Performance Evaluation of Aluminium Alloy 7075 for Use in Tool Design for the Plastics Industry

A.G. Buys[a], V. Cain[b], R.D. Knutsen[c]

Received 3 June 2009, in revised form 27 January 2010 and accepted 12 February 2010

The performance of a high-strength aluminium alloy AA7075 as a candidate injection mould material has been assessed. Particular attention has been focussed on the thermal and wear performance of the AA7075 alloy compared to a standard EN19 tool steel alloy. In view of the fact that aluminium often fails due to poor wear resistance, surface treatment of the aluminium alloy was implemented by hard anodising. The assessment was performed by manufacturing three mould insert sets of identical design from each of the materials, namely EN19 steel, AA7075 and AA7075 in the hard anodised state. Each insert set was subjected to 10 000 shots in an injection moulding machine. The core temperature of the inserts was measured during moulding and wear was assessed by comparing profile measurements of the mould cavities before and after moulding. The EN19 steel and uncoated AA7075 inserts did not show signs of wear whereas edge retention was impaired by hard anodising. The higher thermal conductivity of aluminium compared to conventional tool steel was not affected by hard anodising.

1. Introduction

As the result of a survey of the plastics conversion industry in the Western Cape, South Africa, it was learned that aluminium alloys are widely used in blow moulds where low pressures are experienced. Aluminium is generally favoured in this application due to its ease of machining and favourable thermal conductivity. Parts of the mould prone to high wear such as the clamping areas are often designed with tool steel inserts to increase lifetime. The wear is due to these areas having to pinch and cut the parison (a hollow, warm plastic tube suspended between the mould halves). The main body or label area of the mould is usually constructed of an aluminium alloy. It is generally accepted that aircraft grade aluminium alloy, AA7075, is the preferred material for blow moulds due to its combination of good strength, wear resistance and surface qualities as compared to other aluminium alloys. The AA7075 alloy contains significant Mg, Zn and Cu additions which give rise to precipitate strengthening during ageing heat treatments.

a Student member SAIMechE, Researcher
E-mail:: buysalex@gmail.com.
b MSAIMechE, Lecturer, Researcher, Mechanical Engineering Department, Cape Peninsula University of Technology, P.O Box 652, Cape Town, 8000
E-mail: cainv@cput.ac.za
c MSAIMechE, Director, Centre for Materials Engineering, UCT, Private Bag X3, RONDEBOSCH 7701
E-mail: Robert.Knutsen@uct.ac.za

The situation is quite different in the injection moulding industry in that tool steels are mostly used as a mould material and aluminium alloys are only used for short runs and prototypes. In particular, companies that produce large quantities (millions) of thin walled items only use tool steel due to the high clamping forces (between 1 500 and 3 000 N) and injection pressures related to this type of moulding. Maintaining the surface finish and edge retention even after hundreds of thousands of shots is a driving factor in this mould material choice. Notwithstanding this requirement, the use of aluminium alloys can be attractive due to their outstanding machinability as demonstrated by higher cutting speeds and prolonged cutting tool life[1]. These benefits can lead to cheaper mould manufacture and faster delivery times, particularly given that it is sometimes claimed that machining time is typically three times faster than tool steel. Furthermore, aluminium alloys are approximately one third the density of steel and this allows for simpler handling and easier mould changes. Lower inertia of the moulds can make it possible to increase the opening and closing speeds of the moulding process, thereby decreasing the cycle times as well as exerting less strain on the process machinery. Better thermal conductivity of the alloy can aid in improving the cycle time by cooling the moulded part faster. According to Harris *et al*.[2], the faster the cooling rate the less crystallinity is developed in certain polymers and thus the less shrinkage is observed in the part. Despite the advantage offered by higher thermal conductivity, the main drawback with using aluminium as a mould material is increased susceptibility to wear. Although several opinions exist regarding the relative merits of using aluminium alloys in the design of injection moulds, there are no records of systematic studies conducted to assess the performance of aluminium alloys in injection moulding. The purpose of the present work is to investigate the relative performance of tool steel, uncoated AA7075, and hard anodised AA7075 inserts during standard injection moulding cycles with a view to assessing the applicability of using aluminium in certain injection moulding processes. Emphasis is placed on the characterisation of the mould inserts before and after moulding in order to establish wear behaviour, particularly with regard to the prospect of wear being reduced by hard anodising the AA7075 alloy.

