PERFORMANCE EVALUATION OF ALUMINIUM ALLOY 7075 FOR USE IN TOOL DESIGN FOR THE PLASTIC INDUSTRY

by

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DECLARATION

I, Alexander George Buys, declare the contents of this thesis represent my own unaided work and the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology

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ABSTRACT

The objective of this project was to measure the performance of high-strength aluminium alloys as injection mould material compared against conventionally used tool steel.

Particular attention was paid to the thermal and wear performance of the tool steel and aluminium alloy used as the mould material. As aluminium has a substantially lower wear resistance than tool steel, a hard anodised mould insert was manufactured to establish if the wear resistance of the aluminium could be improved with surface treatment.

As thermal conductivity of an aluminium alloy is far greater than steel, it was considered beneficial to use this alloy to reduce the cycle time of the injection moulding process.

Three mould inserts were designed and manufactured. Each insert was in turn fastened into a modified bolster for testing in an injection moulding machine, to simulate an industrial environment. One insert was manufactured from M201 tool steel, a common alloy used for injection moulding, two others, were manufactured from aluminium 7075–T651 The three inserts were manufactured identically, but one aluminium insert was hard anodised.

Each insert set was run in a 90 ton toggle clamping injection moulding machine for at least 10 000 shots. The core temperature of each insert was measured during the moulding runs to monitor thermal behaviour Pre- and post-geometrical measurements were also made to establish wear

The thermal measurements indicated the profile of the aluminium alloy inserts showed a steeper gradient during heating (injection of the hot polymer) and a sharp apex, while the tool steel insert expressed a rounder profile. The aluminium alloy reached its peak at 20% of the cycle time, whereas the tool steel insert reached its maximum at 33% of the cycle time. This faster rate of thermal energy absorption might result in faster cycle times during production, even cooling and less complicated cooling channel designs. The hard anodised aluminium insert's thermal profile had a profile similar to the uncoated aluminium insert, therefore, the anodised layer had an insignificant effect on the thermal behaviour of the mould.

All inserts completed 10 000 shots without significant quality loss to the product. The hard anodised insert did show material loss on the sharp edges around the cavity (the hollow in the mould face resembling the product shape) indicating that the anodic layer began chipping off at stress concentrated areas. Higher clamping forces experienced on the lower half of the

mould - caused by imperfect alignment - resulted in pitting on the lower half of the steel and uncoated aluminium inserts. This effect was not observed on the hard anodised insert face.

The chipping, evident around the cavity of the hard anodised insert was caused by the stress concentrations at the sharp edges. At these places the concentrated stress and differences in thermal expansion between the base alloy and the anodic layer aggravated the creation and propagation of micro-cracks. The hardness of the anodic layer resisted pitting on the insert - as found on the tool steel and the uncoated aluminium alloy

There was concern that contact of the aluminium alloy 7075-T651 with the hot polymer might cause a heat treatment effect thereby deteriorating its properties. Hardness values of the aluminium alloy taken before moulding were compared with values taken at the cavity and on the split face after moulding.

There were no significant differences in the hardness values before and after moulding, therefore, it is believed the aluminium alloy maintained its properties during the moulding run.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1 1 Background

The Advanced Metals Initiative, with funding from the Department of Science and Technology is interested in promoting the use of light metals in South Africa's engineering industry The subject of "high performance aluminium alloys for use in the plastic moulding industry" was proposed.

Currently certain tool steels are frequently used in the manufacture of plastic injection moulds. Aluminium alloys are also used, but usually only for short runs and prototype moulds. A run is an amount of products produced. There is no fixed rule regarding the difference between a long (full production) and a short run. For the purpose of this work, a short run is in the region of a few hundred to thousands of shot (mouldings); long runs can amount from hundreds of thousands to millions of shots.

Injection moulds were the focus of this project in order to promote the use of aluminium in mould design in the Western Cape. Aluminium alloys are also widely used in other processes such as blow moulding and vacuum forming because of the lower forces involved

Aluminium alloys could be extremely beneficial to the plastic moulding industry as mould materials because of properties such as:

- High thermal conductivity resulting in faster cooling times and even cooling of products;
- advantageous machining properties such as high cutting speed, low cutting forces, excellent finish, close control of dimensions and longer cutting tool life resulting in lower mould manufacturing costs (Handbook of Aluminium 1970:84) and
- lighter moulds resulting in easier mould handling

Tool steel is often used as a mould material for injection moulds because of its high wear resistance and surface finish retention. Wear resistance is the area where aluminium and light alloys are weak. Poor wear resistance results in a short mould life. At this point the condition of the mould affects the product quality or production, leading to the mould having to be discarded.

Because of injection moulds normally being highly expensive, companies try to avoid them failing prematurely by rather using high-wearing tool steels and various surface treatments to increase their lifespan.

To improve the performance of aluminium alloys as injection mould materials a suitable alloy was to be chosen, as well as a surface treatment to improve the wear resistance.

These test moulds were to be run in an injection moulding machine, simulating an industrial environment to provide a comparison between the mould materials' performance.

1.2 Aims

The aim of the project was to determine the current use and technologies available regarding light metals (particularly aluminium) in the South African plastic moulding industry with particular attention to the Western Cape. This project also deals with developing a comparison between tool steel moulds and aluminium alloy moulds.

The investigation was performed with the following objectives.

- Investigate current plastic moulding industry practices;
- investigate available aluminium alloys (as well as their mechanical and physical properties);
- investigate the suitability of aluminium alloy moulds for plastic moulding as well as a suitable treatment to increase the materials wear resistance;
- investigate different mould designs that could benefit from the use of aluminium;
- design and manufacture a suitable mould incorporating the use of coatings to improve the wear resistance and,
- compare the moulds via a pre-determined test procedure.

2 Literature Review

2.1 Injection moulding

In the production of moulded plastic products many types of dies or moulds are used to confine a quantity of moulding material as it hardens to a desired shape.

Many processing systems are in use because of the variety of materials available and a reluctance of manufacturers to discontinue the use of old equipment and techniques.

Some examples of processes used in industry are: continuous extrusion, vacuum forming, rotational moulding blow moulding, reaction injection moulding (RIM) and injection moulding (Dubois & Pribble, 1987:2).

Continuous extrusion involves molten plastic forced through a die to form long components of a required cross-section. During the vacuum forming process a thin sheet of polymer is heated into a formable state, then drawn onto a pattern or mould by use of a vacuum.

Rotational moulding is frequently used during the manufacture of large hollow products. Polymer granules or powder is placed inside a mould after which the mould is placed into an oven and rotated about two axes to allow the polymer to melt and cover the inside of the mould The mould is then cooled and the product is removed from the mould.

The blow moulding process involves an extruded tube, called a parison, enclosed in a mould. The parison is then inflated and forced to take the shape of the mould cavity Blow moulding is used for the manufacture of hollow items (Fisher, 1971.2).

RIM is a process which manufactures products through implementation of a polymerisation reaction inside the mould from highly reactive chemicals. The most common polymer moulded in this way is polyurethane, but other materials such as polyamines, epoxies and polyesters are also processed this way (Sweeney, 1979:1 Sweeney 1987:1).

With injection moulding a large quantity of material is held in a heated chamber, while a smaller quantity is injected into a closed mould. The moulding material (plastic) in the barrel or screw plasticiser is externally heated by heater bands which control the temperature. The material is heated to its plastic (molten) state where it can then be forced into a mould when the screw is pushed forward When moulding thermoplastics, the mould is cooled to a temperature below that of the material so that it will harden. The cooling system removes heat from the mould by pumping chilled water through a network of channels in the mould material. When moulding thermosetting materials, the hot material is pushed into a heated mould where it continues to set (Michaeli & Pötsch, 1995:2).

An injection moulding machine is comprised of two parts, namely an injection unit and a clamping unit. The injection unit usually consists of a hopper and a barrel (a dryer unit is often used for certain polymers). The hopper feeds the polymer material into the barrel; heater bands are attached to the barrel. A screw inside the barrel feeds, compresses and melts the polymer before injection into the mould cavity Figure 2.1 shows the injection moulding machine used for this project.

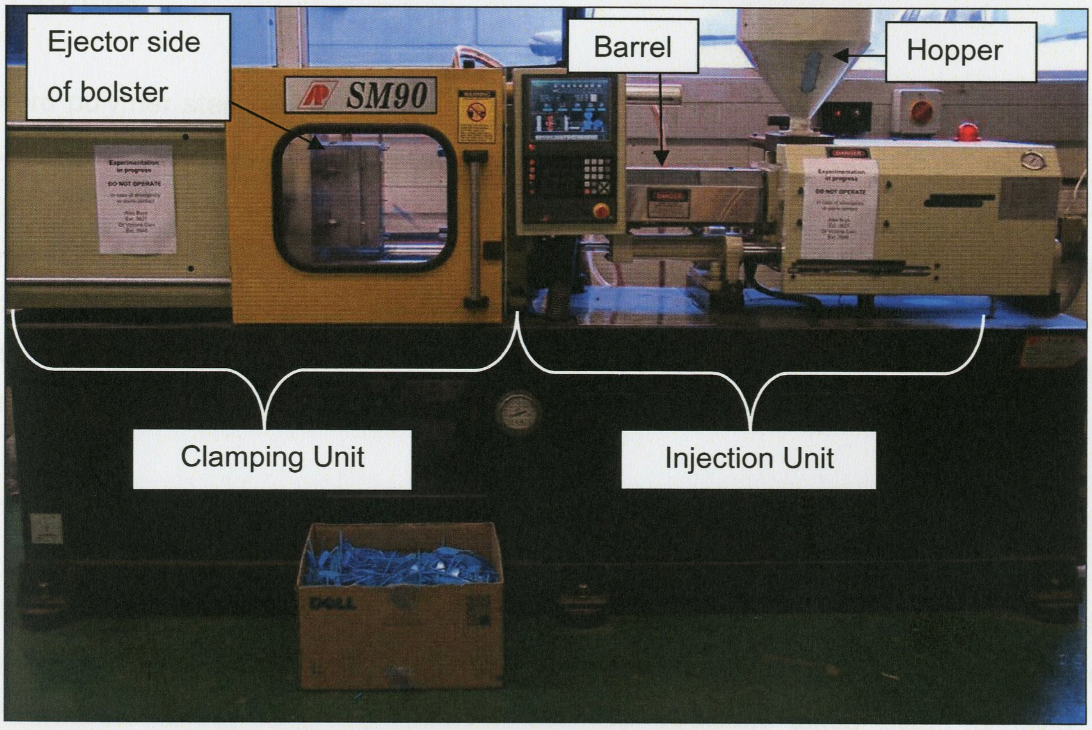

Figure 2.1 The injection moulding machine used for testing

The clamping unit consists of the clamping system, platens, ejector system, guards and gates, movement controls and limit switches. The platens of the machine are the large plates on to which the two halves of the mould are clamped.

The mould is an assembly of a (or multiple) hollow cavity spaces in the shape of the product, with the function of producing (usually large quantities of) plastic products (Rees, 1995:1).

The female space that creates the mould product is called the cavity and the male part, called the core. The mould is mounted into an injection moulding machine, as already described, to fill the cavity spaces.

The machine is usually automated to:

- Close the mould·
- start the injection of the molten plastic into the cavity spaces,
- hold the mould closed while the plastic is cooled and ready for ejection;
- open the mould and
- eject the product (Rees, 1995:1 Michaeli & Pötsch, 1995:2).

Injection moulding is usually suited to products requiring high production volumes. This compensates for the expense of mould design and manufacture, as well as machine setting, which may be time consuming (Whelan, 1982:1).

2.2 Polymers

The word polymer stems from the Greek words. "Poly" meaning many and "mers" meaning particles. This describes a molecule made up of many identical parts (Ram 1997:2). For example polyethylene is formed during the polymerisation of ethylene (a gas) when its carbon atoms are bonded to other ethylene molecules, forming a chain of ethylene molecules of high molecular weight named a polymer In their finished form plastics often contain ingredients such as fillers, pigments and additives like stabilisers and processing aids. However they are still referred to by their polymer designation.

Polymers are wholly categorised in two groups, thermoset plastics and thermoplastics.

Thermoset plastic: These have a more complex three-dimensional densely cross-linked structure of high molecular weight. They are of little use in their raw state, but when heated to a prescribed temperature, an irreversible chemical reaction takes place causing the molecules to crosslink. Thermoset plastics are the stiffest and hardest plastics and are insoluble after curing. Their properties are less affected than thermoplastics by changes in temperature. Typical examples of thermosetting plastics are phenolics, urea, melamine, alkyds and epoxies.

Thermoplastic: These have a more linear molecular structure. Upon heating, thermoplastics soften until the melting point is reached, where they become liquid. When cooled, the thermoplastic re-solidifies. This process is repeatable. Common examples of thermoplastics are polyethylene, polypropylene, polystyrene, polyvinyl chloride (PVC) and Nylon (polyamide) (Beck, 1980:2-3; Monk, 1997:2).

