ANALYSIS OF THE THIXOEXTRUSION OF Al-4,5wt%Cu ALLOY

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ABSTRACT This work analyses the formability of Al-4,5wt%Cu alloys in the semi-solid state, by extrusion (thixoextrusion process). Semi-solid rheocast material, produced by controlled partial melting of ultra-refined structures, was submitted to direct extrusion tests in a specially developed apparatus. Forming forces were monitored during the processes, as a function of processing time. Processing parameters analysed were volume fraction of solid (billet temperatures of 617 and 625°C), and extrusion ratio (**Re** varying from 40 to 90%). Results were as follows: good formability for all conditions, equiaxial and fine macrostructure, microstructure containing globular α-phase with no residual stress. Results also showed that forces required in semi-solid extrusion can be significantly lower than in fully solid.

Keywords: *thixoextrusion, rheocast, aluminium-copper-alloy, semi-solid forming.*

1. INTRODUCTION

Semi-solid processing originated at MIT in the early 70's with Flemings et al [1]. Since then, it was developed from a laboratory curiosity to a fully commercial process for a production of near net shape components in a variety of materials for many industries. Since the early eighties semi-solid metals has been used commercially for the manufacture of components in the automobile, aerospace, military and other high quality and safety industrial applications, by die-casting mainly. It offers new opportunities for an economical production of high performance metal parts [2].

Metals in rheocast semi-solid state include both solid and liquid components, due to the temperature of processing (within *solidus* and *liquidus* temperatures). The solid component, in this case, is a very homogeneous Aluminium α-phase with globular shape, surrounded by liquid containing high Copper content. In such a condition, the slurry presents peculiar visco-plastic properties which are quite different from those of solid metals. The bonding force among grains/globules is very weak; therefore, the semi-solid metal has very low flow stress, high formability and excellent fluidity [3].

The flow behaviour of the rheocast slurry is characterised as thixotropic, non-Newtonian. In this situation the semi-solid metal can be handled as a solid, even when containing certain liquid fraction and presents low resistance to deformation under pressure. Such behaviour means lower forming energy requirements when compared to conventional solid forming [4,5]. Taking advantage of these characteristics, new foundry technologies has been already developed.

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It was also demonstrated by many authors [6,7] that considerably less energy is required to deform semi-solid alloys when compared to solid alloys. There are many important works in the area of semi-solid processing, including results in die-casting (very high liquid fraction) [8] and in forging processes (very high solid fraction) [9] for different kinds of alloys, however, little has been done when it comes to deal with extrusion in the semi-solid state.

The aim of this work is to analyse the extrusion behaviour of Al-4,5wt5Cu in the semi-solid state, observing the influence of the process parameters.

2. EXPERIMENTAL PROCEDURE

Billets of Al-4,5wt%Cu alloy were initially prepared by grain refining with Ti/B master alloy additions to produce an ultra-refined cast structure. Semi-solid rheocast samples were produced by controlling partial melting of this structure, resulting in a fine globular, low liquid fraction slurry. The billet produced was machined to a cylinder with 19mm in diameter and 20mm high.

Extrusion tests were carried out in a vertical MTS press machine, with force control; an electrical furnace around the extrusion die and sample gives the desired solid fraction in the metal. Figure 1 shows a scheme of the experimental device used in the work; the die core is changeable to produce billets from 6 to 15mm final diameter.

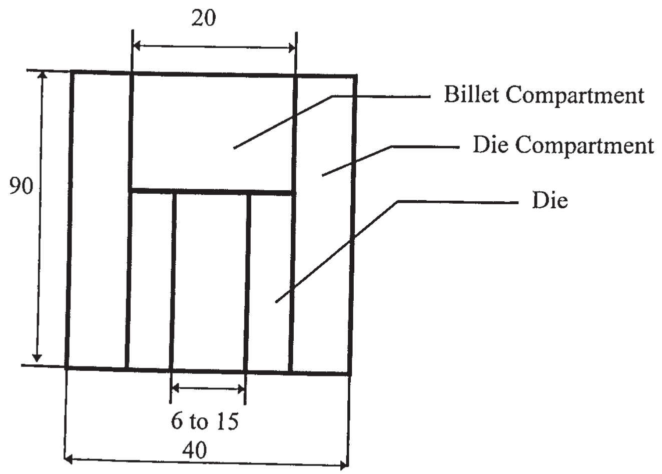

Figure 1) Scheme of the experimental device used for thixoextrusion tests.