2. Experimental Methodology

A standard production injection moulding process was utilised to mimic actual processes in a commercial factory. To this end a Super Master 90 (Asian Plastics) toggle clamping machine, equipped with a standard water chiller was set up in a testing laboratory. The two mould materials employed for comparison in this study were sourced locally and were used in the condition specified by the supplier. The low alloy EN19 tool steel was supplied in the hardened and tempered condition which realised a Brinell hardness (HB) value of 330. The AA7075 alloy was heat treated to the maximum strength T6 condition for optimising wear resistance with an average hardness of 185 HB.

2.1 Mould design

Identical mould insert sets were manufactured for each material variable. The mould cavity was designed to produce a simple key tag as demonstrated in figure 1(a). The key tag product is 70 mm long, 35 mm wide (maximum), 2 mm thick and the lettering is 0.5 mm deep. The intention of the product design was such that the lettering provided high definition to allow critical monitoring of the wear behaviour of the cavity surfaces. Although the focus was directed at the assessment of the wear of the cavity surfaces as a result of the polymer flow during injection, attention was also given to assessing damage on the parting faces and outside edges of the cavities which experience high clamping forces during each mould cycle. The key tag was moulded from polypropylene because of its rigidity and ease of moulding.

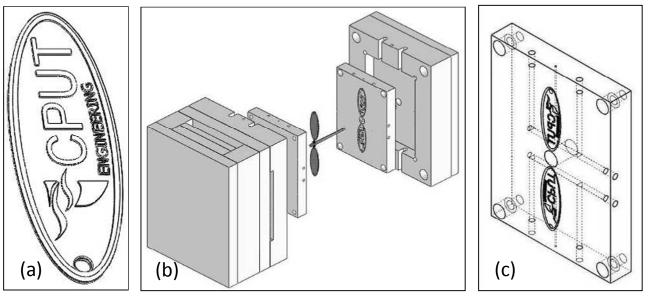

Figure 1: Injection mould and insert design.

The insert sets were mounted in an insert-and-bolster arrangement as shown in figure 1(b). Figure 1(c) indicates the dual cavity configuration which was incorporated to retain symmetry in the mould. The cooling channels were also designed to accommodate 1.5 mm diameter Type-K thermocouples which were placed inside the injector insert at approximately the centre position for each product. Temperature was continuously measured during the moulding process to assess the relative heat conductivity of each insert set. Although the moulding process was performed in an experimental laboratory, the injection moulding machine was set up to simulate real production conditions. In order to assess the endurance of the insert sets, each set was subjected to 10 000 shots with an average cycle time of 17 seconds. The total number of shots was based on information gained from local toolmakers; the expectation to observe a measurable amount of wear after 10 000 shots and a related study, which was recently completed[3] (where the batch size was 10 000 shots).

Rama Krishna *et al.*[4], Rateick *et al.*[5] and Forn *et al.*[6] suggest, in their research involving hard anodising of aluminium, that a layer thickness of between 30 and 60 μm should be applied. The hard anodising process can generally be complex, often due to factors such as bath temperature, base alloy composition, acid concentration and agitation. This can lead to inconsistent results. Different aluminium alloys yield different anodic layer growth rates. However, it is generally accepted that an estimation of the anodic layer thickness is obtained by keeping the product in the anodising bath for one minute per micrometre anodic layer thickness required. To produce the anodic layer on the AA7075 insert set, it was immersed in an electrolytic bath of sulphuric acid with a concentration of 220 g per litre at 0 °C for 50 minutes. The voltage and current settings of the process were 35-40 Volt and 350-400 Ampere respectively. After anodising, the inserts were sealed in distilled boiling water for 30 minutes. A sample of the aluminium alloy was hard anodised in the same bath as the insert set to verify the thickness of the anodic layer. The polished cross-section of this sample is presented in figure 2 and indicates an oxide layer thickness of approximately 70 μm.