Fillers are widely used in the manufacture of plastic products. Various methods producing composite polymers allow an available volume of polymer to be extended, while improving many its properties. Some common fillers include kaolinite, glass fibre, talc, calcium carbonate, mica and graphite (Katz & Milewski, 1987:3-7).

Additives are substances introduced to the polymer matrix to modify them to aid production and other product requirements such as flame retardants, lubricants, plasticisers, antistatic agents, fungicides and ultra violet light stabilisers (Mascia, 1974:1-2). Pigments can be added to polymers to match a required product colour.

2.3 Light metals

The term 'light metals' has traditionally been given to both aluminium and magnesium as they are frequently used to reduce the weight of components and structures; titanium and beryllium are also included in this definition (Polmear, 1989:1).

The light metal alloys considered for use in this project were aluminium, titanium and magnesium. Table 2.1 shows a material property comparison of these materials.

Table 2.1 Light material property comparison

Properties at 20°C	Density (kg/m^3)	Yield Stress (MPa)	Modulus of Elasticity (GPa)	Thermal Conductivity (W/mK)	Melting Point (min °C)
Aluminium alloy 7075 T6 (Matweb, n.d.)	2810	803	71 7	130	477
Magnesium WE54 (Matweb, n.d.)	1850	225	44	52	550
Titanium Ti 6-2-4-6 (Matweb, n.d.)	4650	1120	114	7 7	1595
Copper-beryllium (Uddeholm, 2005)	8350	1170	131	131	±1000

When these metal alloys are compared it is apparent, because of the density, strength and especially the thermal conductivity properties, that a high strength aluminium alloy would be most suitable for plastic moulds. Titanium could be strong enough, but its thermal conductivity is too low Taking into account the high material cost and availability makes it unsuitable as a mould material. The magnesium alloy has good thermal conductivity, but is too weak because of its low yield stress. The magnesium alloy's cost and irregular availability also makes it unsuitable as a mould material. Other materials of interest to have been used for mould cores are copper beryllium alloys (Knutsen, 2007). They are selected because of their high thermal conductivity, although normally as an insert in a tool steel mould because of cost considerations. Copper beryllium alloys did not fit into the light metal category as described earlier in this section and were not considered for this project.

2.4 Aluminium alloys

Aluminium is obtained from bauxite, the name given to ores containing 40-60% hydrated alumina together with impurities such as iron oxides, silica and titania (Polmear, 1989:8). Alumina (Al_2O_3) is extracted from the crushed bauxite by digesting it with strong caustic soda solution taking place at temperatures up to 240°C. This is known as the Bayer process. From this point the alumina is dissolved into a molten solvent, cryolite (Na_2AlF_6) and by electrolysis the aluminium extracted (Polmear, 1989:8; Malan & Paterson, 1993:vi).

Aluminium alloys are generally divided into two classes depending on fabrication methods used, namely cast and wrought alloys. Wrought alloys are those that are worked by forging, rolling, extruding, drawing, and forming into the desired shapes. They are available in various forms including plate, sheet, extrusion, wire and rod. Cast alloys are poured while in a molten state into a mould cavity, resulting in a cast shape resembling the finished product. Both wrought and cast alloys can be either heat treatable or non-heat treatable - a second major class differentiation (Malan & Paterson, 1993:4).

According to Polmear (1989:144) cast aluminium alloys exhibit inferior mechanical properties in most areas when compared with wrought alloys. The only area in which cast aluminium alloys exceed wrought alloys is for increased creep resistance. Wrought aluminium alloys were considered for this project as they have superior properties to cast alloys.

The 3xxx, 5xxx and 8xxx series aluminium alloys are non-heat treatable wrought alloys. The 3xxx series aluminium alloy includes magnesium and manganese as its main alloying elements. In general the 3xxx series alloys are used when medium strength, high corrosion resistance and excellent ductility is required. They are usually considered for the manufacture of beverage cans, foil, cooking utensils and roof sheeting (Polmear, 1989:79).

The 5xxx series has magnesium as its main alloying element. Its strength properties are achieved by cold working. Al-Mg alloys, widely used for welded applications, with high corrosion resistance, can be polished to a bright surface finish (Polmear, 1989:81-83).

The 8xxx series aluminium is a miscellaneous alloy group containing several dilute alloys. The 8001 (Al-1 1Ni-0.6Fe) alloy is often used for nuclear energy installations where resistance to corrosion by water at high temperatures and pressures is necessary Alloys such as 8280 and 8081, which are based on the Al-Sn system, play an important role in the motor industry as bearing alloys.

The 2xxx (Al-Cu, Al-Cu-Mg), 6xxx (Al-Mg-Si) and 7xxx (Al-Zn-Mg, Al-Zn-Mg-Cu) series are aluminium alloys which respond to heat-treatment to enhance their properties and can be divided into two groups: Those with medium strength which can be readily welded (6xxx and Al-Zn-Mg 7xxx series) and the high strength alloys that have been developed mainly for the aircraft industry (2xxx and Al-Zn-Mg-Cu 7xxx series) most of which with limited weldability

The 2xxx series (Al-Cu) alloy contains complex changes occuring during ageing that have been studied in greater detail than any other system. However, few commercial alloys are based on the binary system. The 2xxx series (Al-Cu-Mg) alloys came to being during the accidental discovery of age hardening by Alfred Wilm in Berlin in 1906. He was trying to develop a stronger aluminium alloy to take the place of brass in the manufacture of cartridge cases. This work led to the production of the alloy Duralumin (Al-3.5Cu-0.5Mg-0.5Mn) which was soon used for structural members of Zeppelin airships and then later in aircraft manufacture (Polmear, 1989:88). Today it is often used in stressed aircraft components and other engineering structures (Malan & Paterson, 1993:57-60).

The 6xxx series (Al-Mg-Si) is a widely used medium strength structural alloy It has good weldability, corrosion resistance and stress-corrosion cracking resistance; 6082 has typical applications in stressed and heavy duty structural parts such as machinery, towers, roof trusses, cranes and bridle plates. The 6xxx series alloy is produced in South Africa.

The 7xxx (Al-Zn-Mg) series alloys have the greatest potential of all aluminium alloys to be age hardened, although the high strength alloys always contain additions of copper to improve their resistance to stress corrosion cracking There is, however, a range containing little or no copper, giving it an advantage of being readily weldable. This range differs from other weldable alloys in that it age hardens drastically at room temperature.

The 7xxx (Al-Zn-Mg-Cu) is typically used in the aircraft industry (Polmear, 1989:70; Anon, 2005). During its development it was found to be sensitive to stress corrosion cracking, but because of this alloy's importance in the aviation industry the problem has been the subject of continuing research. For military needs in the 1930s and 1940s for aircraft alloys of high strength-to-weight ratios, a number of Al-Zn-Mg-Cu alloys were developed, of which 7075 is perhaps the most well known. The 7xxx series alloy is imported into South Africa.

The temper condition of a heat-treatable alloy is denoted by a letter after the alloy and then, if applicable, a number defining a process. “F” donates as fabricated or cast, “O” indicates annealing, H defines strain hardening and “T” indicates that the alloy has been thermally treated to produce other stable tempers other than F,O or H (Malan & Paterson, 1993:36). The T6 temper is a process involving solution treatment, quenching and artificial ageing. T651 is a temper where the T6 temper has been stress relieved by stretching. T7 is a process where the alloy is solution treated the stabilised (Polmear, 1989:71). For example, an alloy specified as 7075-T651 is an Al-Zn-Mg-Cu alloy that has been solution treated, quenched and artificially aged, then stress relieved by stretching

2.5 Mould material

Currently, high strength aluminium alloys are used as a mould material for blow moulds and vacuum moulds (Uddeholm, 2005), but have limited applications for injection moulding because of the higher injection pressure and clamping forces involved (Knutsen, 2007).

High strength aluminium alloys such as ALUMEC from Alcoa are available that specify their suitability to blow moulding and vacuum forming. RIM-moulding is possible, but long-running products are not recommended However, in some cases aluminium moulds could be used, depending on the moulding conditions where the injection pressures are not too high and production quantity is controlled Aluminium alloy moulds are limited in injection moulding to short runs and prototypes (Uddeholm, 2004). These moulds are discarded or recycled after their lifespan, or when they have undergone wear that negatively influences product quality (Wilson, 2007).

As aluminium alloys have outstanding machinability, higher cutting speeds can be achieved as well as increased cutting tool life (Uddeholm, 2004). These advantages can lead to cheaper mould manufacturing costs and quicker delivery times, with machining time typically three times faster than in steel production (Alcoa Europe. n.d.). For complex machining the raw material cost is usually a fraction of the total mould cost (Wilson, 2007), even though imported aluminium 7075 is a little bit more than twice the cost per kilogram of M201 tool steel (Seldon, 2007).

Aluminium alloys are one third the density of steel. This allows for simpler handling and mould changes (Uddeholm, 2004). A lighter mould will lead to less awkward transportation and accidental damage. 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 (Alcoa Europe, n.d.).

The primary physical property of importance is thermal conductivity, which is up to three times greater for aluminium than for steel. It is important because it has the greatest impact on the production cycle time. If a mould was able to conduct heat better it would result in faster setting of the moulded product, thereby decreasing completion time.

In regard to crystalline[1] polymers, the cooling rate has an extremely significant influence on the crystallinity developed in the moulded product. The faster the cooling rate the less crystallinity developed, thus the less shrinkage is observed in the product. Amorphous[2] polymers on the other hand are unaffected by a cooling rate resulting from the mould material (Harris, Newlyn, Hague & Dickens, 2003).

For some applications, the core of an injection mould might have been manufactured from a copper beryllium material because of its good wear resistance and thermal conductivity (Uddeholm, 2005). This is usually when water channel cooling is difficult to achieve in a small, deep core. An example of this would be the core for a plastic cup. To overcome this, tool materials with a higher thermal conductivity are used to draw the heat away from the moulded product toward the cooling channels (Knutsen, 2007).

Aluminium alloy grade 7075 is available in South Africa and often used in the un-surface treated form for the manufacture of blow moulding moulds (Barnes, 2007).

Uncoated aluminium alloys fail as a trusted injection mould material when compared with steel because of inferior strength and wear resistance. It was found that heat treated 7xxx aluminium alloys had improved wear resistance compare with age-hardened 5xxx alloys (Elleuch, Mezlini, Guermazi & Kapsa, 2006:1320).

Another alternative to enhance the properties of aluminium could be to shot peen the surface of the mould before plating. Shot peening is a process where the surface of a material is blasted with glass beads. The impact of the glass beads impart compressive stresses into

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[1] Crystalline polymers have an ordered arrangement and regular occurrence of molecular structures (Beck, 1980:399)

[2] Amorphous plastic materials have no definite order of crystallinity (Beck, 1980:398)

the surface that relieved residual stress in the material formed during manufacture. Recent research has disclosed that the axial fatigue strength of aluminium alloy 7075-T751 can be increased by up to 50% by shot peening with glass shots before a hard chromium electroplated layer of 100µm was applied (Carvalho & Voorwald, 2006).

The preferred material for the use of moulds is high chromium tool steel because of its toughness, wear and corrosion resistance and good surface finish retention. As a result it is used for high production where millions of shots are required (Wilson, 2007). Alternative materials such as aluminium alloys are often used depending on the application in various processes. Aluminium alloy moulds are often used in vacuum and blow moulding because of the low forces involved and the thermal and machining properties of aluminium alloys compared with tool steel.

Mould design plays a crucial part in the use of aluminium alloys as injection mould materials. New techniques use tool steel pillar inserts inside an aluminium mould to experience the clamping force. This design is known as the aluminium injection mould (AIM) frame and is reported to be able to endure 500 000 shots or more (Kirkland, 2003). The method relieves the aluminium from the deteriorating effect of the clamping action so the material's thermal properties can be exploited The mould is still largely manufactured from aluminium alloy and thus is faster to machine, resulting in cheaper moulds. Should a manufacturer need to produce many millions of products, then tool steel would be preferred, but in other cases aluminium could be satisfactory using this method. The aluminium alloy used in the manufacture of these moulds is Alcoa's QC-7 (Goldsberry, 2003).

Research by a collaboration of companies in a project ALAMO saw test moulds manufactured to compare the behaviour of P20 steel, aluminium and anodised aluminium as mould materials. P20 tool steel has a Brinell hardness of 290-341 and an ultimate tensile strength of 896-1010MPa (Matweb, n.d.). An anodising process developed by a pan-European project team was applied to the aluminium moulds. A four-cavity injection mould was manufactured in each of the materials and subjected to a production run of 10 000 shots with an abrasive glass-filled-nylon polymer The anodised aluminium mould performed close to the standard of the steel unit. However, there was marked wear in the gate area of the uncoated aluminium mould (Anon, 2006).

