

# Thixoforming of Stellite Powder Compacts

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**Abstract.** Thixoforming involves processing metallic alloys in the semi-solid state. The process requires the microstructure to be spheroidal when part-solid and part-liquid i.e. to consist of solid spheroids surrounded by liquid. The aim of this work was to investigate whether powder compacts can be used as feedstock for thixoforming and whether the consolidating pressure in the thixoformer can be used to remove porosity from the compact. The powder compacts were made from stellite 6 and stellite 21 alloys, cobalt-based alloys widely used for e.g. manufacturing prostheses. Isothermal heat treatments of small samples in the consolidated state showed the optimum thixoforming temperature to be in the range 1340°C-1350°C for both materials. The alloys were thixoformed into graphite dies and flowed easily to fill the die. Porosity in the thixoformed components was lower than in the starting material. Hardness values at various positions along the radius of the thixoformed demonstrator component were above the specification for both alloys.

**Keywords:** Thixoforming; semi-solid processing; stellite; powders.

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## INTRODUCTION

The shaping of an alloy in the semi-solid, rather than fully liquid state as in casting, or in the fully solid state as in forging, offers many advantages. These include energy savings, reduced die wear and a fine and homogeneous microstructure. Semi-solid processing utilizes the thixotropic behaviour of alloys in the semi-solid state; provided the microstructure consists of solid spheroids in a liquid matrix it will flow when sheared but thicken up again when allowed to stand [1]. Many aluminium and magnesium alloy components are now manufactured commercially by semi-solid processing. The challenge is to extend the application of the process to a wider range of materials including those which require higher temperature treatment and oxidize during reheating, such as the stellites. These are Co-Cr-based alloys which have excellent resistance to many forms of mechanical and chemical degradation over a wide temperature range [2]. They are used for a range of applications including power

generation, automotive, aerospace and medical (eg. for prostheses). However, forming these materials into shape (including machining) is difficult because they are hard. Components are generally produced by casting or powder metallurgy. Here we set out to investigate whether consolidated and sintered billets can be shaped by thixoforming. Previous work using powder based thixoforming feedstock routes has concentrated on Al-based systems eg. 2124Al+SiC<sub>p</sub> composites from cold compacted mechanically alloyed powder [3] and densified hypereutectic Al-Si [4]. Co-Cr alloys have previously been processed by thixoforming using sprayformed feedstock and material produced using a deformation/recrystallisation(RAP) route [5,6] but this study represents the first using Co-Cr alloy thixoformable feedstock produced from powder.

## MATERIALS AND EXPERIMENTAL PROCEDURE

The material was produced by spray atomizing followed by consolidation and sintering. The powder particle size is <45µm. Cylindrical slugs (32mmΦx 40mm) of stellite 6 (S6) and stellite 21 (S21) alloy were supplied by Deloro Stellite. The melting range for stellite 6 is 1282-1393°C and for stellite 21, 1338-1366°C. The nominal compositions are given in Table 1. Stellite 6 has a high C content and exhibits excellent wear resistance. Stellite 21 has less C and additions of Mo to promote the formation of Mo carbides. This leaves more Cr in solution [2], and the material is more suited to applications where corrosion resistance is important.

	C	Cr	Fe	Mn	Mo	Si	W	Ni	Co
S6	1.15	27.8	3	1 max	1 max	1.15	4.5	-	Bal.
S21	0.25	28	2 max	1 max	5.5	2 max	-	2.5	Bal.

**Table 1.** Nominal chemical compositions of stellite 6 and stellite 21 (all compositions are in wt% unless otherwise stated).