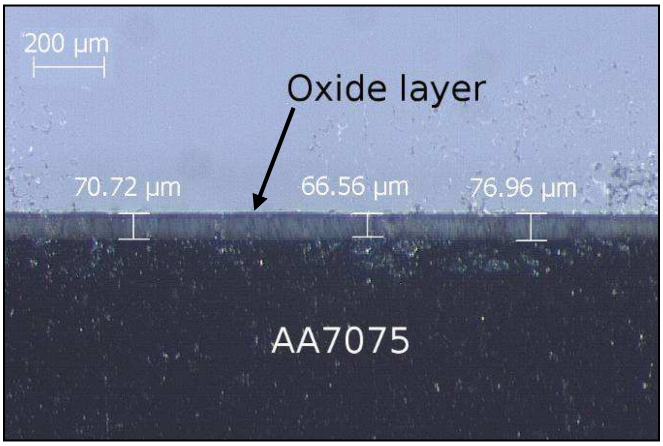

Figure 2: The hard anodised layer (aluminium oxide) has an average thickness of 70 µm.

2.2 Assessment of wear resistance

In order to assess the propensity for wear damage of the cavity detail as function of the number of mould cycles, the profiles of the inserts were measured at specific locations using a Renishaw Cyclone three-dimensional scanner. The repeatability of this instrument is 5 μm[7]. A probe of 100 mm long with a ball diameter of 0.5mm was used to follow the surface contours at a pitch of 0.01 mm (i.e. measurements were recorded at intervals of 0.01 mm as the probe moved in the X or Y direction). The same areas were also examined using a Leica MZ8 stereo light microscope to complement the profilometry analysis. The high definition detail was measured before and after moulding to determine dimensional changes that may have occurred as a result of wear during moulding. The specific measurement locations included profiles across the bosses (raised 4 mm diameter circle that forms the hole in the key tag) and the logo in the X direction, and along the length of the cavities in the Y direction as indicated in figure 3.

Although the profilometry analysis intends to determine the extent to which the cavity detail has been altered during moulding, the relatively high temperature of the cavity surface also suggests that the AA7075 alloy might be susceptible to microstructural change as a result of over-aging during exposure to elevated temperature. In order to assess this probability, the hardness of the AA7075 alloy was measured before and after moulding.

3. Results and Discussion

The moulding process was successfully carried out at 10 000 shots for each insert set and from an operational perspective, the mould sets behaved nearly identical. Slight

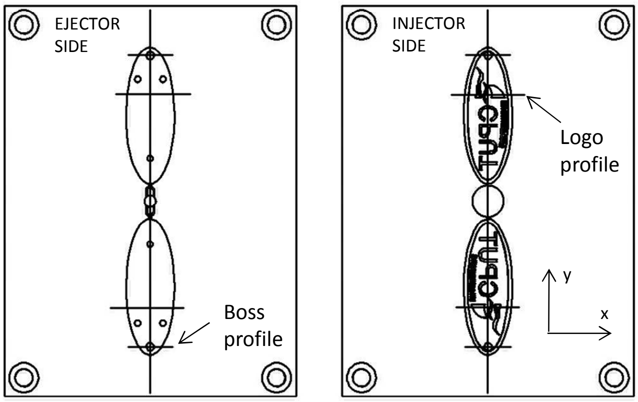

Figure 3: The various profiles that were measured on the insert sets before and after 10 000 shots