2.6 Mould surface treatment

For tool steel moulds hard chrome plating is commonly applied to resist the corrosive nature of some polymers. It is also used to increase the surface hardness of through-hardened steel as well as a different surface condition to make one side of a mould less likely to "seize" with another A thin 25µm chrome coating could be applied to moulds with thin walled products to improve the flow of polymer over the surface during injection (Rees, 1995:600-601; Dubois *et al.*, 1978).

Hard anodising, chemical nickel plating (typically 30 - 100 µm thick) and hard chrome plating (typically 100 - 200µm thick) are techniques used to increase the wear resistance of aluminium moulds (Uddeholm, 2004).

Anodising is an electrolytic process where the aluminium product to be coated becomes the anode in a bath of electrolyte capable of yielding oxygen. A direct current is passed through the electrolyte causing oxygen ions to migrate to the anode (aluminium product) forming an oxide film on its surface. The oxide film thickens at the oxide-metal surface during further electrolysis. After anodising the product is dipped in hot water to seal the pores. Because of the porous nature of the film, pigments can be added to the layer before sealing (Malan & Paterson, 1993:29).

Hard anodising differs from decorative anodising in that a thicker hard coating with high abrasion resistance is achieved. Sulphuric acid bath of a concentration of between 15% and 35% is favoured and lower operating temperatures between -5°C and 5°C with high current densities (Malan & Paterson, 1993:29). Anodic layers of 25 µm -100µm can be achieved (Blatt, 2007).

3 Industry Survey

3.1 Industry practice

As described in Section 1.2, an investigation into the Western Cape plastic moulding industry was undertaken to explore common practices regarding alternate mould materials and the viability of the proposed project.

Initially, moulding and tooling companies were visited to acquire knowledge of the moulding process, as well as different methods of moulding and tool making. Special attention was given to the use of aluminium as a mould material. The companies visited are shown in Table 3.1.

Table 3.1: List of companies consulted

Company	Location
Bohler Uddeholm Africa (Pty) Ltd.	Paarden Eiland, Cape Town
Bowler Plastics (Pty) Ltd.	Ottery, Cape Town
C & C Tooling CC	Somerset West, Cape Town
Cape Anodising (Pty) Ltd.	Blackheath, Cape Town
Habitat Industries CC	Killarney Gardens, Cape Town
Insight Plastic Injection Moulds CC	Killarney Gardens, Cape Town
Plasquip (Pty) Ltd.	Killarney Gardens, Cape Town
Polyoak Packaging (Pty) Ltd.	Diep River, Cape Town
U V Tooling CC	Killarney Gardens, Cape Town

It was found that aluminium alloys were widely used in the blow moulding industry because of its ease of machining and thermal conductivity The blow moulding process works by a parison that is suspended between the mould halves. A parison is an extruded molten plastic tube. The mould is closed and the parison is inflated from the inside forcing the plastic against the mould cavity where it cools. The mould is opened and the parts of the parison that do not form part of the moulded component are then cut off; many bottles and hollow containers are made by this method.

The high wearing areas of the mould, such as the clamping areas, often have tool steel inserts to increase the moulds' lifespan. The wearing is due to these areas having to pinch and cut the parison. The main body or label area of the mould is usually constructed of an aluminium alloy (see Figure 3.1). Habitat Industries, which specialises in the manufacture of blow moulds, utilises this method for its moulds.

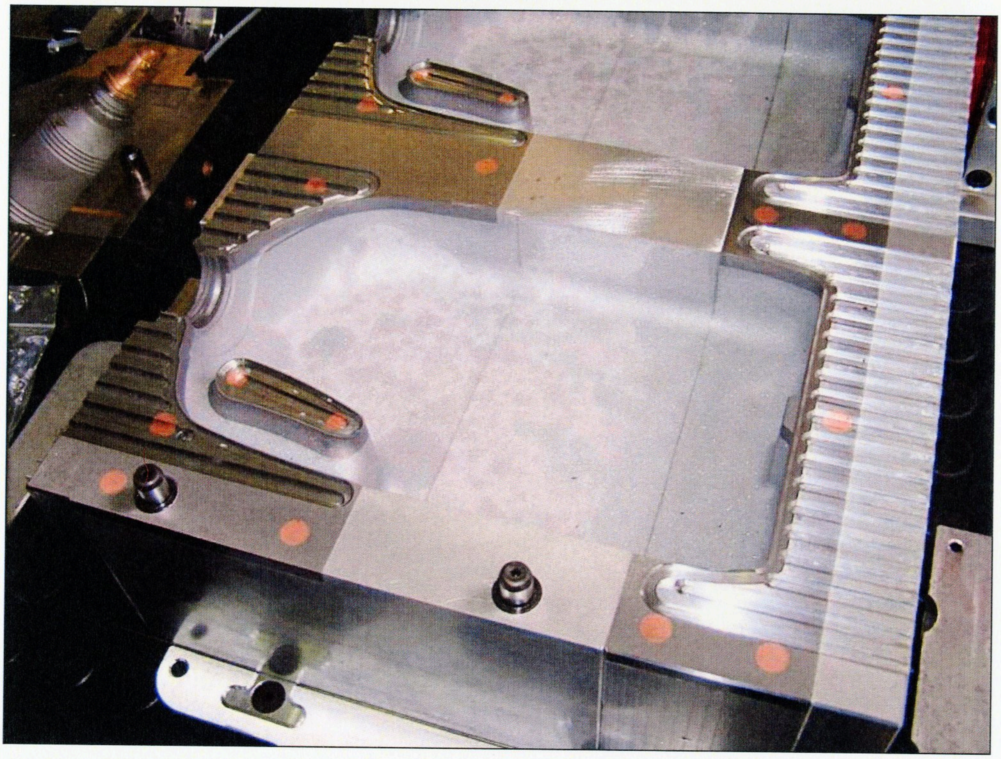

Figure 3.1 Aluminium blow mould of 5L bottle with tool steel inserts at wear areas

According to Barnes (2007) of Habitat Industries, aircraft grade aluminium alloy, 7075, is the preferred material for blow moulds because of its strength, wear resistance and surface qualities compared to other local alloys. Other readily available alloys, such as 6082, are also used, possibly as it is cheaper than 7075, for use as prototypes. To increase the wear resistance of 6082 it is anodised which delivers a better anodised finish than 7075. However the time taken to machine and anodise the 6082 is longer than the 7075, which is not anodised for the use in blow moulds, so the 7075 is, preferred (Barnes, 2007). The anodised layer can be ground and polished to a smooth surface finish according to Blatt (2007) of Cape Anodising.

In the injection moulding industry, aluminium alloy moulds are predominantly used for short runs and prototypes. For companies producing large quantities (millions) of thin walled items, only tool steel is used because of the high clamping forces (between 150 and 300 tons) and injection pressures related to this type of moulding. Wilson (2007) of Polyoak Packaging also notes surface finish retention is a driving factor in this mould material choice, where the polished cavity retains its finish after hundreds of thousands of shots.

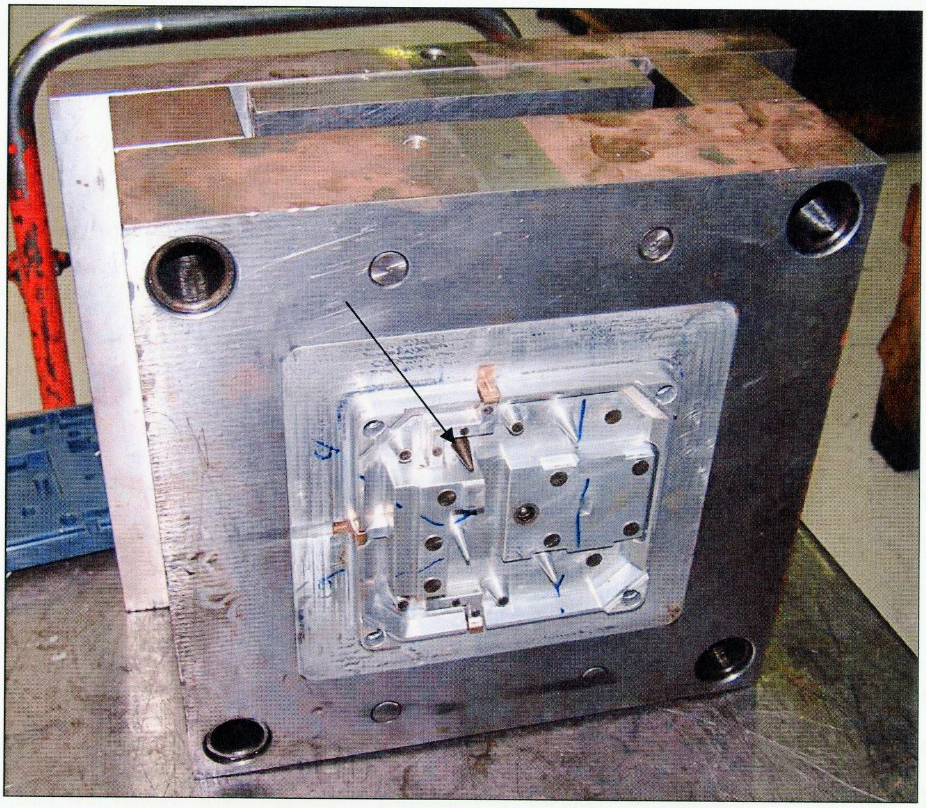

Figure 3.2: Aluminium injection mould at UV tooling

An aluminium injection mould was observed at UV Tooling. In Figure 3.2 a standard bolster is used with an aluminium alloy insert. This is a prototype mould and has already undergone in the region of 5 000 shots. According to Du Plessis (2007) of UV Tooling the aluminium injection mould is in a satisfactory condition to undergo more shots. He did note that in this case the insert has small protrusions (cores) and one broke off during production. The broken core was substituted with a steel insert (arrowed in Figure 3.2). This indicated aluminium alloy moulds as being often limited in application depending on the geometry of the product.

When moulds had deep and narrow cores and where cooling channels were difficult to construct, high strength, high thermal conductivity inserts were used to draw heat to accessible cooling channels. Often copper beryllium alloys were used because of their high strength and thermal conductivity Only a small amount of this material was present in the mould as the material cost remained high according to Knutsen (2007) of Bowler Plastics.

3.2 Industry practice conclusion

Injection moulds were normally manufactured from tool steel This was often hardened especially for large runs of thin walled products. The thin flow path required high injection pressures resulting in high wear in the mould The tool steel most commonly used in industry for injection mould cavities was M201 according to Seldon (2007) of Bohler Uddeholm Africa. This was a general purpose grade for injection moulds and selected to most accurately simulate an industrial scenario during testing.

Today aluminium alloy injection moulds are largely used as prototype moulds and for products requiring short runs. As a result, only a few specialist companies design and manufacture aluminium alloy moulds. An injection mould was observed designed with an aluminium insert and standard tool steel bolster which had run in the region of 5 000 shots. According to Du Plessis (2007) it was still in a satisfactory condition to produce more products. It was noted careful design considerations relating to the moulded product geometry must be taken into account during the design of an aluminium injection mould. Small cores or protrusions, as seen in Figure 3.2, might cause weaknesses in the aluminium mould which can break during production. As a result, tool steel inserts are often used in such sensitive areas.

Aluminium alloy 7075 is already established in the local moulding industry because of its high strength and good anodising properties (Barnes, 2007).

From an investigation into increasing the wear resistance of aluminium, the hard anodising surface treatment was selected Hard anodising was preferred over other surface treatments because of its ease of application and availability of local facilities.

4 Experimental Methods

4.1 Mould material choice

For comparison, three identical mould cavity sets were manufactured and tested under controlled conditions to simulate an industrial environment. The inserts were manufactured and mounted into a standard bolster detailed in Section 4.5.

The tool steel injection mould insert set was manufactured from a common injection mould tool steel M201 Since tool steel was predominantly used in the injection mould industry, this material was used as a control variable and the performance of the aluminium inserts measured against it.

The other two insert sets were manufactured from aluminium alloy 7075-T651 as this alloy had been established in the plastic moulding industry (Barnes, 2007). The T651 temper of this alloy was used because it was available and had undergone a stress relieving process. The 51 numeral after the T6 temper indicated it had been stress relieved by stretching.

To increase the wear resistance of the aluminium alloy, one insert set was hard anodised The entire mould face was hard anodised, but not polished To polish the surface of the hard anodised insert would have cost additional time and thereby defeated the purpose of using aluminium alloys as a cheaper mould material for an injection mould

4.2 Material properties

To validate the material properties received from the material supplier tensile and hardness tests were carried out. The tensile tests were carried out on a Zwick 1484 tensile test machine at the University of Cape Town (UCT).