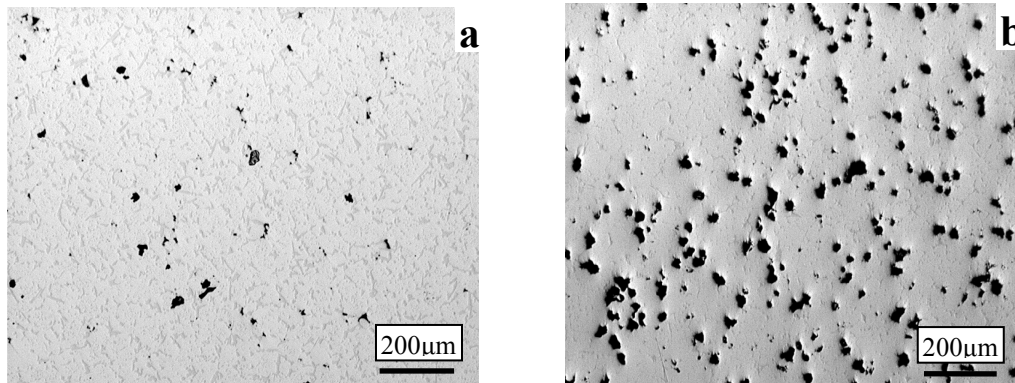
Isothermal heat treatments of the samples were carried out in a vertical tube furnace in air. Samples were held isothermally for 5 minutes and quenched into water. The samples were polished to 0.25µm colloidal silica and examined optically and with image analysis. Thixoforming was carried out using the 100kN servo-hydraulic thixoforming press at the University of Sheffield with an injection velocity of 500mms<sup>-1</sup>. The dies were machined in-house from graphite. Reheating to the required temperature was accomplished using induction heating under a shielding atmosphere of either nitrogen or argon to avoid excessive oxidation of the surface of the samples during heating to the semi-solid state. The reheating time was ~ 6 minutes.

## RESULTS AND DISCUSSION

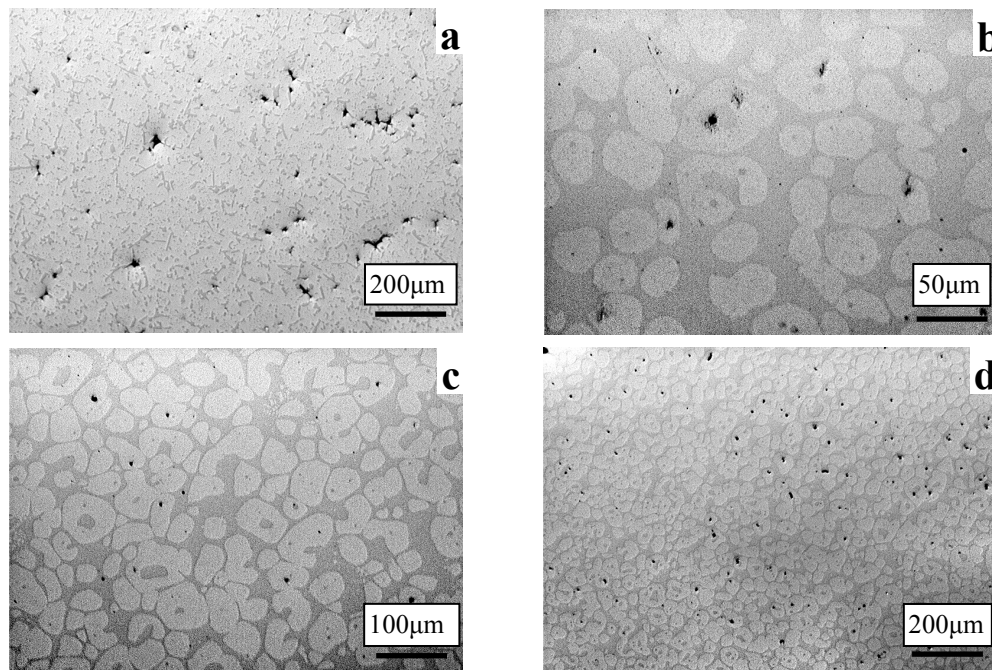
### Microstructure of Starting Material and Isothermal Heat Treatments

The as-received microstructures of S6 and S21 are given in Fig. 1. The porosity levels found using image analysis were ~1 area% for S6 and ~7 area% for the S21.