differences in the thermal cycles were detected by the thermocouples that were placed inside the injector inserts despite the fact that the constant flow of cooling water was maintained at 12.5 °C. Figure 4 exhibits a graph of the thermal profile for each insert set during production. The molten polymer, which was at a temperature in the region of 220 °C, was injected into the mould cavity over an interval of 1.7 s during each cycle. The mould was held closed for ±3.5 s after injection to effect sufficient cooling before the product was ejected. The entire cycle lasted 17 s and consequently a thermal print was developed for each cycle as the temperature increased during injection and decreased thereafter. Although the recorded temperature rise in all the insert sets was more or less constant at ±3.4 °C, the shape of the temperature profile was influenced by the different insert materials as shown in figure 4. The tool steel profile shows a rounded shape at its apex, while both aluminium inserts indicate a much sharper apex. In addition, the tool steel insert reached its maximum temperature at 33 % of the cycle time while both aluminium alloy inserts reached their maximum temperature at 20 % of the cycle time. The sharp apex and steeper heat gain of the aluminium alloy inserts indicated that the higher thermal conductivity of the aluminium alloy provided a much faster response to temperature change in the mould. The hard anodised layer does not produce a noticeable effect on the thermal conductivity of the aluminium alloy in this case. Furthermore, the bulk hardness of the aluminium alloy was not altered by the elevated temperature exposure during the moulding process and thus indicating that the temperature rise was insufficient to cause significant microstructural change.

The wear resistance of the mould insert sets was investigated by comparing the 3D scans before and after the production process involving 10 000 shots for each set. Emphasis was placed on identifying deviations in the respective profiles that may have been caused by wear during moulding. If there was minimal deviation in the profile after comparing the situation before and after moulding then it was considered that wear did not take place.

Profile measurement was repeated along the same traverses that are indicated in figure 3 after 10 000 shots and were compared to the original profiles that were acquired before injection moulding. In order to illustrate the extent to which the cavity surfaces have been altered as a result of the injection cycles, the form of the profiles in the Y direction of the lower and upper cavity edge as well as the profiles in the X direction over the lower and upper logo of the injector side are compared. The position of these profiles is illustrated in figure 5 and the actual profiles, both before and after moulding, are exhibited in figures 6 – 8.

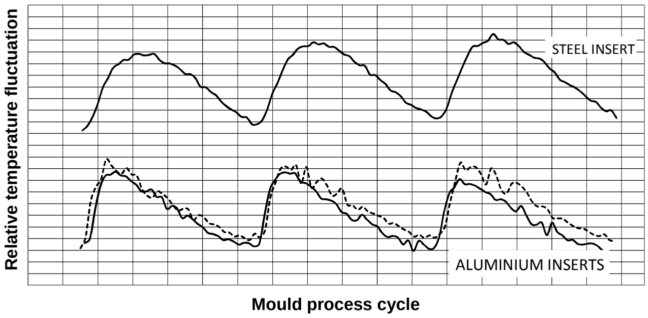

Figure 4: Comparison of the thermal profiles for the different inserts as function of mould process cycle.

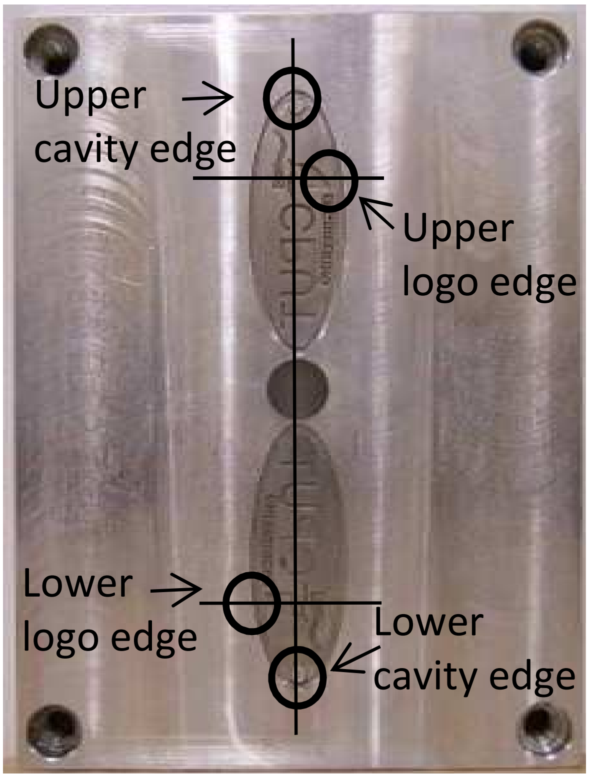

Figure 5: Injector side insert indicating the position of the lower and upper logo and cavity edge profiles which are compared in figure 6

