Thixoforming at the University of Sheffield

Research work at the University of Sheffield in England is helping industry to further exploit the advantages of thixoforming.

Thixoforming is the near net shaping of metals in the semi-solid state, ie within the freezing or melting range between the fully solid and fully liquid states (fig 1). During thixoforming, when the material is in the semi-solid state, it exhibits thixotropic properties, the unsupported material remaining stiff (consistency of butter) and holding its shape so it can be readily handled. However, it rapidly thins and flows like a liquid when sheared (fig 2). It is this behaviour that is the key to the thixoforming process where material flows as a semi-solid slurry into a die, as in conventional diecasting.

This behaviour is exhibited in all metal alloys that possess a specific microstructure, namely one that consists of metal spheroids. An example is αAl in aluminium alloys, surrounded by a contiguous layer of eutectic liquid when heated to the semi-solid state. This microstructure is key to producing successful thixoformed parts.

There are various routes for obtaining the necessary spheroidal microstructures, but commercially this is done either by continuous casting with magneto-hydrodynamic stirring of the melt during solidification (MHD), or through the New Rheocasting (NRC) route where the melt is cooled down into the semi-solid state prior to thixoforming.

The thixoforming process has advantages over both the casting and forging processes. These include fine, uniform and virtually free of porosity microstructures; products that may be heat treated to give mechanical properties superior to those of casting; reduced energy consumption and reduced die thermal shock and therefore longer die lives, due to the lower heat content of the semi-solid material. In addition, higher melting point alloys, such as hyper-eutectic aluminium silicon alloys with very high silicon contents (~25-40%), superalloys or tool steels, which cannot be easily diecast, may nevertheless, be thixoformed.

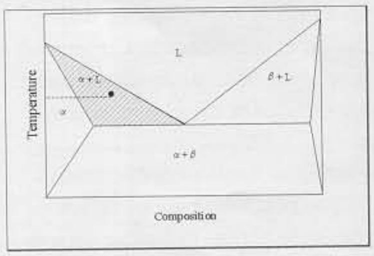

Fig 1. Schematic representation of the thixoforming range in the solid a plus liquid region. In this case the alloy is a simple binary one with a hypo-eutectic composition.

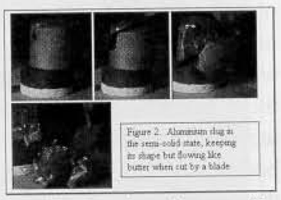

Fig 2. Aluminium slug in the semi-solid stare, keeping its shape but flowing like butter when cut by a blade.

Commercial applications

Since its discovery some 30 years ago at MIT, and especially during the past decade or so, there have been significant developments in this technology. Thixoforming is now a commercial process, with millions of components being produced each year. Recipient sectors include the automotive industry (fuel rails, suspension and engine parts). Aluminium alloys are used with conventional or slightly modified diecasting alloy compositions, eg Al-7Si-0.3-0.6Mg (356/7 type alloys) and for the consumer products/electronics markets mainly using magnesium alloys (computer, VCR, mobile phones accessories, sports goods).

The full scale manufacture of thixoformed components has been assisted by the introduction of flexible diecasting machines. Several companies have now introduced such flexibility into their machines, recognising the future importance of semi-solid metal processing technology.

Because of the fine microstructures and the high integrity associated with thixoformed products, they can replace steels and forged, machined or cast aluminium parts, with the consequent saving in manufacturing time and weight.

Summarising some of the advantages of thixoformed parts over conventional castings:

- energy savings of about 35%
- reductions in component weight
- higher strength and integrity
- close tolerances and improved surface finish
- clean technology, and foundry safety due to absence of large quantities of molten metal, and low noise levels.

Expertise at Sheffield

The group at Sheffield, has experience with a large range of metal alloys and composites. These include several aluminium alloys (356, A356, 357, A357, 319, 390, 2000, 6000 and 7000 series alloys, Al-SiC metal matrix composites, various 'sprayformed' aluminium high silicon alloys), M2 tool steels, ductile iron, stainless steels, cobalt based super alloys (Stellites), tin-lead alloys, and high electrical conductivity copper alloys.

As well as looking for new applications for conventional alloys, the group has examined methods of tailoring alloy compositions and microstructures to suit the particular characteristics of the thixoforming process.

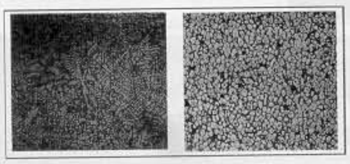

Fig 3. Conventional dendritic cast microstructure (left) compared with spheroidal thixoformable microstructure.

As a relatively new process, before proving its value as a commercial success, thixoforming has had to exploit alloys that were already available.

However this phase of development is now over and millions of thixoformed automotive parts are now in every day use in the cars we drive. An expanding portfolio of alloys specifically designed to exploit the potential of the thixoforming process is required to strengthen its market potential, but also address the urgent needs in the aerospace industry for near net shape, high strength, aluminium products.

