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THIXOFORMING - A NEAR NET SHAPING PROCESS

POSTOPEK NATANČNEGA OBLIKOVANJA "THIXO"

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Thixoforming of an electric motor endplate. Optimisation of die design. Optimisation of the forming process. Verification of internal filling by X-radiography and seeing of flow pattern. Product quality and dimension reproductibility. Analysis of defects origin.

Keywords: thixoforming, near net-shape, semi-solid metal processing

Končne plošče elektromotorja, izdelane po postopku ulivanja "thixo". Optimizacija oblike orodja. Optimizacija oblikovanja. Preverjanje notranje polnitve z radiografijo in verifikacija pretoka materiala. Kakovost in ponovljivost dimenzij. Analiza vzrokov napak.

Ključne besede: postopek "thixo", oblika blizu končne, oblikovanje v polstaljenem stanju

1 INTRODUCTION

Thixoforming- or Semi-Solid Metal Processing (SSM) - is the shaping of metal components in the semi-solid state. For this to be possible the alloy must have an appreciable melting range and before forming the microstructure must consist of solid metal spheroids in a liquid matrix. In this state the alloy is thixotropic: if it is sheared the viscosity falls and it flows like a liquid but if allowed to stand it thickens again. A slug of alloy, heated into the semi-solid state, can be cut with a knife and spread like butter, provided the microstructure is non-dendritic. This extraordinary behaviour was first discovered at MIT[1] and has since led to extensive work on the thixotropy of alloy slurries and the exploitation of the process, using the advantages afforded by filling a die with a lower temperature slurry which flows in a non-turbulent manner.

Several companies in Europe, Japan and the US have recently started to manufacture in this way, producing millions of components annually for the motor industry[2]. However, it should be borne in mind that production of all aluminium castings in North America, Europe and Japan is ~2,500,000 tonnes, of which thixoforming represents only around 1%. Pressure die casting and permanent mould casting are still dominant.

One of the issues affecting theuniversal acceptance of thixoforming by industry is a lack of publicly available quantitative data justifying the claim that thixoformed components really are "near-net shape". The work in this paper aims to provide such data and show that thixoforming can live up to this claim. This is done by means of a study on the thixoforming of a demonstrator component - an electric motor endplate. The steps taken to produce and assess the quality of this component are described below.

2 THIXOFORMING OF THE ELECTRIC MOTOR ENDPLATE

2.1 Optimisation of Die Design

The motor endplate is a disk with a central hole for a rotor shaft and a spigot at the edge for fitting to the motor body. Usually, there are flanges for mounting bolts, often tailored to customers' requirements. These pose problems for pressure die casting, especially if only a short run is required and customised endplates often have to be made by sand casting of grey iron. The task at Sheffield University was to show that good quality, reproducible endplates could be thixoformed using a standard casting aluminium alloy, into a non-hardened steel die. The intention in industry would be to make quickly non-hardened "half dies" or inserts to accommodate customised mounting flanges, thereby cutting down on costs with respect to pressure die casting and reducing lead times in comparison to the cast iron route.

The die **(Figure 1)** - manufactured by our partners, Brook Hansen Ltd. - was first designed according to conventional pressure die casting practice, with a tapered runner and narrow gate to allow easy removal of the biscuit from the component. Feeding was from the side rather than the centre so that the rotor boss did not need to be drilled. An overflow was placed opposite this entrance. This configuration is best seen from the photograph of the thixoformed endplate - **Figure 2**. The die material was H13 (non-hardened) and the alloys used

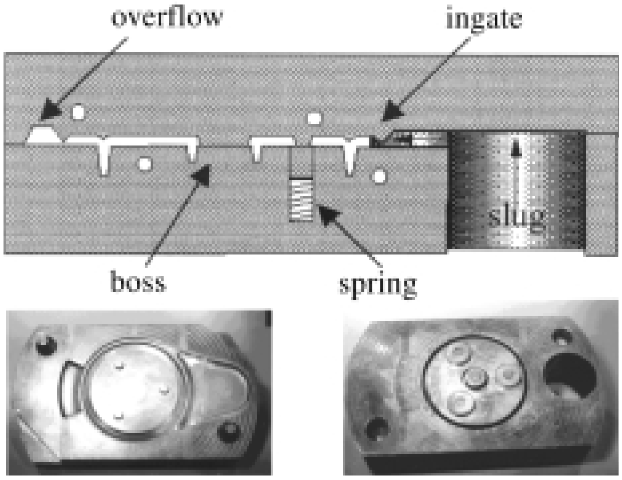

Figure 1: Die used for thixoforming the endplate
Slika 1: Orodje za "thixo" oblikovanje končne plošče