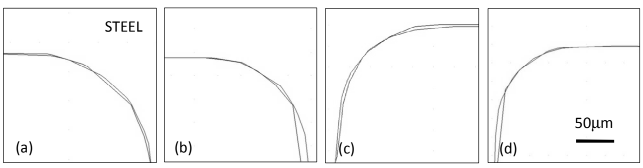

Figure 6: Comparison of cavity profiles for the steel insert set before and after 10 000 shots: (a) and (b) lower logo and cavity edge; (c) and (d) upper logo and cavity edge

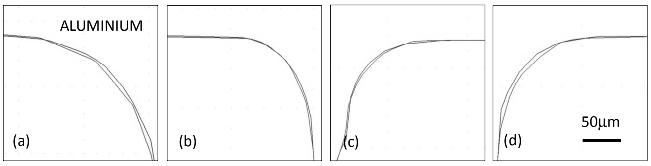

Figure 7: Comparison of cavity profiles for the aluminium insert set before and after 10 000 shots: (a) and (b) lower logo and cavity edge; (c) and (d) upper logo and cavity edge

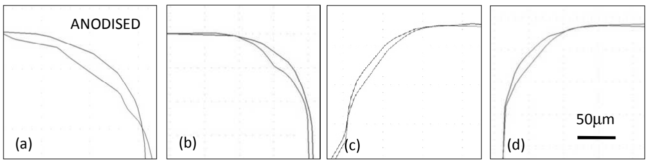

Figure 8: Comparison of cavity profiles for the anodised aluminium insert set before and after 10 000 shots: (a) and (b) lower logo and cavity edge; (c) and (d) upper logo and cavity edge