Figure 4.1 Zwick 1484 tensile test machine (UCT)

Five specimens of each material were tested The M201 tool steel and the aluminium alloy 7075-T651 were supplied in plate form and a test specimen with a gauge length of 40mm was machined from the same piece as those used for the injection mould inserts (See Appendices B and C for the material certificates of each material and Appendix D for the drawing of the test specimen).

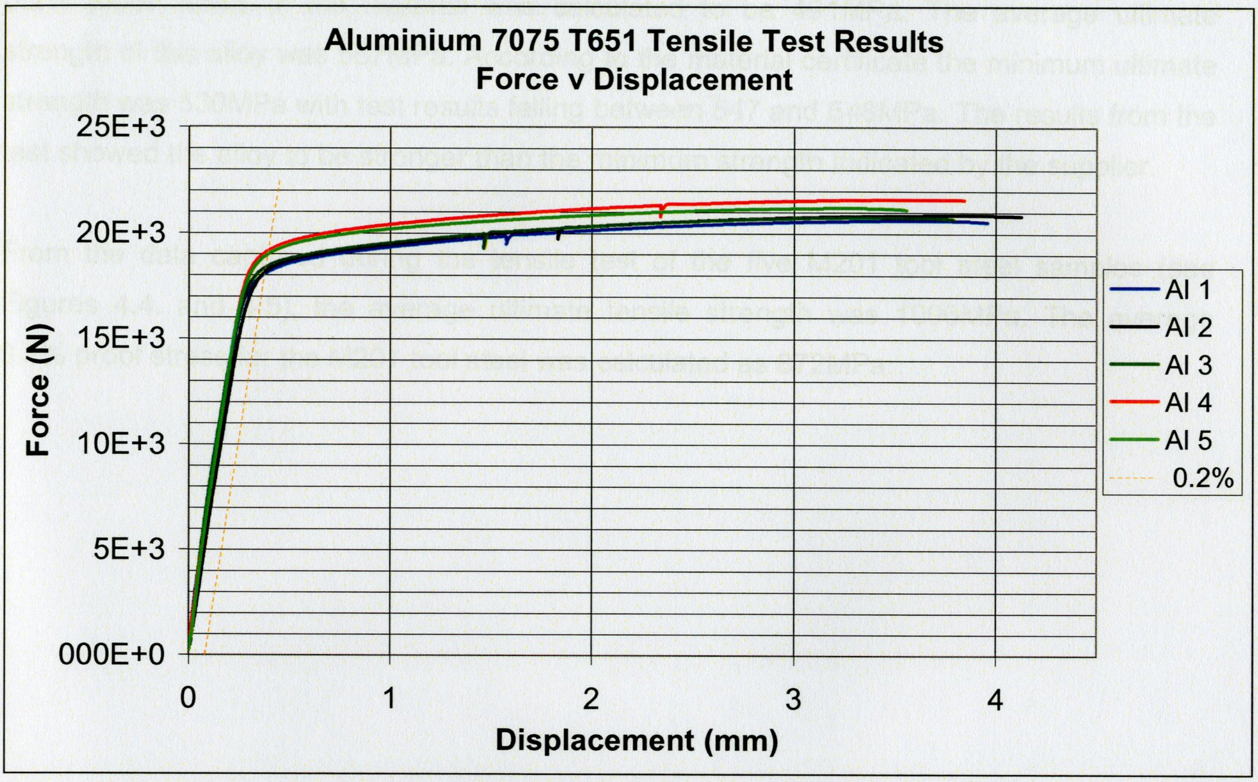

Figure 4.2: Force v displacement graph AA7075-T651 tensile test

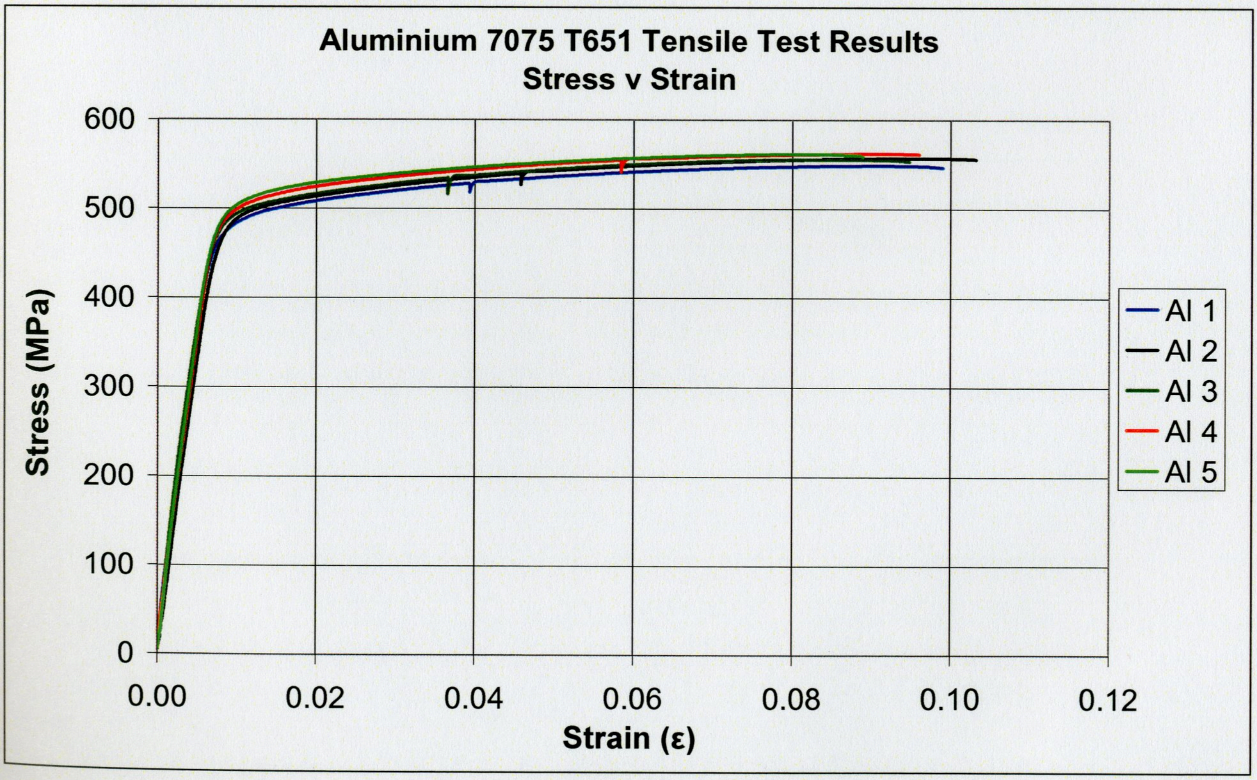

Figure 4.3: Stress v Strain graph AA7075-T651 tensile test

From the data collected from the samples of five aluminium alloys 7075-T651 the average 0.2% proof stress of the material was calculated to be 491MPa. The average ultimate strength of this alloy was 557MPa. According to the material certificate the minimum ultimate strength was 530MPa with test results falling between 547 and 548MPa. The results from the test showed the alloy to be stronger than the minimum strength indicated by the supplier

From the data captured during the tensile test of the five M201 tool steel samples (see Figures 4.4. and 4.5), the average ultimate tensile strength was 1006MPa. The average 0.2% proof stress for the M201 tool steel was calculated as 872MPa.

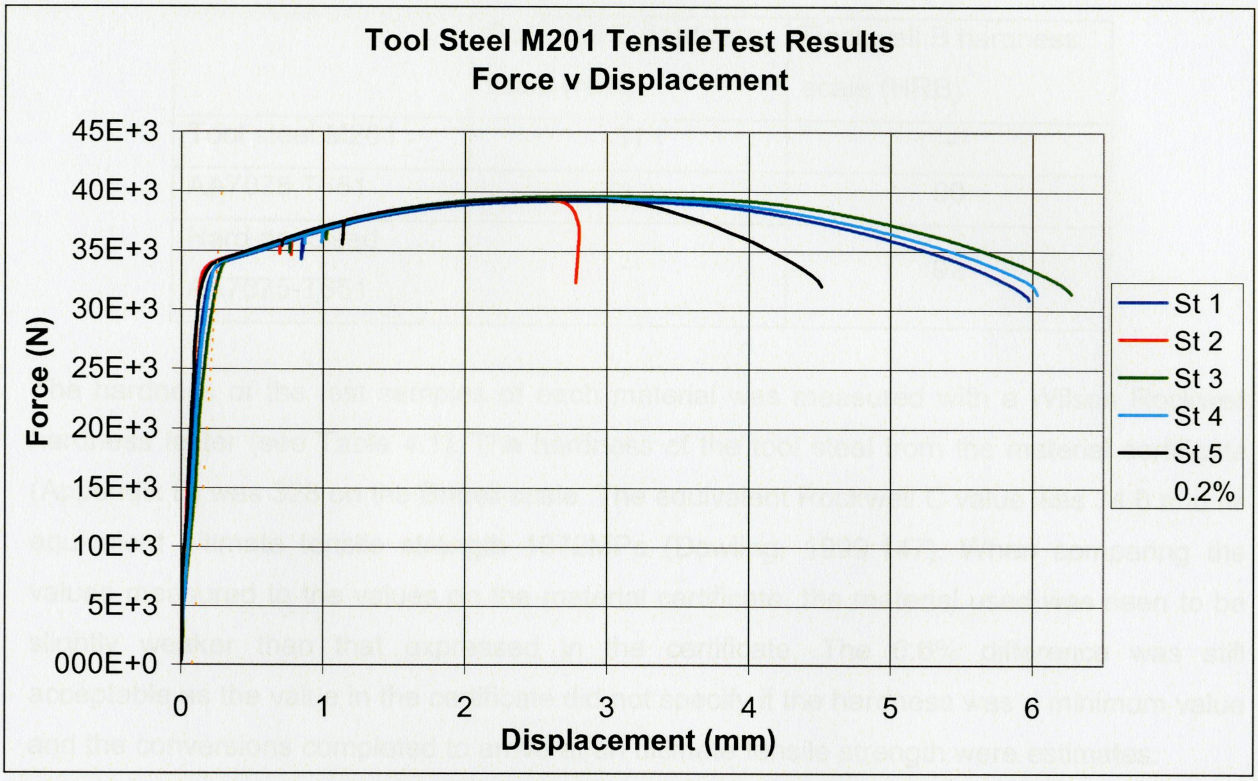

Figure 4.4: Force v displacement graph M201 tool steel tensile test

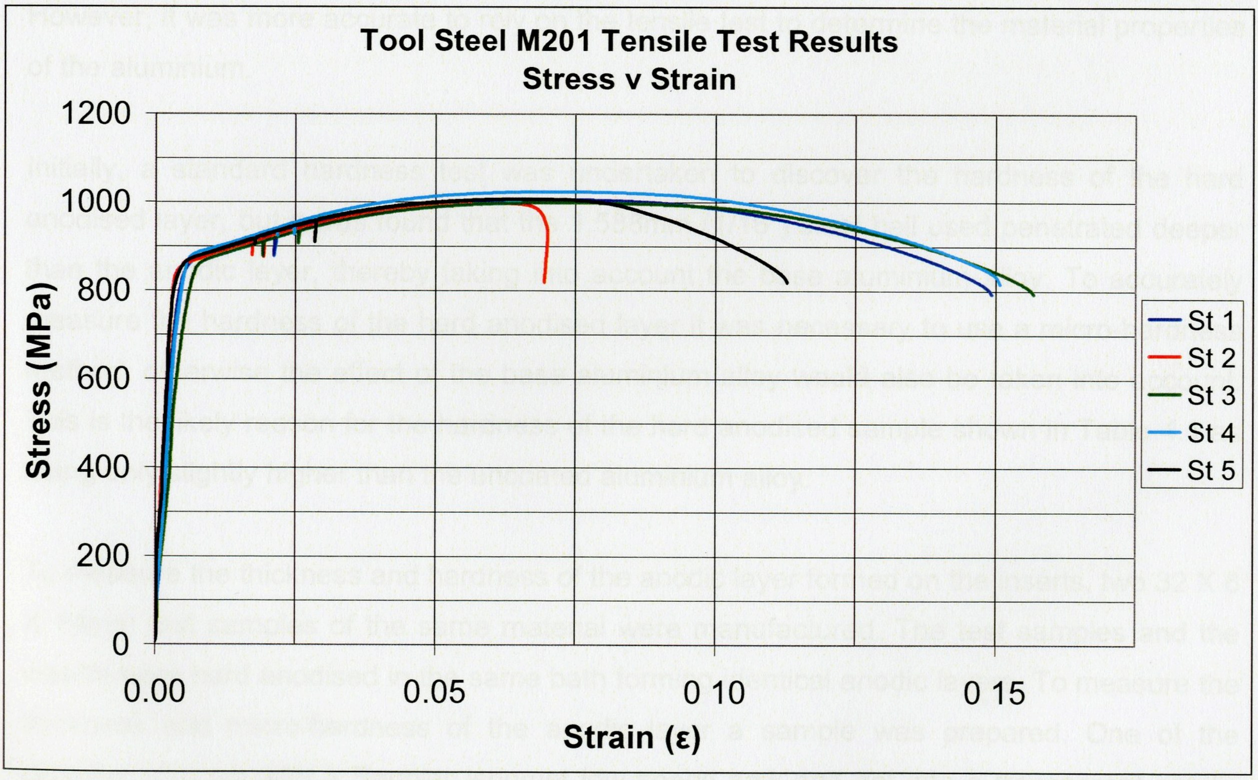

Figure 4.5: Stress v strain graph M201 tool steel tensile test

Table 4.1 The average hardness results before production

	Rockwell C hardness scale (HRC)	Rockwell B hardness scale (HRB)
Tool steel M201	31	-
AA7075 T651	-	90
Hard anodised AA7075-T651	-	92

The hardness of the test samples of each material was measured with a Wilson Rockwell hardness tester (see Table 4.1). The hardness of the tool steel from the material certificate (Appendix B) was 328 on the Brinell scale. The equivalent Rockwell C value was 34.6 and its equivalent ultimate tensile strength 1072MPa (Dowling, 1999:147). When comparing the values measured to the values on the material certificate, the material used was seen to be slightly weaker than that expressed in the certificate. The 6.6% difference was still acceptable as the value in the certificate did not specify if the hardness was a minimum value and the conversions completed to arrive at an ultimate tensile strength were estimates.

