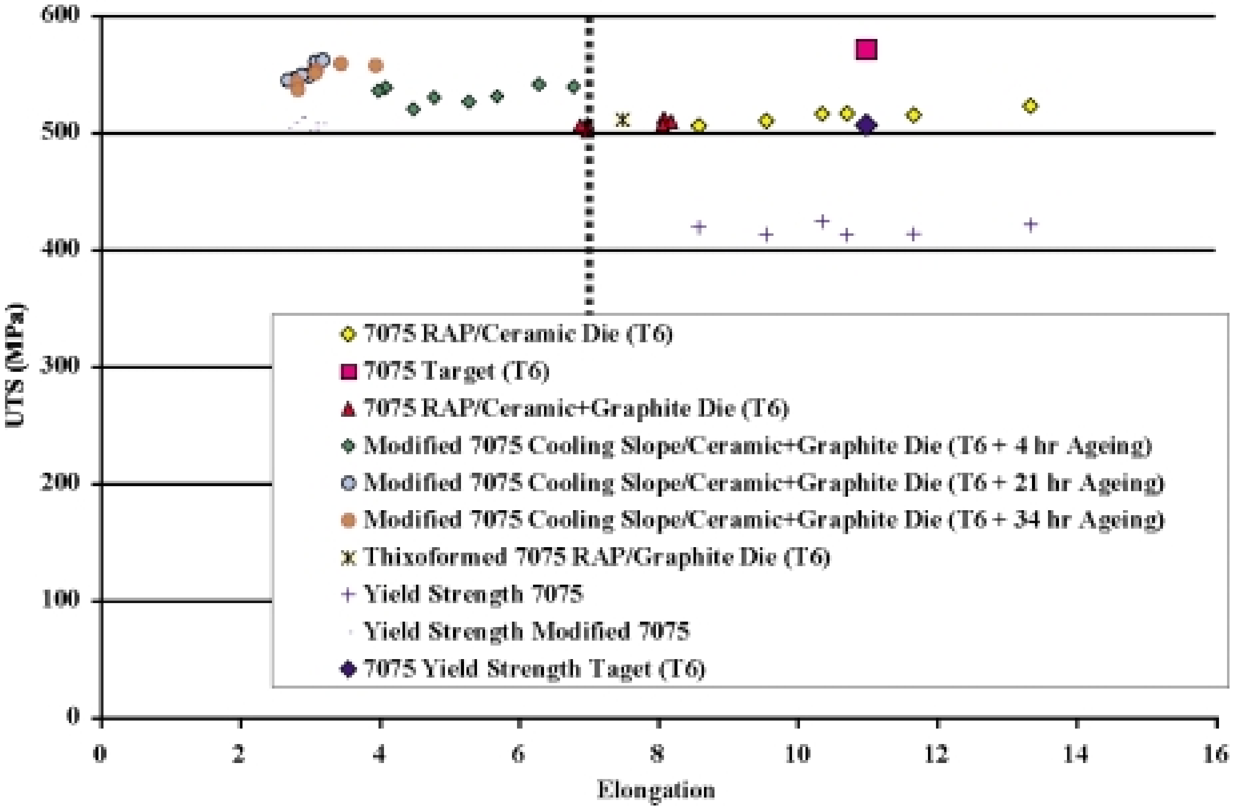


Figure 11. Mechanical Properties of Thixoformed 7075 Alloys



<u>DISCUSION AND CONCLUSIONS</u>

The results of the recent investigation on thixoforming wrought alloys have been very encouraging as confirmed by the figures above. What has become clear from this work is the fact that conventional heat treatments are not always the most appropriate when it comes to the thxoformed alloys. In addition, it is equally clear that the history and especially the cleanliness of the feedstock material are critical to the consistency and magnitude of the mechanical properties of the final products. Despite the at times narrow temperature intervals appropriate for thixoforming exhibited by these alloys, the process window has been shown to be adequate for a number of wrought alloys. Tweaking the composition can extend this process window and improve the thixoformability of these alloys, however, the flip side of such action is the fact that the properties of these alloys will also be altered and therefore not only we face the challenge of proving the thixoformability of wrought alloys but also a possible lengthy approval of once proving the suitability of the ‘new’ alloys themselves.

The fact that the 201 casting alloy, of a composition similar to the 2014 wrought alloy, when thixoformed appears to give consistent properties very similar to those expected by its wrought equivalent has been one of the highlights of the work.

Results such as described in this paper, together with the fact that new forms of solid state welding, such as Friction Stir Welding [5], that allow conventional thixoformed parts to be built to much bigger structures are hopeful signs that thixoforming might be moving to the next stage of its development, that of providing near net shape parts for aerospace applications.

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