Both microstructures consisted of a primary Co-rich matrix phase (fcc at the thixoforming temperature) plus carbide phases which typically consist of  $M_6C$ ,  $M_{23}C_6$  and/or  $M_7C_3$  carbides [7].



**FIGURE 1.** a) Stellite 6 and b) Stellite 21 in the as-received condition, showing differing porosity levels.



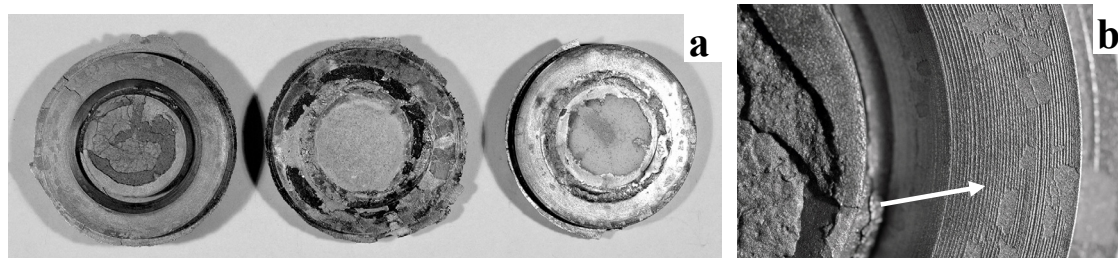
**FIGURE 2.** Optical micrographs of the S6 alloy isothermally heat treated for 5 minutes at a) 1330°C, b) 1340°C, c) 1350°C, d) 1360°C.

Candidate thixoforming temperatures for the two alloys were 1330-1360°C for S6 and 1345-1355°C for S21. Fig. 2 shows the microstructure of S6 at various holding temperatures. At 1330°C, no liquid was present after 5 mins. At 1340°C and above, liquid was present and the microstructure evolved to give discrete spheroids surrounded by liquid; the required microstructure for thixoforming. 1340°C was selected as the thixoforming temperature as it is generally good practice to thixoform at as low a thixoforming temperature as possible whilst still obtaining die filling; this minimizes shrinkage effects and die wear. For S21, all the heat treatment temperatures produced spheroidal solid particles with contiguous liquid but there was less liquid

present than in the S6 samples. This arises because of the reduced carbon content and therefore the reduced amount of eutectic (which forms liquid). A thixoforming temperature of 1350°C was selected for this alloy.

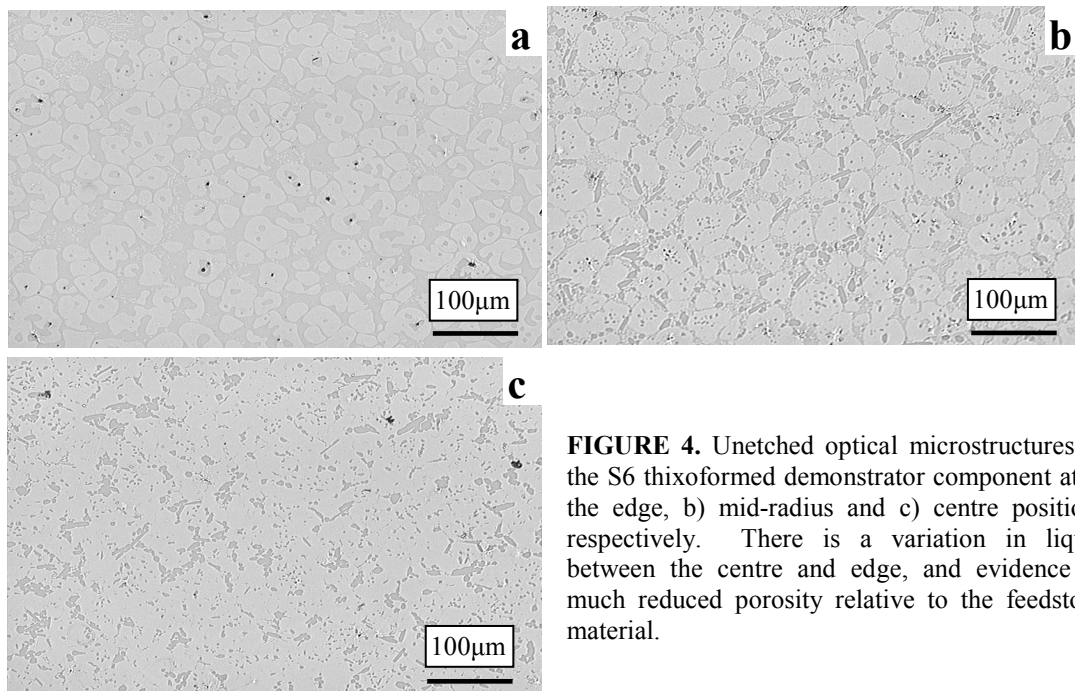
### Heating Schedule Trials and Thixoforming