The billets were placed in the die at room temperature. The die, punch, die-compartment and billet were heated up to the required temperature in order to obtain and maintain the appropriate semi-solid state. When the desired temperature was reached, the extrusion process was performed. During heating and extrusion, cooling of the billet must be prevented in order to maintain the appropriate liquid fraction throughout the extrusion process. After extrusion, the products were rapidly quenched in a water cooled mould positioned in the exit of the die.

The variables of the process were billet temperature and reduction Ratio (**Re**). The temperature was measured with appropriately positioned thermocouples in the die and in the billets. The extrusion force and temperature were continuously monitored by data acquisition system.

Two temperatures were utilised to produce two solid fractions: 890K (617^{0}C) for 65% of solid fraction and 898K (625^{0}C) for 85% solid fraction.

The reduction from 19mm to 6, 9, 12 and 15mm represents reduction ratio (Re) of 90, 78, 60 and 38%, respectively.

Each test condition was repeated at least 6 times.

The resulting products were prepared for macro and microstructure observations.

3. RESULTS

Figure 2 presents the extruded billets of the Al-4,5wt%Cu alloy for Re = 78% and Re = 60%. The products obtained show good quality in terms of dimensional accuracy and surface finishing, when compared to those obtained by conventional (100% solid) forming for the same extrusion ratios.

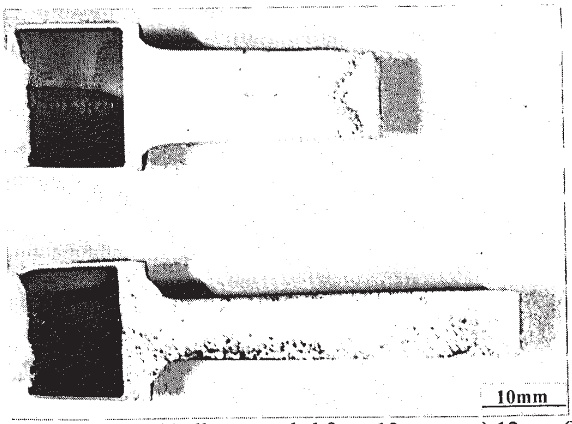

Figure 2) Macrostructures of Al-4,5wt% alloy extruded from 19mm to: a) 12mm (Re = 60%) and b) 9mm (Re = 78%).

A reverse extrusion can be observed in the upper edge of the extruded billets showing a sort of cup with very thin wall (less than 1mm thick). This confirm the high formability of the raw material.

The product's macrostructures show an homogeneous material, with fine equiaxial grains. Some liquid segregation in the initial edge of the extruded billet can be observed, due to separation of liquid/solid phases when submitted to extrusion forces. With higher magnification it is possible to observe some grain alignment in the extrusion direction; however, this orientation is not significant when compared the high orientation observed in solid extrusion, indicating that the structure is almost free of residual stresses, unlikely conventional extruded material.

Figure also shows that neither porosity nor segregation can be observed in the extruded samples.

The size and shape of grains in the semi-solid alloys are depending on the heating temperature and holding time. Fine grains usually tend to coarsen in a short time during heating and holding; therefore, the control of the heating and holding conditions is very important to get a good rheocast semi-solid microstructure, with a primary phase presenting a globular morphology and small dimensions. Globules with irregular shape and/or big dimensions will present poor flow behaviour.

The microstructure of the ultra-refined as-cast alloy (initial billet) and the final globular structure (extruded billet) can be observed in figure 3.