were Al/7Si/0.3Mg and Al/6Si/3Cu/0.4Mg, produced commercially by magnetohydrodynamic (MHD) stirring, which is a method of obtaining the spheroidal microstructure.

Thixoforming was performed using the University of Sheffield thixoforming press (made by Servotest Ltd). The vertical configuration of the press allows *in situ* heating, which means that the cylindrical slugs of the alloy do not require transfer to the press while semi-molten. This method of heating requires that the top of the ram on which the slugs sit be non-metallic. Induction heating of the slugs was by a medium frequency generator (Taylormade Induction Ltd. Bakewell). The billet size was 75 mm high by 60 mm diameter.

Optimisation of thixoforming consisted of the following stages:

– Induction heating and thixoforming trials to establish a reproducible slug heating regime and the ram velocity and die temperature necessary to ensure complete die filling. Checking of product quality using X-radiography. Partial die fills in order to see the flow pattern.
– Reproduction using CFD of the flow patterns found experimentally. The only parameter adjusted in the model to achieve correspondence between the model and the experiment was the viscosity of the slurry.
– Use of the CFD model to redesign the die to give the best die filling pattern, consistent with practicability in production.
– Adjustment of the die, further thixoforming and verification of the prescriptions of the model using partial fills and radiography.

It was possible to obtain a complete thixoformed component using a cold die. However, it was found that the tapered ingate in the initial die design caused the slurry to flow preferentially down the centre of the component, filling the overflow early and then flowing back towards the entrance. This narrow fluid flow front caused entrapment of air, which could be seen in radiographs, even in samples thixoformed into a die heated to 350 °C.

Using flow modelling and partial die-filling studies[3], it was demonstrated that a narrow gate produces defects near the die entrance, whilst both widening the gate and deepening it improved die filling but that the former was more critical and more practical. The widening of the entrance allows a more even flow across the whole width of the component. The overflow fills last: the slurry is not reflected back from the far end of the die. The marked improvement in product quality achieved through flow modelling and die modification meant that it was possible to move on to a study of reproducibility.

2.2 Study of Product Quality and Reproducibility

A run of 25 endplates with the modified die was carried out. They were examined for internal defects using X-radiography. The samples were taken to Brook Hansen Ltd. and inspected visually for external defects, according to their standard practice for pressure die castings. Twenty-five pressure die cast endplates, which had passed the visual inspection stage at the manufacturers, were also examined by X-radiography.

Figure 2: Thixoformed electric motor endplate
Slika 2: Oblikovana končna plošča za električni motor po postopku "thixo"

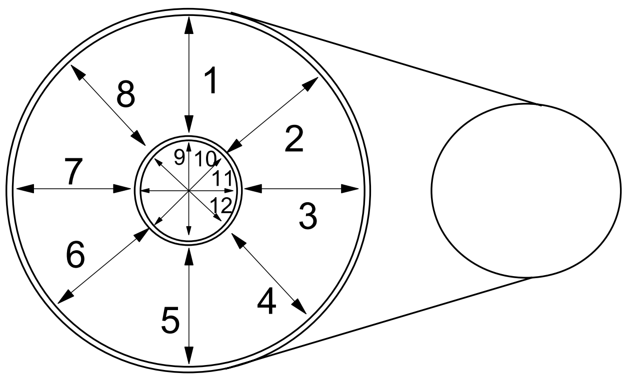

Figure 3: Positions of dimensional measurements of thixoformed endplates
Slika 3: Mesto dimenzijskega preverjanja oblikovane končne plošče po postopku "thixo"

Of the 25 shots thixoformed, one was rejected after radiography as possessing too great a quantity of internal porosity. Four samples were rejected by the inspector, due to a failure of the flow fronts to weld fully as they met at the far side of the spigot, near the overflow. The cause of these defects is discussed below. The quality of the other 20 shots was extremely high, as evidenced by the radiograph in **Figure 3**, where a comparison with a typical pressure die cast endplate is made.