For the S6 alloy, a simple disc shaped die cavity was used with changes in section and sharp corners to indicate the ability of the semi-solid material to fill the die. The die machining marks were reproduced in the outer ring of the component as shown in Fig. 3, indicating the potential to produce complex shapes using this technique. There was oxide present on the surface despite the use of cover gas. In industrial practice, techniques have been established to remove this by skimming the surface as the material enters the die.



**FIGURE 3.** a) Appearance of three of the S6 thixoformed components and b) Image of the outer ring of the component showing that the machining marks on the die surface have been reproduced.

The microstructures in the thixoformed component at the centre, mid-radius and edge of the component are shown in Fig. 4.



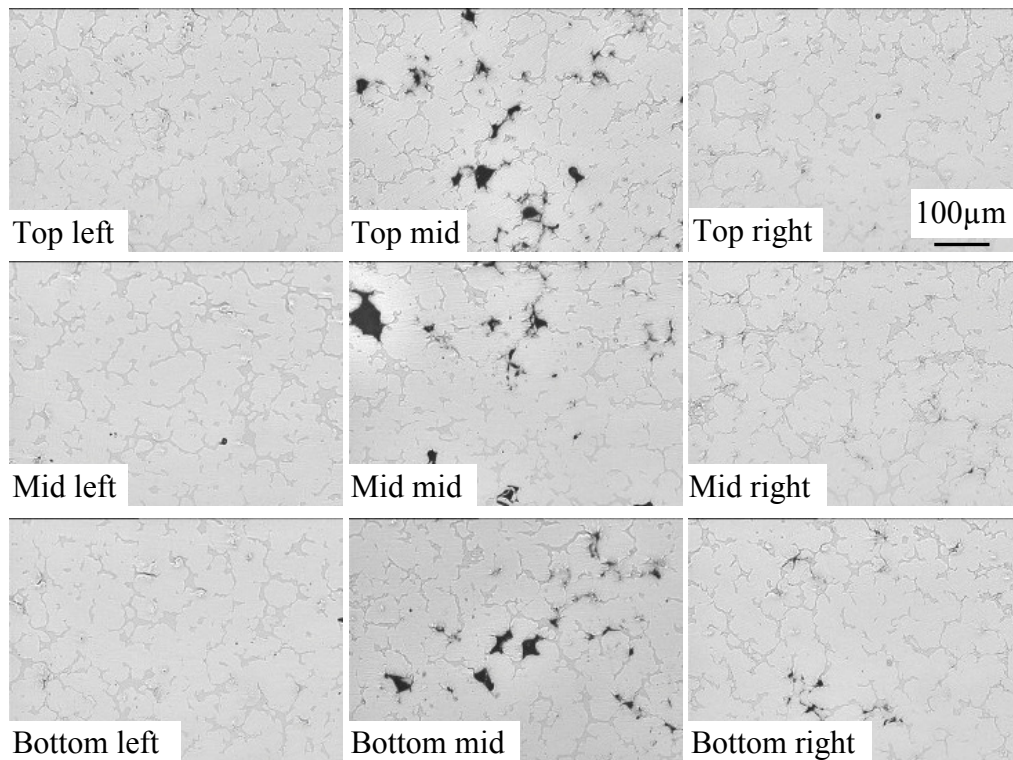
**FIGURE 4.** Unetched optical microstructures of the S6 thixoformed demonstrator component at a) the edge, b) mid-radius and c) centre positions respectively. There is a variation in liquid between the centre and edge, and evidence of much reduced porosity relative to the feedstock material.