Alloy development work at Sheffield involves developing an understanding of the key scientific principles on which alloy design and development for semi-solid processing must be based, and to produce aluminium alloys specifically tailored to exploit the thixoforming process and with performance approaching that of the wrought specification aluminium alloys.

Analytical techniques utilised are a combination of

- thermodynamic modelling using MTDATA with the current NPL Alloy Solution Database (version 1.1)
- thermal analysis
- heat treatments/quenching coupled with quantitative metallography.

CFD modelling

Computational fluid dynamic (CFD) modelling of die filling during thixoforming places particular demands on the software package being used. Not only are the velocities of the metal slurry in the die very high, the viscosity is too, and in addition it also changes with shear rate (ie with changes in cross sectional area of the region the slurry travels through) and with time, as the injected material is thixotropic.

The CFD software therefore requires good free surface tracking, accurate implicit solutions of the flow equations (as the CPU times for explicit solutions at high viscosities are impractical) and a model that adequately describes the slurry thixotropy. Finally, reliable, experimentally determined viscosity data are required.

Fig 4. Thixoformed aluminium automotive parts (top): engine brackets and steering knuckle (courtesy of Stampal SpA) and thixomoulded electronic magnesium components (courtesy of Thixomat Inc).

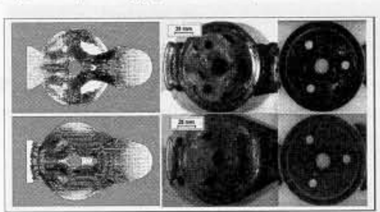

Fig 5. Illustrating the power of CDF to aid die design. The top row shows the effect of flow in the die using a conventional fully liquid diecasting entrance. The holes in the component near the entrance on the right are accurately predicted using CFD. X-rays of the components reveal gross porosity where the flow fronts have re-converged. The lower row shows a much improved flow pattern, with a steady progression of the flow font obtained by tailoring the entrance design. The final product is defect free.

The approach at Sheffield has been in the form of experiments on tin-lead and aluminium alloy slurries using rapid compressive tests, which closely mimic commercial thixoforming conditions and rotating cylinder viscometry, followed by modelling using 'FLOW-3D'. This package is known for its ability to track free surfaces accurately. Compressive tests allow rapid changes in shear rate to be imparted to the slurry, without wall slip, while the simple geometry of the viscometer makes it possible to compare analytical and numerical solutions.

It is important that the flow of the semi-solid material remains unbroken, otherwise the final product will contain defects. Using experimental data obtained using semi-solid rapid compression testing and CFD modelling to accurately predict the flow pattern, the die entrance of a simple 'end-plate' design was modified from a conventional fully liquid diecasting type entrance.

The final product with the tailored entrance was shown to be free of defects by x-ray (**fig 5**). Note the close match between the CFD simulation of the flow pattern and the final product, arising from sound, experimentally verified input data.

High temperature working

The Thixoforming Group is one of the few groups currently working with high temperature materials. The group is backed up by the resources of the Department of Engineering Materials, in the areas of alloy preparation, chemical and microstructural analysis. More details on the activities of the group are described on its web site (http://www.shef.ac.uk/uni/academic/D-H/em/SSM/index.html).

For its practical research work and feasibility studies (demonstrator component production), the group uses a vertical, computer controlled, servo-hydraulic thixoforming press, with 100 tonne die clamping force. The ram of the press has a stroke of one metre, maximum load of 10 tonnes and maximum velocity of two metres per second. The press is computer controlled and is capable of applying customised velocity and load profiles to the semi-solid thixoforming slugs. Metal dies can be heated to 300°C (allowing isothermal work with Sn-Pb alloys) and can be fitted with a load cell to measure directly the die filling loads. However, because of the very low loads involved in thixoforming, dies made of graphite, machinable or castable ceramics are also routinely used.

Heating of alloy slugs in the semi-solid state is provided in-situ, using a versatile, 100kW medium frequency induction heater. The press is capable of performing the entire thixoforming cycle within a protective gas atmosphere, and is therefore particularly suitable for the thixoforming of ferrous, copper based and other oxidation prone alloys.

The group has over 15 years research experience on all aspects of thixoforming and provides fully confidential consultancy services. In addition it is expected that a fully commercial spin off company will be formed in 2002 that will be associated with the University. Further details can be obtained from Dr P Kapranos (p.kapranos@sheffield.ac.uk).

Summary

Thixoforming is a rapidly emerging technology. It produces complex near-net-shaped components of high integrity, with mechanical properties better than cast components. Current commercial applications rely mainly on aluminium alloys, based on conventional diecasting alloy compositions. However, the technique is suited to processing a diversity of alloys, including those that may not be shaped easily by conventional casting techniques. Research work is in progress with various alloys, both aluminium and high temperature alloys, to further exploit the potential benefits of this significantly under utilised metal forming technique.