In order to study reproducibility, a special jig was constructed for mounting the endplate on a dividing head. Of particular importance with the motor endplate is the concentricity of the rotor shaft hole and the spigot on the endplate rim. A significant deviation would mean that the rotor would not run true and the life of the motor would be reduced. Twelve dimensions, as shown in **Figure 4**, were measured using an electric probe, accurate to ±0.005 mm. The mean values of the bush-spigot distances and the internal bush diameter were evaluated. It was also useful to compare some of the 12 measures over all 20 components. Using these, it was possible to isolate any variation which may be due to inaccurate manufacture of the die or to distortion of the face of the endplate. Finally, the die itself was measured before and after the 25 shots.

The results of the measurements on the endplates are presented in **Figures 5 and 6**. For measurements 1-8, the maximum difference over all the specimens was 0.16 mm (tolerance ±0.08 mm), while for 9-12, the value was 0.10 mm (tolerance ±0.05 mm). Even these raw figures are within the tolerance limits for pressure die cast aluminium of ±0.13 mm and ±0.10 mm respectively. The measurements on the die before and after the series of shots showed no differences that could result from wear. For instance, the slot which forms the spigot was found to be narrower in some regions, which presumably was due to build-up of lubricant.

Figure 7 shows that, in general, where one dimension is greater than the mean, the measurements on the opposite side of the plate and perpendicular to these two are also larger (but there is one outlying measurement on sample no. 107). This means that the plate as a whole is larger and that the small differences

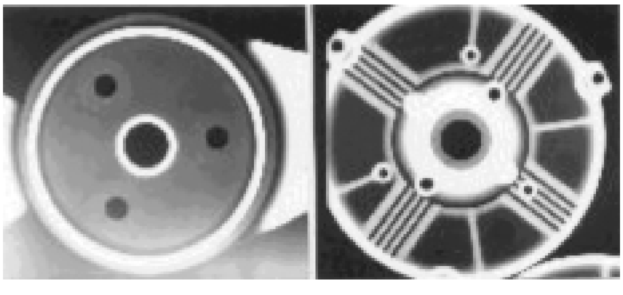

Figure 4: X-ray radiographs of a) thixoformed and b) die cast endplates

Slika 4: Radiografija a) oblikovane plošče po postopku "thixo" in b) v kokilo ulite plošče

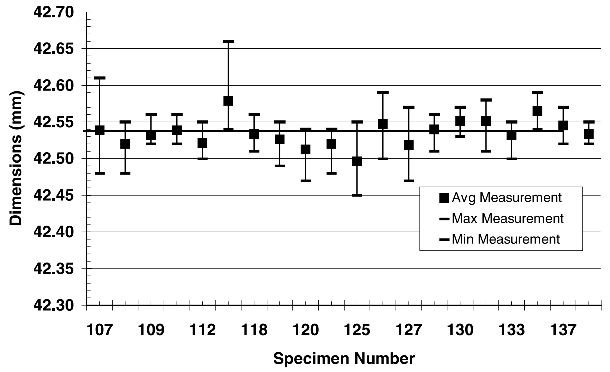

Figure 5: Dimensional variability of thixoformed endplates at positions 1 to 8

Slika 5: Dimenzijska sprememba oblikovane plošče na mestih 1 do 8

in dimension in the thixoformed endplates that were recorded cannot be attributed to changes in the die shape or to distortion of the endplate face.

It is likely that the cause of this variation in overall size between the endplates is that in the Sheffield press the component is removed from the die manually. The differences in time (and temperature) of removal are exacerbated by the fact that some shots were more difficult to remove than others. This was because the pedestal used to hold the slug in the induction heater and force it into the die is made from a non-conducting, non-metallic material (Sindanyo or Tufnol). Wear of these materials causes "backflow" of metal slurry around the pedestal which binds the component more tightly into the die. A difference of 50 °C in the temperature of the component on removal could lead to a change of 0.05 mm in dimensions 1-8. Sample 116 was particularly difficult to remove from the die and it is therefore not surprising that it was one of the largest components.