The hardness of the aluminium alloy was measured at 90HRB as shown in Table 4.1 The estimated ultimate tensile strength was 600Mpa when converted (Dowling, 1999:147). However, it was more accurate to rely on the tensile test to determine the material properties of the aluminium.

Initially, a standard hardness test was undertaken to discover the hardness of the hard anodised layer, but it was found that the 1.588mm (1/16") steel ball used penetrated deeper than the anodic layer, thereby taking into account the base aluminium alloy To accurately measure the hardness of the hard anodised layer it was necessary to use a micro-hardness method, otherwise the effect of the base aluminium alloy would also be taken into account. This is the likely reason for the hardness of the hard anodised sample shown in Table 4.1 as being only slightly higher than the uncoated aluminium alloy

To measure the thickness and hardness of the anodic layer formed on the inserts, two 32 X 6 X 14mm test samples of the same material were manufactured. The test samples and the inserts were hard anodised in the same bath forming identical anodic layers. To measure the thickness and micro-hardness of the anodic layer a sample was prepared. One of the samples was cut with a Beuhler Isonmet low speed saw and set into a transparent acrylic resin using a Struers LaboPress 3 Hot Mounting apparatus. After mounting, the specimen was ground and polished on rotating polishers using a series of polishing mats and lubricants specifically prescribed for aluminium.

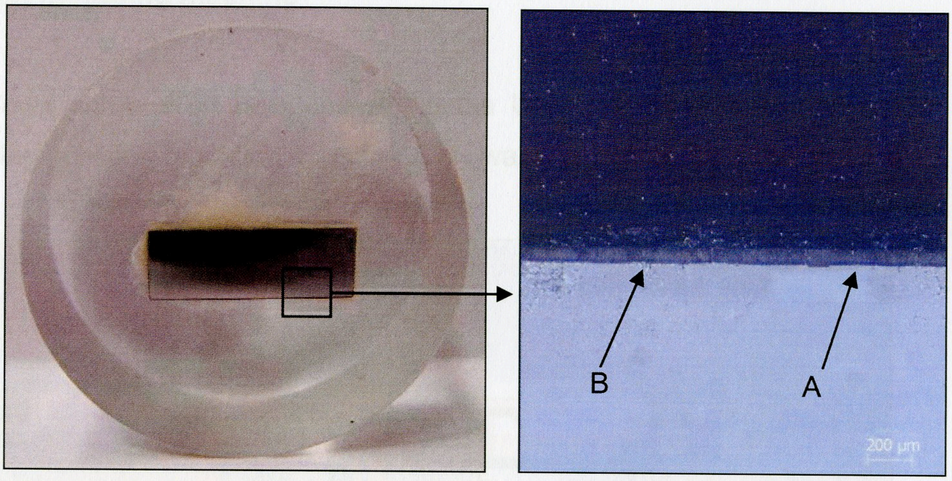

Figure 4.6: Hard anodised test sample mounted in resin indicating areas of measurement

Table 4.2: Micro-hardness measurments of the hard anodised layer

	Standard test with 704.2 Vickers hardness (HV) test piece 200 g force	**Hard anodised layer Vickers hardness (HV) 100 g force**	
		Area A	**Area B**
Average HV	703.6	381.5	326.1
Standard deviation	10.5	10.0	19.4
Rockwell C equivalent	60HRC	39HRC	33HRC

The tests were completed using a Matsuzawa MXT-α7 micro-hardness tester To prove the accuracy, a test was conducted on a known sample of hardness 704.2HV using a 200 g force. From Table 4.3 it can be deduced that the average achieved hardness for this sample was 703.6HV, with a standard deviation of 10.5. A 100 g force was used on the hard anodised layer in two areas, A and B, as shown in Figure 4.6. The average hardness for area A (shown in Figure 4.6) was 381.5HV with a standard deviation of 10. This value has a 39HRC equivalent. Area B has an average hardness of 326.1HV with a standard deviation of 19.4 and its Rockwell C scale equivalent is 33HRC. It is interesting to note that the hardness of the anodic layer in both areas is greater than the tool steel of 31HRC.

The hardness of the anodic layer is inconsistent as the values differ from 33 - 39HRC. This is possible because the area at A was thicker than at area B. During testing there was a small amount of cracking, seen under the microscope, in the anodic layer at the corners of the pyramid-shaped impression which could have influenced the results.

4.3 Injection moulding machine

The Cape Town campus of the Cape Peninsula University of Technology has a 90-ton, toggle clamping injection moulding machine. This was used to perform the test runs.

Figure 4.7: Super Master (SM) 90 Injection moulding machine

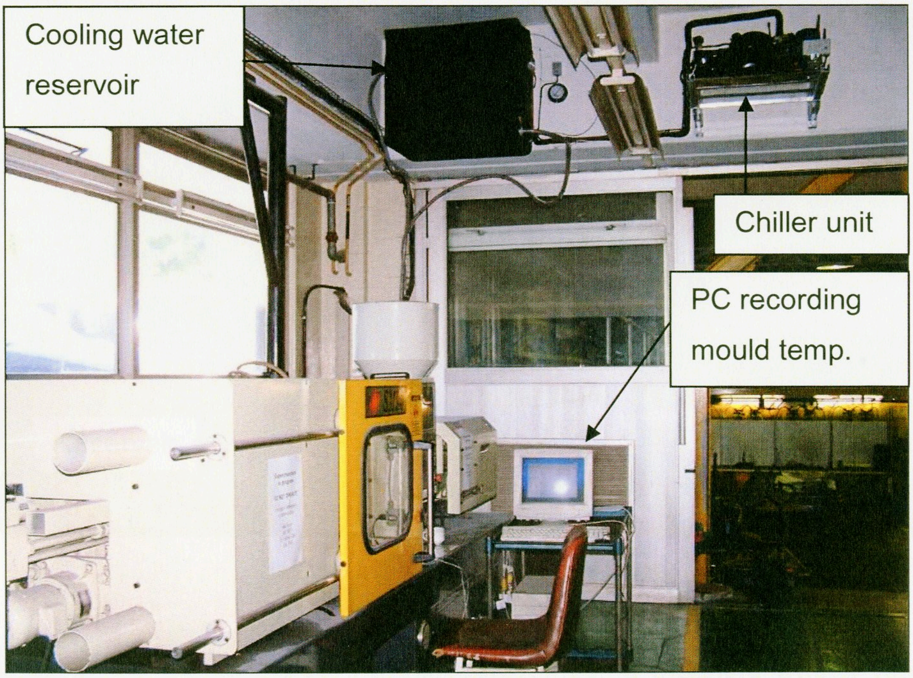

Figure 4.8: Test equipment layout

During operation of the injection moulding machine heat needed to be extracted because of the hot polymer requiring to be cooled in the mould Heat was also generated by the hydraulic oil system. Initially the injection moulding machine was equipped with a pump and reservoir to circulate water through the machine. Later this proved to be insufficient as the water temperature increased greatly during production. A means to cool the cooling water was needed and, therefore, installation of a cooling system was investigated.

A chiller unit was designed and mounted onto a wall near a water reservoir (see Figure 4.8) with the evaporator coil of the chiller inside the tank to chill cooling water The chiller unit commissioned is a commonly used item for the Super Master (SM) 90 injection moulding machines (see Figure 4.9). During production the temperature inside the cooling water reservoir was monitored and recorded using a Testo 175 data logger

The piping of the system ran through both cavities of both sides of the mould (see Figure 4.18), as well as through the hydraulic oil heat exchanger in the machine. The chiller unit was also installed to control the cooling water temperature through the mould. The chillers thermostat was set to 10°C, the ideal mould temperature according to Wilson (2007). During testing a constant flow of cooling water was passed through the mould. The flow control valves were all set so that the flow meters indicated 1.5 units on the flow meter for all four of the channels. One unit on the flow meter was estimated to be 0.5 l per second.

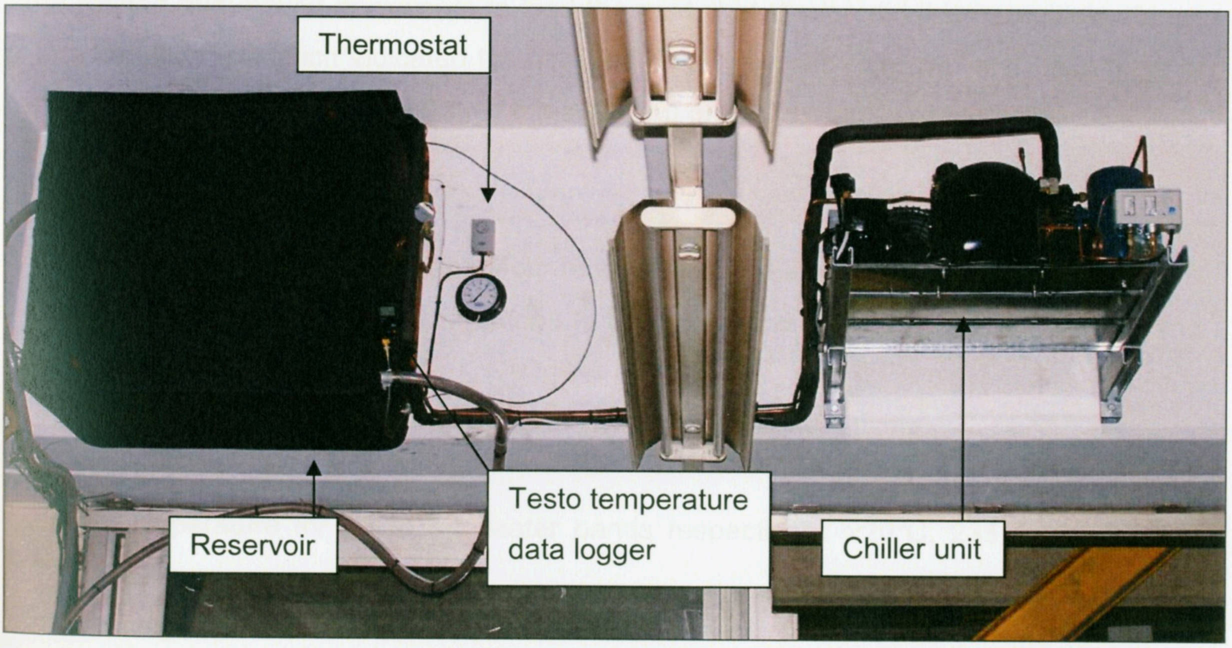

Figure 4.9: Cooling water system

The setting up of the mould inside the injection moulding machine was a vital part in the production process. Firstly it involved mounting the mould between the platens as well as setting the temperatures of the band heaters on the barrel to melt the polymer, the clamping speed and forces and the injection forces and pressures. Setting the mould was a skilled operation and companies often employ professional setters to accurately set the mould for maximum production output. Setting the injection moulding machine correctly was necessary to optimise cycle time as well as product quality To an unskilled person this process can be time consuming - for a guide regarding the setup procedure for the SM90 injection moulding machine see Appendix A.

A workshop titled “An introduction into injection moulding” was presented by the Plastics Federation of South Africa in the early stages of the project. This training was found to be invaluable in the operation of the injection moulding machine used during the experimentation. Further advice was supplied by Plasquip (Pty) Ltd. in Killarney Gardens, agents for the injection moulding machine.