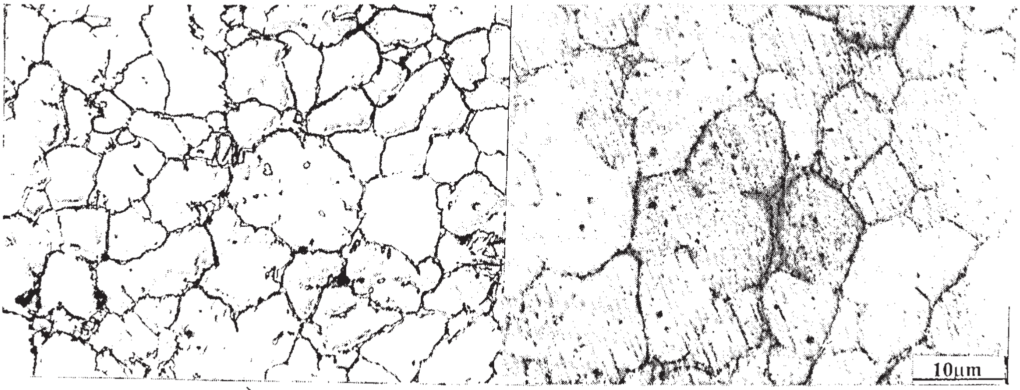

Figure 3) Microstructure of alloy Al-4,5wt%Cu in the a) ultra-refined as-cast condition and b) rheocast condition after processing by extrusion.

The as-cast structure (figure 3a) shows a very fine equiaxial dendritic structure with rosette-like morphology of aluminium α - phase surrounded by the eutectic. Initial grain sizes were in the order of 50μm.

After extrusion (figure 3b) the microstructure shows a typical rheocast structure composed by primary aluminium α - phase with globular shape (with average globular diameter around 30μm) surrounded by the eutectic phase. For the particular conditions utilised in this work (ultra-refined starting material) a very little amount of pools of entrapped liquid can be detected within the primary phase in the final product. Such pools in the slurry, typical of coarsening phenomena during structure modifications taking place to produce rheocast material, are deleterious concerning flow behaviour of the slurry and also concerning mechanical properties of the final product; therefore, their absence here is positive.

The dimensions of rosettes in the as-cast microstructure and globules in the thixoextruded are similar, indicating an easy and quick globularization process taking place to produce the rheocast material: the re-heating of cast structures is sufficient to modify the microstructure from rosette to globular.

Related to extrusion forces, Table 1 shows the maximum values as a function of temperature and extrusion ratio. The results show that higher Re, higher the necessary force for extrusion, and higher the temperature, smaller the extrusion force required. Similar tendency was observed in previous work by Lehuy [3].

Table 1) Maximum extrusion forces for both temperature in different extrusion ratios:

Extrusion ratio (Re) (%)	F_{max} for 890K (617°C) (MPa)	Temperature 898K (625°C) F_{max} (MPa)
90	534	453
78	213	108
60	78	69
38	41	28

Figure 4 shows the variation of the extrusion forces as a function of processing time for different extrusion ratios and temperatures. These curves show smooth increase in the force during the process, to reach a peak in the end (in conventional extrusion process the gradient of the curve F x t is higher from the beginning of the deformation, due to the highest resistance to deformation imposed by the solid material).

The slope of the curves increases as the deformation degree increases: for the lower Re, there is only a small variation in the applied force, indicating the high formability of the material, it flows at almost constant force (mainly in the case of the highest liquid fraction). For the higher Re, the force increases after 2-4 seconds, reaching in the end a value 4 times higher than the initial force.

It can be observed the influence of temperature: lower the liquid fraction, higher the required forces for extrusion; nevertheless, the general decrease is not too significant in the range of temperatures utilised in this work. The required forces for thixoextrusion, therefore, can be lowered by increasing liquid fraction in the feed stock (which, however, must be kept low to prevent material de-cohesion during deformation) or decreasing reduction ratio.