More liquid is evident at the edge. This arises from the non-uniform microstructure in the partially remelted slug prior to thixoforming. The heating schedule could be

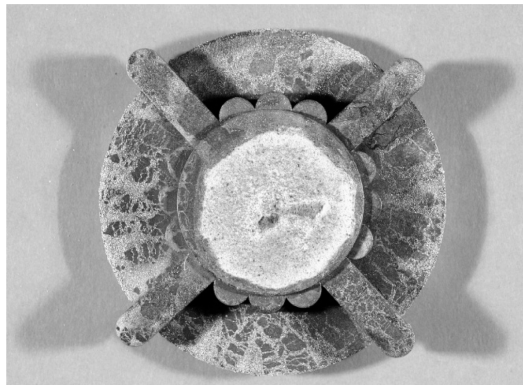


refined to reduce this variation and hence inhomogeneities in the final component. The carbides present in the starting material (Fig. 1) may have reprecipitated but in a form too fine to be resolvable with optical microscopy at these magnifications. The thixoforming has not had a deleterious effect on the hardness as will be shown later. The porosity level in the thixoformed component taken at five positions along the sample radius and determined by image analysis was approximately 0.2 area%. This indicated that thixoforming was effective in virtually eliminating the porosity present in the feedstock material.

For S21, a star-shaped component with several protrusions, sharp corners and changes in section was produced. The microstructure was more uniform than for the S6 demonstrator (Fig. 5).



**FIGURE 5.** Unetched optical microstructures at various positions in the heat treatment sample slug. The microstructure consists of relatively spheroidal grains surrounded by a contiguous layer of liquid.



**FIGURE 6.** Appearance of the S21 thixoformed component.

This was due to the relative uniformity of the microstructure in the slug prior to forming as shown in Fig. 5. The component is shown in Fig. 6. The porosity levels in the thixoformed component were ~1.75 area% at the edge, 0.75 area% at the mid-radius position and between 1 and 7 area% at the centre. The relatively high levels were associated with regions where the material had not flowed laterally. Again overall

these results indicate that thixoforming can be effective in reducing the porosity in consolidated powder feedstock material. Hardness values in the thixoformed S6 material ranged between 43-46 R<sub>c</sub>. This compares with a specification value of 39-43 R<sub>c</sub>. For S21, the range was 38-41 R<sub>c</sub> compared with a specification of 30-35 R<sub>c</sub>.

## CONCLUDING REMARKS

Thixoformable feedstock can be produced from atomized and consolidated powders of the high temperature Co-Cr alloys Stellite 6 and Stellite 21. Thixoforming temperatures were 1340°C for S6 and 1350°C for S21. Demonstrator components were produced using graphite dies and heating to the semi-solid state in ~ 6 minutes. The microstructures exhibited variations in the liquid content from the centre of the component to the edge. Porosity in the S6 components was approximately 0.2 area%, indicating that thixoforming had been effective in virtually eliminating the porosity present in the sintered feedstock. Porosity in the S21 thixoformed component was greater, but only in regions where lateral flow of the semi-solid slurry had not occurred. The hardness values taken at various locations in the components were 43-46 R<sub>c</sub> for the S6 alloy and 38-41 R<sub>c</sub> for the S21 alloy. These values are above the specification for this alloy.

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