The injection moulding machine used a percentage system to determine forces and pressures for various machine functions. Forces or pressures were set in terms of a percentage of the maximum allowable parameter The maximum achievable clamping force was 90 tons, which would equate to 100%. The injection moulding machine was able to inject the polymer in multiple stages. This allowed the polymer to be injected at a certain speed and pressure initially and then with progressively higher pressures over multiple stages to overcome the cooling of the plastic as it entered the mould. During dosing, the screw of the barrel rotated and moved backwards to load the next shot. It also did this in multiple stages up to a set distance which indicated the distance the screw had retracted and thus the shot amount. The basic settings used during the moulding of the key tags were as follows:

- High clamping pressure: 65%;
- clamping force: 10 tons;
- injection pressure for stages one to four respectively: 40%, 40%, 45% and 45%[3];
- dosing (injection amount) for stages one to four respectively: 8.4mm, 2.1mm, 0.2mm and 0.1mm. 10.5mm in total;
- injection time: 1 7 sec;
- cooling time: 3.5 sec;
- barrel temperature for T1 to T4 heater bands respectively: 220°C, 235°C, 200°C and 190°C;
- mould height: 262.4mm and,
- cycle time during testing: 17 sec.

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[3] Percentage of the maximum allowable pressure

4.4 3D scanner

CPUT's three-dimensional Renishaw Cyclone scanner was used to measure the geometry of the mould before and after moulding to determine if any wear had taken place during test runs. The scanner is frequently used for reverse engineering products by creating a three-dimensional image of the measured item. The item is then able to be reproduced using a computer numerically controlled (CNC) milling machine.

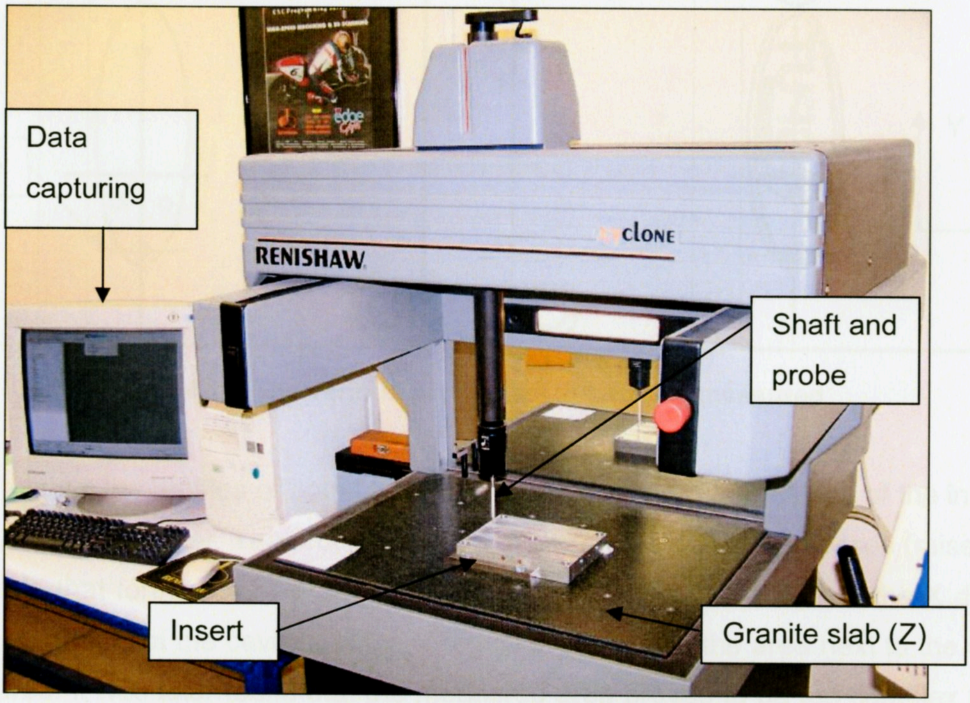

Figure 4.10: Renishaw 3D scanner

The scanner has a shaft and probe arrangement that moves along the measured item and records the profile at a selected pitch. The 100mm shaft was used for the probe to be able to touch and reference the granite slab, as well as measure the item. For reasonable accuracy a probe with a 0.5mm diameter ball was used. To compare the mould inserts before and after moulding, various single line profiles were recorded. These profiles were chosen in areas where wear was expected.

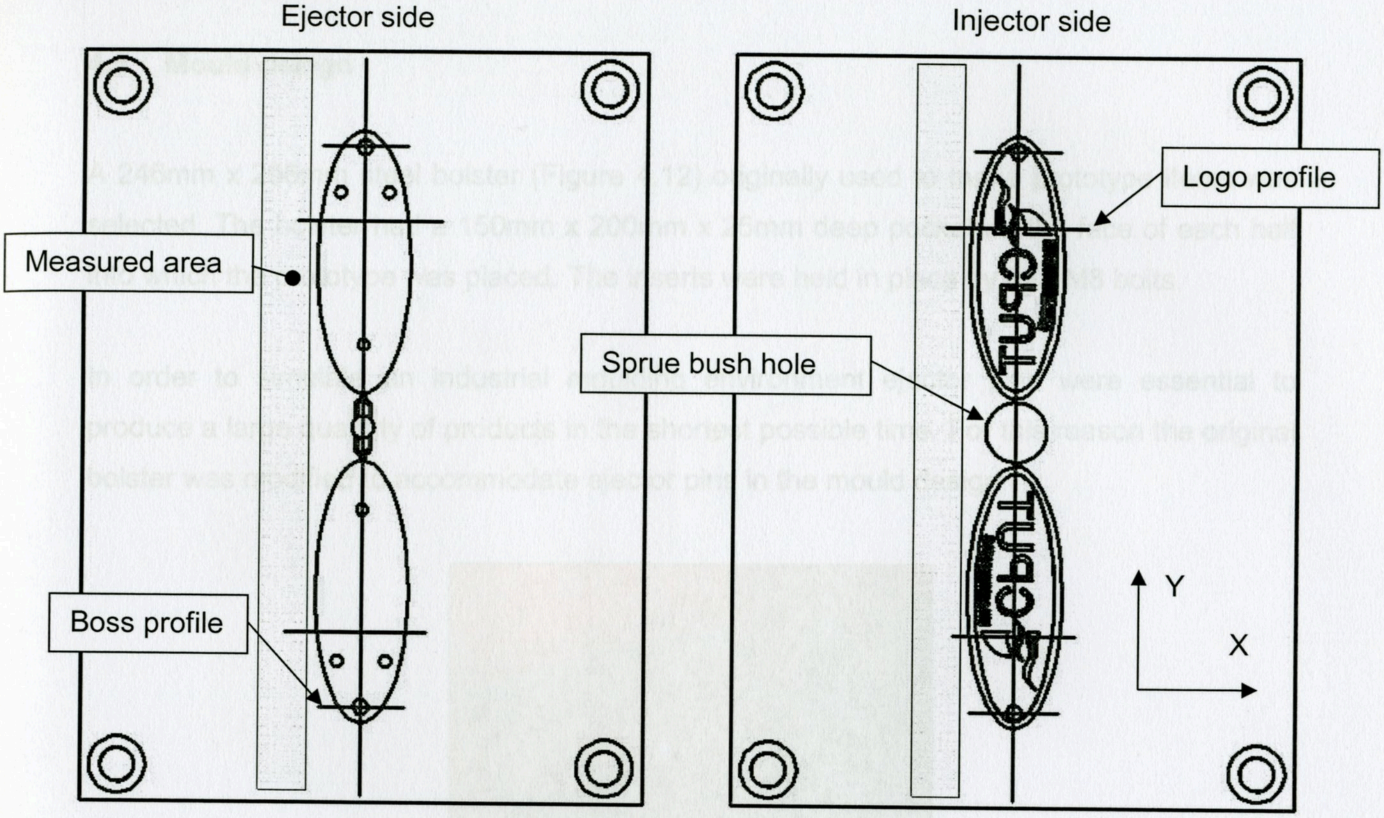

Figure 4.11: The various profiles on the inserts measured

Figure 4.11 shows the profiles of both upper and lower cavity and both sides of the insert set recorded by the 3D scanner The profiles measured were those over the bosses (raised 4mm diameter circle that forms the hole in the key tag) in the X direction, logo in the X direction and across the length of the cavities in the Y direction as well as the area next to the cavities were measured. It was later found that the measured area proved to be too complex to draw conclusions from, thus was excluded from the study

A pitch of 0.01mm was chosen, meaning every 0.01mm, as the probe moved in a certain direction (X or Y), it would take a reading.

The mould inserts were orientated as shown in Figure 4.10. The granite slab of the machine was referenced as 0 in the Z axis (vertical). This was to reference a point that would remain constant. For the injection side mould inserts, the sprue bush hole was referenced as 0 in the X and Y directions; similarly for the ejection side insert. The Y axis was also aligned to the edge of the insert.

The before and after moulding line drawings of the various profiles were evaluated by aligning the origins in the drawing package, Unigraphics NX5.

4.5 Mould design

A 246mm x 296mm steel bolster (Figure 4.12) originally used to make prototype items was selected. The bolster had a 150mm x 200mm x 25mm deep pocket on the face of each half into which the prototype was placed. The inserts were held in place by four M8 bolts.

In order to simulate an industrial moulding environment ejector pins were essential to produce a large quantity of products in the shortest possible time. For this reason the original bolster was modified to accommodate ejector pins in the mould design.

Figure 4.12: Original bolster (closed)

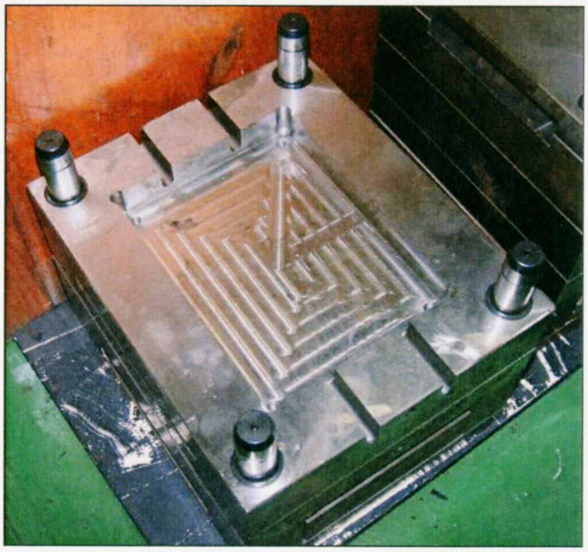

Figure 4.13: Ejector side of the original bolster showing the insert pocket without ejector pins