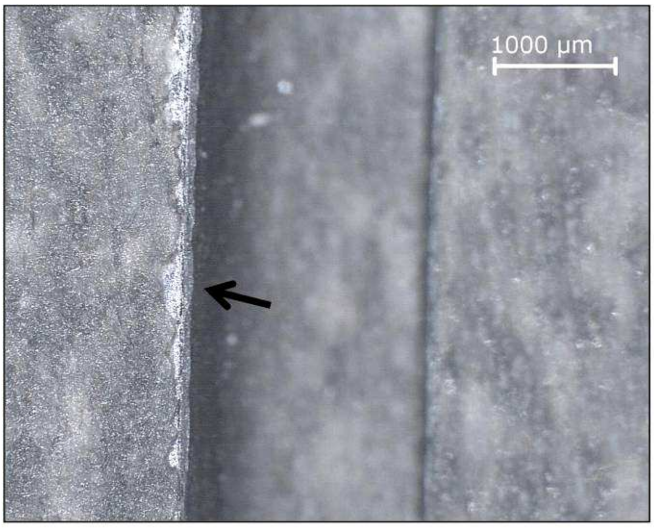

Figure 9: Fracture of aluminium oxide at sharp edge inside mould cavity

The rounded profile of the edges in figure 6, 7 and 8 are created by the spherical shape of the measuring probe used. The profiles for the steel cavity in figure 6 illustrate that the general shape had not changed and consequently the cavity did not suffer any damage at all after 10 000 shots. This is not unexpected as this grade of tool steel is commonly used for injection moulding and often endures many more than 10 000 shots in a lifetime. The uncoated aluminium alloy insert profiles shown in figure 7 also indicate that the cavity surface has retained its original edge profile and thus has not suffered any notable wear or deformation after 10 000 shots. The hard anodised insert profiles, on the other hand, differed from the previous two materials in that significant deviation from the original profiles can be detected as demonstrated in figure 8. There is a distinct "flattening" of the anodised surface on all of the edges and it is evident that material has been removed. This situation is demonstrated in all the profiles and is further supported by visual examination of the cavity edges. In a number of cases, particularly on the lower cavity, the base aluminium alloy is clearly visible when examined using low magnification light microscopy. An example of visible deterioration of the cavity edge is shown in figure 9. The hard anodised layer has been removed at the cavity edges as a result of the combination of the brittle behaviour of the anodised layer and the higher localised stress at this point. The abrupt transition between the hard anodised layer (aluminium oxide) and the base material provides an incompatibility in the accommodation of stress, and consequently the anodised layer fractures thereby causing wear. Although this damage to the cavity did not manifest in any alteration in the appearance of the polymer product, this situation will become more exaggerated as the number of shots increases. Therefore, it is indicated that despite the higher hardness of the anodised layer and the expectation that better wear resistance would be provided, the susceptibility to edge damage has been identified. Consequently, there may be very little advantage, if any, in considering hard anodising surface treatments where precise retention of cavity edges is required. However, it may still be advantageous to employ anodising to promote general wear resistance when retention of edge detail is less important. Although this particular aspect was not studied carefully in the present work, it was noticed that the anodised insert set was much less prone to pitting wear on the insert mating faces compared to the steel and uncoated aluminium insert sets.

4. Conclusion

The ability to produce moulded parts, up to 10 000 shots, was not influenced by the choice of material type for the mould insert sets. The thermal cycle, which was determined from thermocouples placed inside the mould insert, indicates that the higher thermal conductivity of the aluminium alloy does translate into faster heating and cooling response in the mould. Consequently, aluminium alloy insert sets may provide an opportunity to decrease the cycle time and hence increase the production rate. However, indications of wear on the cavity edges of the hard anodised aluminium inserts suggest that the brittle property of the aluminium oxide layer leads to fracture of the anodised layers at high local stress concentrations. This problem could become exaggerated with increasing number of shots if high definition of detail is required to be maintained in the cavity.

5. Acknowledgements

The authors are grateful to the Department of Science and Technology, and in particular the Advanced Metals Initiative (AMI), for providing financial support for the duration of the project. Special thanks are also extended to SASOL Polymers, South Africa for their donation of polymer materials. Furthermore, the authors also acknowledge the ongoing support provided by the National Research Foundation, and the Research Committees of the University of Cape Town and the Cape Peninsula University of Technology.

References

1. *Uddeholm Tooling*, Svenska, Sweden, High strength aluminium (brochure), http://www.uddeholm.com, November 2004, 2009.
2. *Harris RA, Newlyn HA, Hague RJM and Dickens PM,* Part shrinkage anomalies from stereo lithography

injection mould tooling, *International Journal of Machine Tools and Manufacture*, 2003, 43, 879-887.

3. *Smithers Rapra Technology Research Report,* Shropshire, UK, Development of high performance anodised aluminium tools for the thermoplastic moulding sector, p. 4-6, http://www.rapra.net, 2009.
4. *Rama Krishna L, Sudha Purnima A and Sundararajan G,* A comparative study of tribological behaviour of micro-arc oxidation and hard-anodized coatings. *Wear*, 2006, 261, 1095-1101.
5. *Rateick RG, Binkowski TC and Boray BC,* Effect of hard anodize thickness on the fatigue of AA6061 and C355 aluminium, *Journal of Materials Science Letters*, 1996, 15(15), 1321-1323.
6. *Forn A, Picas JA, Baile MT, Martin E and García VG,* Microstructure and tribological properties of anodic oxide layer formed on Al-Si alloy produced by semisolid processing, *Surface & Coatings Technology*, 2007, 202, 1139-1143.
7. Renishaw Cyclone Scanning System, Data sheet, http://www.renishaw.com, 2009.