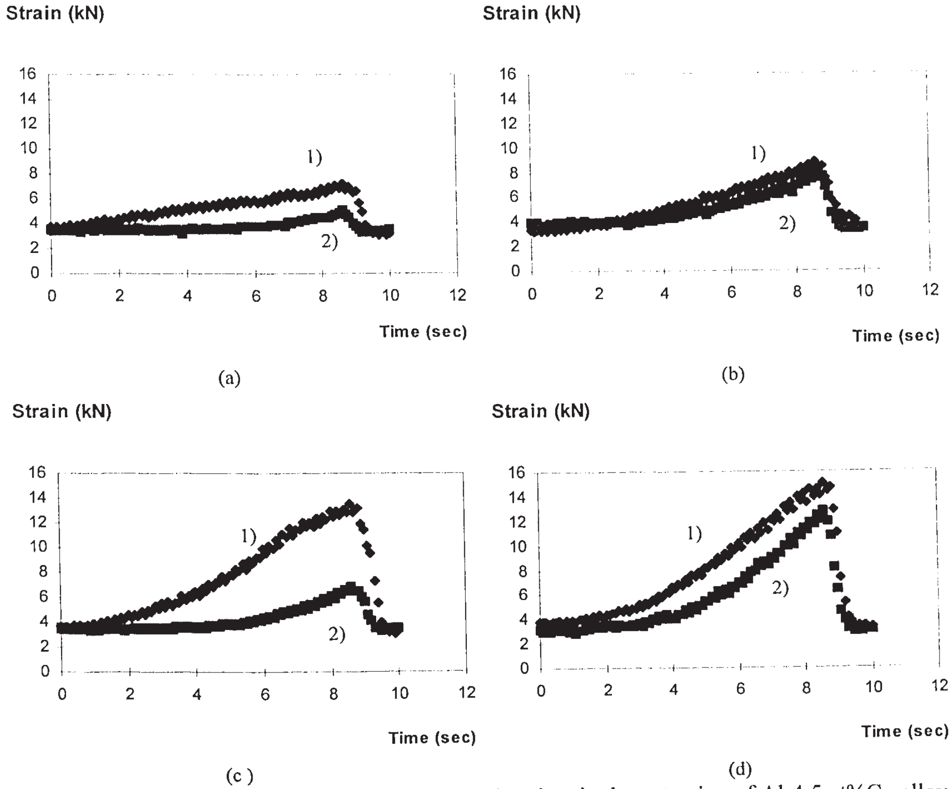

Figure 4) Extrusion forces as a function of processing time in the extrusion of Al-4,5wt%Cu alloy in the semi-solid-state. Conditions: extrusion temperatures 1) 617° and 2) 625°C; extrusion ratios a) 38%, b) 60%, c) 78% and d) 90%.

Results showed that required forces for the extrusion of rheocast semi-solid can be 75% to 80% lower than those required for conventional extrusion, due to the low flow stress of the semi-solid metal [9][10]. The small extrusion pressure required to extrude the semi-solid permit high reduction ratios (Re=90%) in only one operation.

The liquid component in the billet works as a lubricant at interfaces between die and billet, reducing the friction forces. This lubrication effect associated with the smaller required extrusion pressures make it possible that products having complex cross sections and thin wall thickness, can be extruded rather easily. So, due to the distinctively low flow stress of the semi-solid state, the extrusion of semi-solid can be performed very easily. It is possible to say that semi-solid extrusion can be utilised in the manufacturing of parts with relatively complex shapes, with good surface finishing and good properties, by a low cost process.

4. CONCLUSIONS

Extrusion of Al-4,5wt% Cu alloy in the semi-solid rheocast state was investigated. Results showed the feasibility of Al-4,5%Cu thixoextrusion at 890 and 898K (617 e 625°C), for different degree of deformation (from 38 to 90%).The equipment utilised was not complex, being suitable to produce rheocast extruded products with good dimension accuracy and very good surface finishing.

Obtained products presented fine globular homogeneous structure, with very low or nil entrapped liquid, by partial melting of super-refined as-cast material. The product obtained presents fine and equiaxial structure, free of residual stresses.

The forces required were significantly lower than those required for conventional extrusion, resulting in energy economy. This work shows that this process is very potential and effective for innovation in metal forming technology.

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