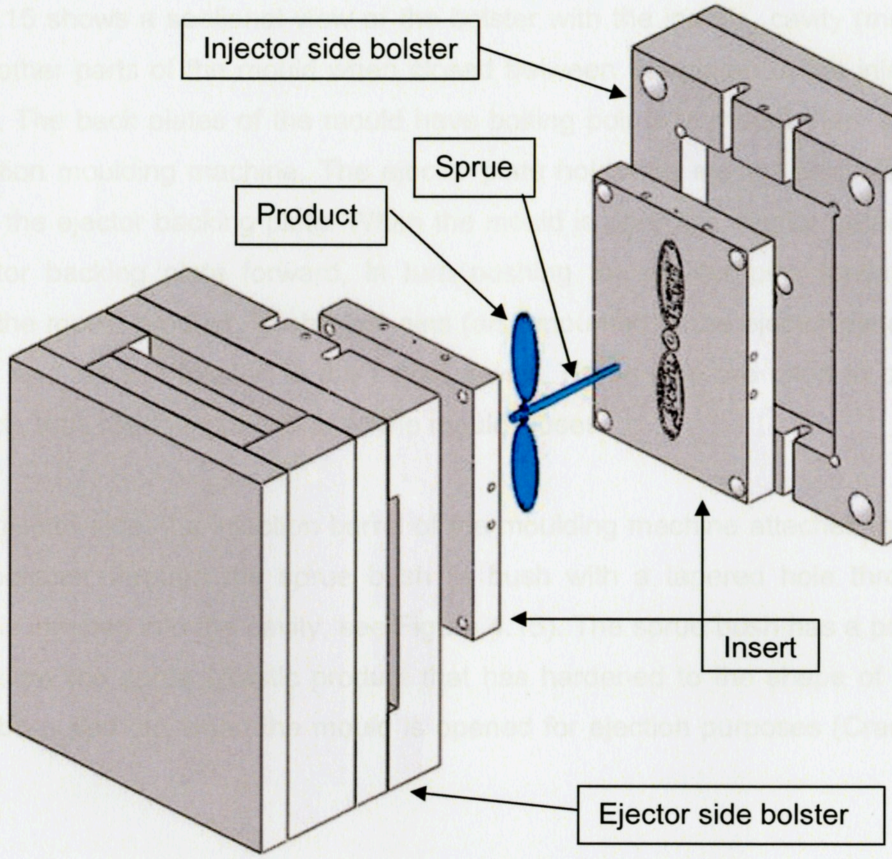

Figure 4.14: Exploded view of the mould assembly

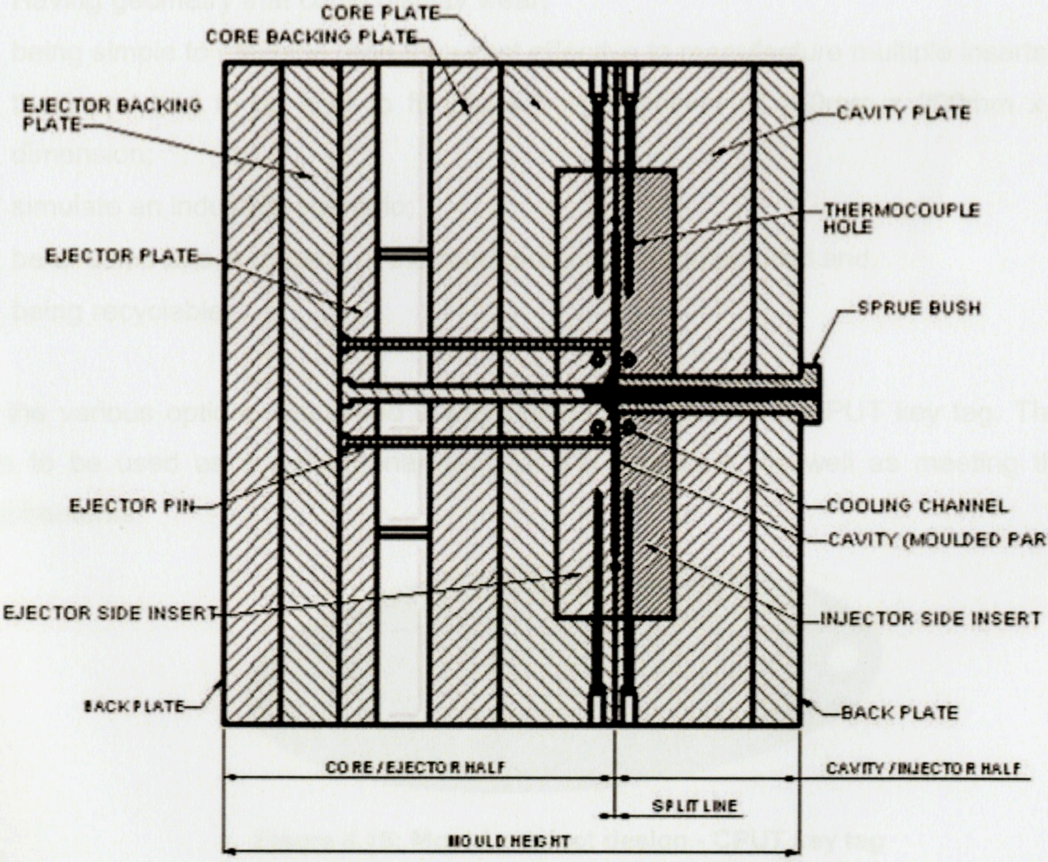

Figure 4.15: Section view of the bolster with mould inserts

Figure 4.15 shows a sectional view of the bolster with the inserts, cavity (moulded product) and the other parts of the mould when closed between the platen of the injection moulding machine. The back plates of the mould have bolting points to mount them to the platens of the injection moulding machine. The ejector plate holds the ejector pins which are fixed in place by the ejector backing plate. When the mould is open the ejector cylinder ram pushes the ejector backing plate forward, in turn pushing the ejector pins forward as well and ejecting the mould product. Push-back pins (also mounted to the ejector plate) have a larger diameter and are not located in the mould cavity These pins are used to push the ejector plate back, thus retracting the pins as the mould closes.

On the injector side, the injection barrel of the moulding machine attaches to and injects the molten polymer through the sprue bush (a bush with a tapered hole through which the polymer is injected into the cavity, see Figure 4.15). The sprue bush has a polished, tapered hole to allow the sprue (plastic product that has hardened to the shape of the sprue bush hole) to be pulled out when the mould is opened for ejection purposes (Cracknell & Dyson, 1993).

For the material of the mould inserts to be tested a polymer product was moulded. The product needed to be of such a design that tests the mould material by:

- Having geometry that could display wear;
- being simple to machine (and thus cost effective to manufacture multiple inserts);
- the insert had to be able to fit into a bolster pocket of 150mm x 200mm x 25mm in dimension;
- simulate an industrial scenario;
- be of some use in respect of the numbers to be manufactured and,
- being recyclable.

Of the various options discussed it was decided to produce a CPUT key tag. The key tag was to be used as a promotional item for the institution, as well as meeting the design requirements.

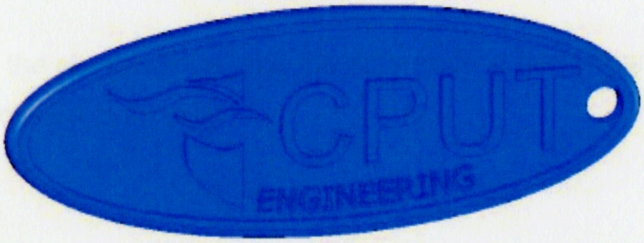

Figure 4.16: Mould product design - CPUT key tag

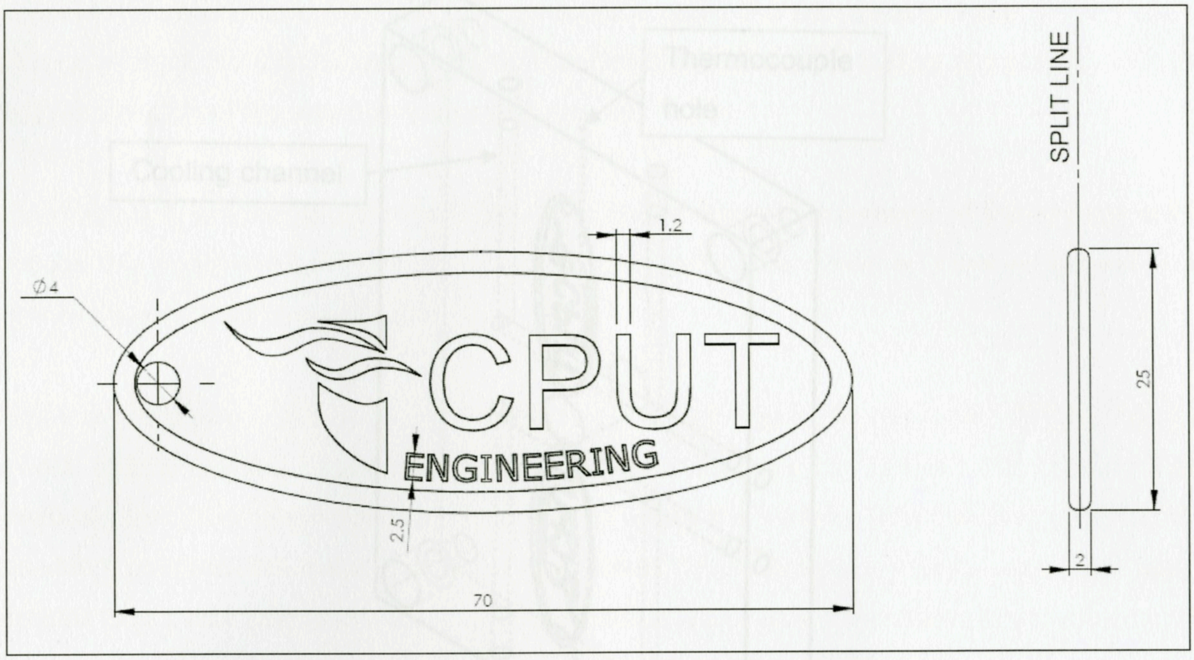

Figure 4.17: Schematic drawing of the key tag

The outside dimensions are 70mm x 30mm x 2mm thick. The sharp edges of the lettering and border could potentially show wear in the cavity This product is of a simple design and will not require complex ejection systems, such as air ejection. Air ejection involves a blast of compressed air which pushes the product out of the mould.

The key tag was moulded from injection mould grade polypropylene; HNR100 donated by Sasol South Africa (see Appendix N). Polypropylene has good resistance to chemicals (such as household detergents), ultra violet light, scratching and is rigid as it is a crystalline polymer It also accepts pigments, allowing the originally clear polymer to be blended to a specific colour It is simple to use as an injection mould polymer, since it does not need drying or pre-heating and, therefore, offers a good choice of product material (Byett, 2007).

Shrinkage of the crystalline polymers is related to moulding conditions (Harris *et al*., 2003), one of which is the cooling rate. The major axis of the moulded product can be measured to establish any changes in shrinkage between the different mould materials.

To properly measure the performance (and the difference in performance) of the three mould inserts they were machined identically

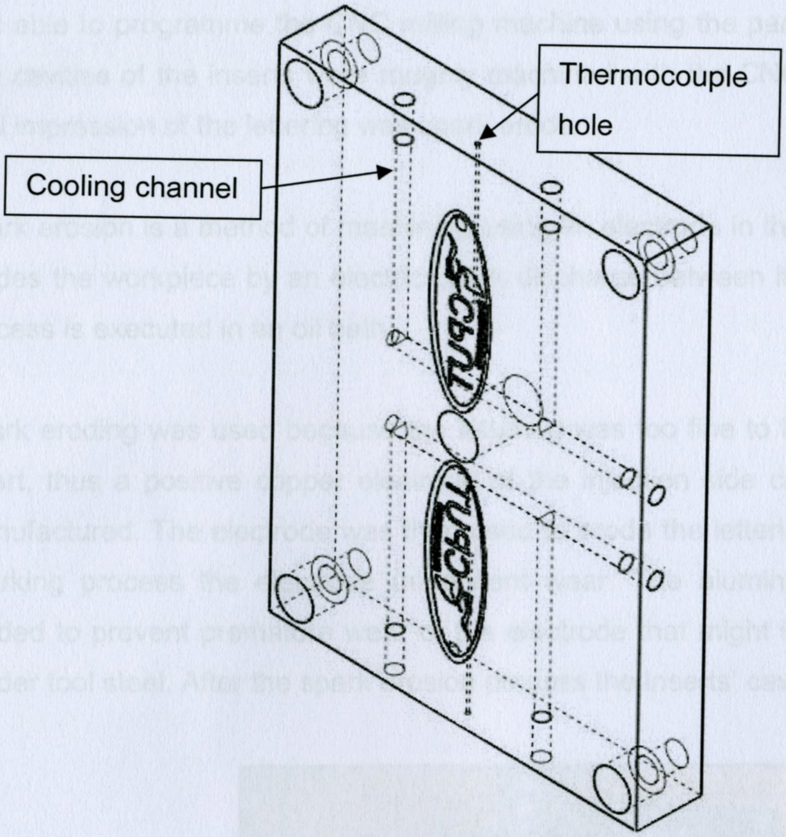

Figure 4.18: Injector side mould insert design

To balance the mould, two cavities were machined into the mould insert. The reason for this is if one cavity was only made, the mould could have more pressure on one side when the plastic was injected. This might cause the mould face to separate in that area and cause polymer leakage. Figure 4.18 illustrates the design for the injector side of the insert. The hidden detail shows the path of the cooling channels around the cavities. The holes for the thermocouples are also visible and will have their points directly behind the centroid of each cavity to measure the mould temperature during operation.

The machining of the inserts and the modification of the bolster was completed by Insight Plastic Injection Moulds CC at Killarney Gardens and some assistance with design provided by C & C Tooling CC at Somerset West. The mould was designed to have ejector pins because of a need for the production standard to be close to that of industry. As a result, the bolster had to be modified to accommodate the ejector pin arrangement on the ejector plate and core plates (see Figure 4.15).

The injection mould inserts were designed and modelled in a Computer Aided Drafting (CAD) package and exported to the manufacturing company (Insight Plastic Injection Moulds) in parasolid format along with the drawings (see Appendices E–J). The bolster and inserts were machined using a computer numerically controlled (CNC) milling machine. The machinist was able to programme the CNC milling machine using the parasolid models of the inserts. The cavities of the inserts were roughly machined with the CNC milling machine before the final impression of the lettering was spark eroded.

Spark erosion is a method of machining using an electrode in the shape of the key tag which erodes the workpiece by an electric spark discharge between itself and the workpiece. This process is executed in an oil bath.

Spark eroding was used because the lettering was too fine to be machined directly into the insert, thus a positive copper electrode of the injection side cavity (with the lettering) was manufactured. The electrode was then used to erode the lettering into the cavity During the sparking process the electrode underwent wear The aluminium inserts were first spark eroded to prevent premature wear of the electrode that might have been threatened by the harder tool steel. After the spark erosion process the inserts' cavities were polished.