Another possible source of scatter in the measurements is that they were made on faces with a 2° draught angle and which were not completely smooth, containing machining marks from the die. Thus, the

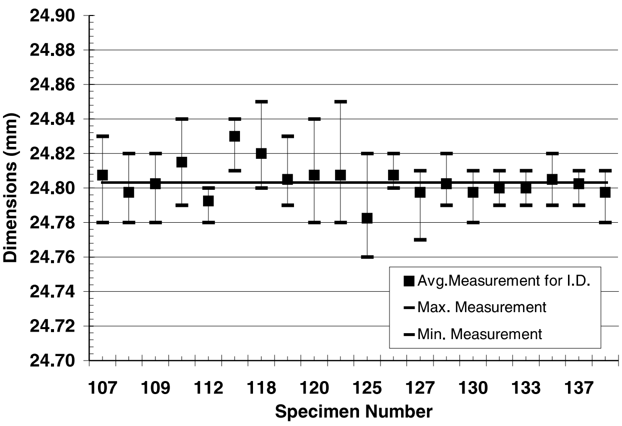

Figure 6: Dimensional variability of central hub diameter in thixoformed endplates

Slika 6: Dimenzijske spremembe centralnega pesta oblikovane končne plošče

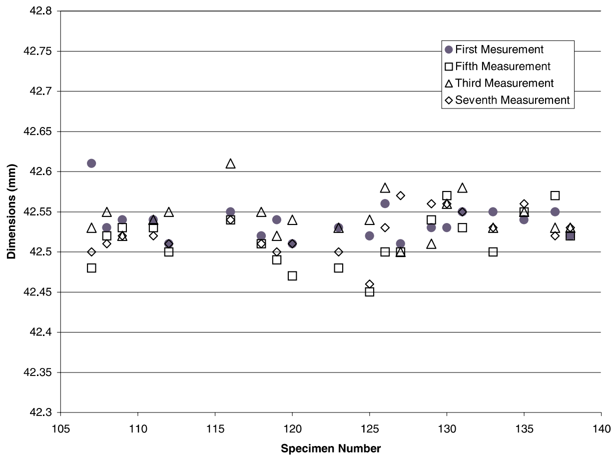

Figure 7: Dimensional variability between thixoformed endplates
Slika 7: Dimenzijske razlike med oblikovanimi končnimi ploščami po postopku "thixo"

position at which the probe contacted the sample was important. This was one of the reasons for constructing a jig to hold the sample. It is difficult to estimate how much this might have affected the measurements but their repeatability was checked by dismantling the jig and dividing head and then rebuilding it and measuring two components for a second time. The average difference between the new and old measurements was 0.02 mm.

Finally, it is necessary to account for the rejected shots. These can mainly be attributed to the "backflow" effect: the freezing of slurry around a worn pedestal preventing the ram from completing its travel. The result is that the overflow and the spigot will not be completely filled, or some internal porosity is present. Backflow would not occur in a press which used metal rams.

3 CONCLUSIONS

This paper has described the process of producing and assessing a high-quality thixoformed component, using a standard aluminium die casting alloy, forced into a non-hardened steel die. It has been shown that die designs based on conventional pressure die casting practice are inadequate. In particular, the higher viscosities of the metal slurries used in thixoforming require modified runners and gates. The design of these can be aided greatly by CFD modelling and this tool will be used more and more in all aspects of die design for thixoforming. (Evaluation of CFD modelling for thixoforming is the subject of another programme at Sheffield).

Radiography shows that product quality can be expected to be consistently higher than is found with pressure die casting. Confidence in the internal structural integrity of a product will allow manufacturers to avoid "overdesign" and thereby to make lighter products. Tolerances in the thixoformed components have also been shown to be within those required of the critical dimensions of pressure die castings. The method of measurement was able to show that there was no discernible distortion of the face of the motor endplate. Automated removal of the component from the die would allow the manufacture of thixoformed components to even stricter tolerances than the excellent results achieved in this study.

Thixoforming is clearly a process with near net-shape capability.

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