Figure 4.19: A spark eroding machine

4.6 Hard anodising

One aluminium alloy insert set was hard anodised, as previously discussed. There were certain areas on the mould inserts that were not allowed to be hard anodised-such as the rear and sides of the insert, as well as the holes where the ejector pins travelled and the sprue bush fitted. This was because the fit of the insert into the bolster and the close tolerances of the pins would be compromised. These areas needed to be protected from the hard anodising process. A metal finishing company, Cape Anodising performed the hard anodising. They suggested a product, "Stop Off" lacquer, a thick liquid that is painted onto an area to shield sections from the anodising process. Three layers of lacquer were applied to the mould insert set as recommended. After the hard anodising treatment the "Stop Off" layer was simply peeled off to expose the un-anodised surface below. Figure 4.20 shows the insert after hard anodising with the "Stop Off" lacquer on the areas that were shielded from the anodising process.

Figure 4.20: AA7075 injection side insert after hard anodising. Note the lacquer around the edges and holes

The hard anodising process can generally be complex, often from factors such as bath temperature, anodising base material, acid concentration and agitation. This can lead to inconsistent results. Different aluminium alloys yield different anodic layer growth rates. An estimation of the anodic layer thickness is obtained by keeping the product in the anodising bath for one minute per micron anodic layer thickness required (Williams, 2007).

The hard anodising was carried out under the following conditions:

- 220g per l concentration sulphuric acid bath at 0°C for, in the region of 50 min;
- 35-40 Volt;
- 350-400 Ampere and,
- sealed in boiling distilled water for 30 minutes.

The anodic layer of the test sample, that was hard anodised in the same bath as one of the aluminium insert sets (see Section 4.2), was measured using optical microscopy Figure 4.21 shows the average anodic layer to be 70µm thick, which is in the acceptable range according to published research involving anodised tribology (Rateick, Binkowski & Boray, 1996; Rama Krishna, Sudha Purnima & Sundararajan, 2006; Forn, Picas, Baile, Martin, García, 2007).

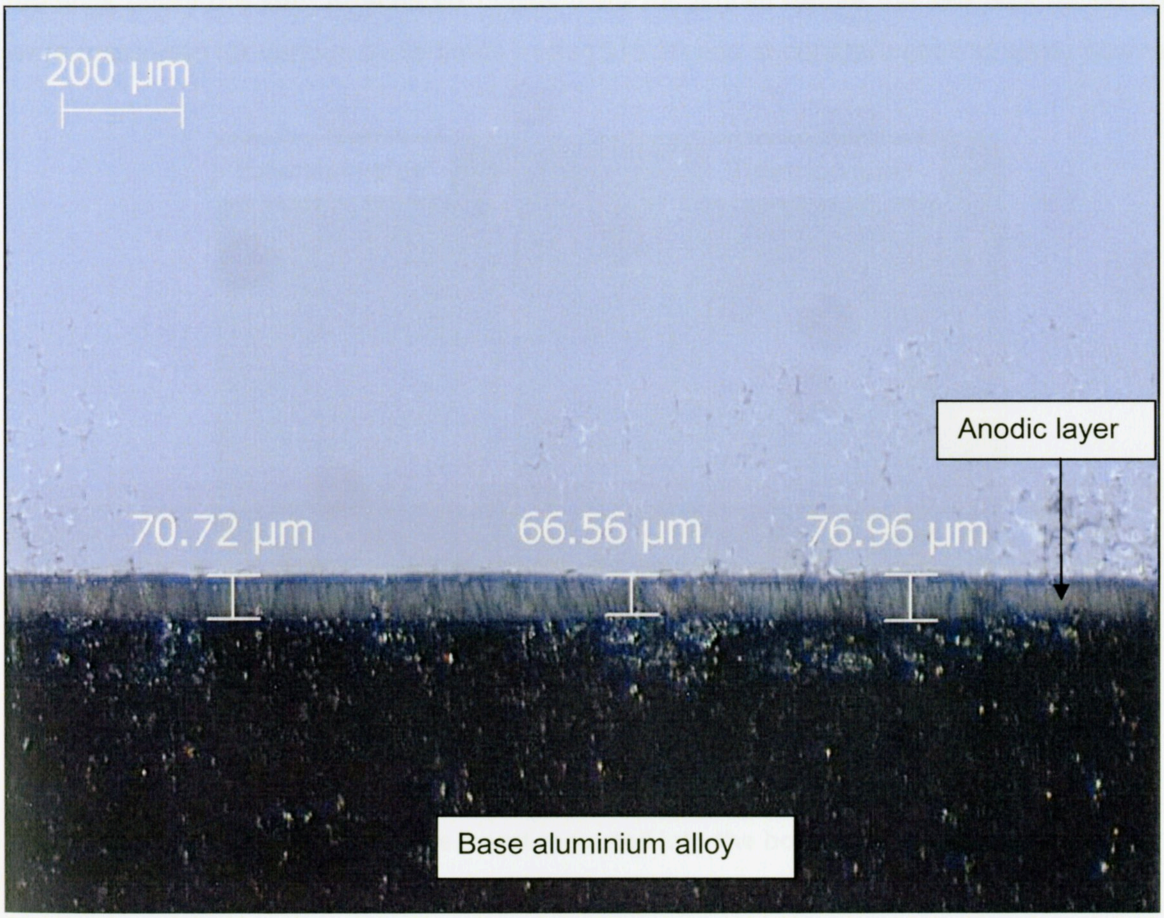

Figure 4.21: A micrograph of the anodic layer Micron marker at 200µm

4.7 Thermal Measurements

In order to test the performance of the various mould materials it was necessary to be able to insert a thermocouple into the mould material to record its temperature during moulding runs. Because of the space limitations, a 5mm diameter thermocouple proved impractical, so a 1.5mm diameter K-type was used. The K-type thermocouple was more sensitive and robust and operated at higher temperatures than the general purpose J-type (Hitzeroth, 2007). The thermocouple measured 100mm long from tip to base of M6 thread. Two thermocouples were inserted into the injector or stationary half of the mould. Each would have their tips behind the centroid of the key tag inside the mould material. The thermocouples were connected to a data acquisition program called Labview 7 1 The programme was set to take readings every 0.5 sec. At least six cycles were measured before the test was halted. Tests were measured for various cycle times from 15 to 20 sec at constant cooling water flow rate.

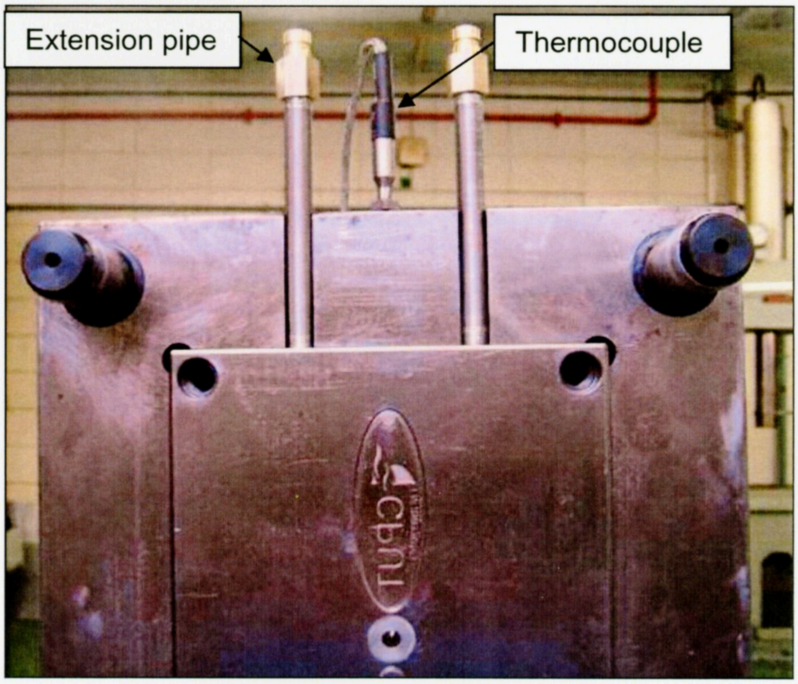

Figure 4.22: The injection side insert mounted into the bolster with cooling water pipe extensions and thermocouple

Another data logging system was used to monitor the mould cooling water temperature. A Testo 175-T3 data logger was used with the same thermocouples as in the mould to record the cooling water temperature in the reservoir This was to correlate the mould temperature measurements with the cooling water temperature for the different insert sets. In this way a data set could be compared with the other insert sets at the same cooling water flow rate, cooling water temperature and cycle time.

4.8 Wear measurement

To be able to compare the same profile of an insert before and after moulding it needed to be orientated in the 3D scanner in the identical manner The parameters needed to be set with the machine were the:

- Z plane (horizontal plane);
- axis alignment (X axis) and,
- X and Y origin.

Once an insert was secured and the parameters set, the various profiles could be measured. The same profiles, namely the upper and lower logo and boss, as well as the profile down the centre in the Y direction, were measured on all inserts before and after the 10 000 shot moulding run, as described in Section 4.

5 Results and Discussion

5.1 Wear results

3D scans were taken of the mould inserts as described in Section 4.4. During an analysis of the scanned profiles, it was found that the method used to orientate the inserts into the machine was not accurate enough for the measured data to be a reliable source. This was because of inconsistent orientation of the inserts in the scanner before and after moulding. The datum points chosen did not align the mould face perfectly, thus causing the profiles to be offset from each other Another contributing factor was an amount of corrosion build-up after moulding was evident on the back of the mould inserts (especially the tool steel). This was caused by cooling water leakage at the points where the flexible hose connected to the extension pipes and at the points where the extension pipes were fastened into the insert. Water seeped between the bolster and the insert, causing some corrosion in the moist environment.

The shapes of the before and after profiles however, remained suitable to be compared to show signs of wear on the inserts. This was the method from which conclusions were drawn to observe any changes between the before after moulding profiles.

The shapes of the profile in the Y direction of the lowest and highest edge on the injector side of each insert were compared. For simplicity, these edges will be known as the lower edge and upper edge. To confirm results, the profiles in the X direction over the lower and upper logo were also compared (see Figure 5.1).

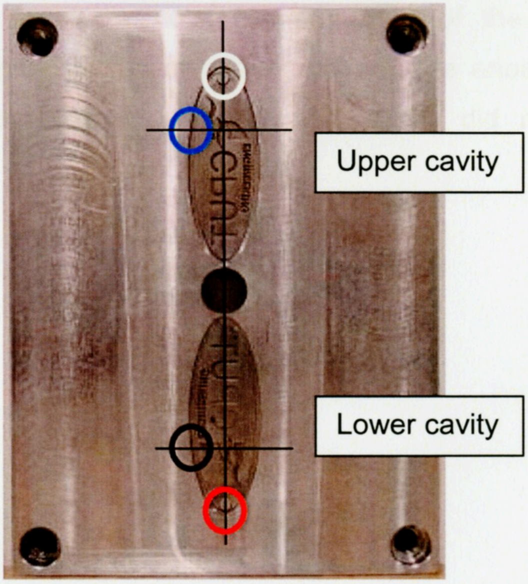

Figure 5.1. Injector side insert with lower edge (red circle), lower logo edge (black circle), upper edge (white circle) and upper logo edge (blue circle)

For the profiles shown in Figures 5.2 to 5.13 the blue line indicates the profile before moulding and the red line the profile after moulding. The black line is present only on aluminium inserts that were hard anodised and represents the profile before the anodising process. Alongside the comparison of each profile is an image of the area taken with a Leica MZ8 microscope to further inspect the edges for signs of wear

The profiles of the steel edges in Figures 5.2, 5.5, 5.8 and 5.11 illustrates the general shape had not changed after the 10 000 shot moulding run. This was expected, as this grade of tool steel was a commonly used injection mould material that often endured many more than 10 000 shots in a lifetime.

The uncoated aluminium alloy insert shown in Figures 5.3, 5.6, 5.9, and 5.12 had also retained its edge profile and, therefore, endured the 10 000 shot moulding run without significant impact on mould or product quality

The hard anodised insert differed from the other profiles, in that the after-moulding profile had a distinct “flattening” of the outer layer on the edge as shown in Figures 5.4, 5.7, 5.10 and 5.13. It was also evident that this shape differed from the before-moulding profile and hence one could deduce material had been removed. In a number of cases, particularly on the lower cavity, (Figures 5.4 and 5.7) the base aluminium alloy was clearly visible. The hard anodising layer was hard and stress concentration would have occurred on the sharp edges resulting in the anodic layer chipping off in these areas (arrowed in Figure 5.16). The transition between the anodic layer and the base material was sudden and thus could be responsible for the chipping in stress concentrated areas of the sharp edges. Other contributing factors were the propagation of micro-cracks in the anodic layer at the stress concentrated areas. The imperfections in the mould cavity did not, however, impact significantly on product quality

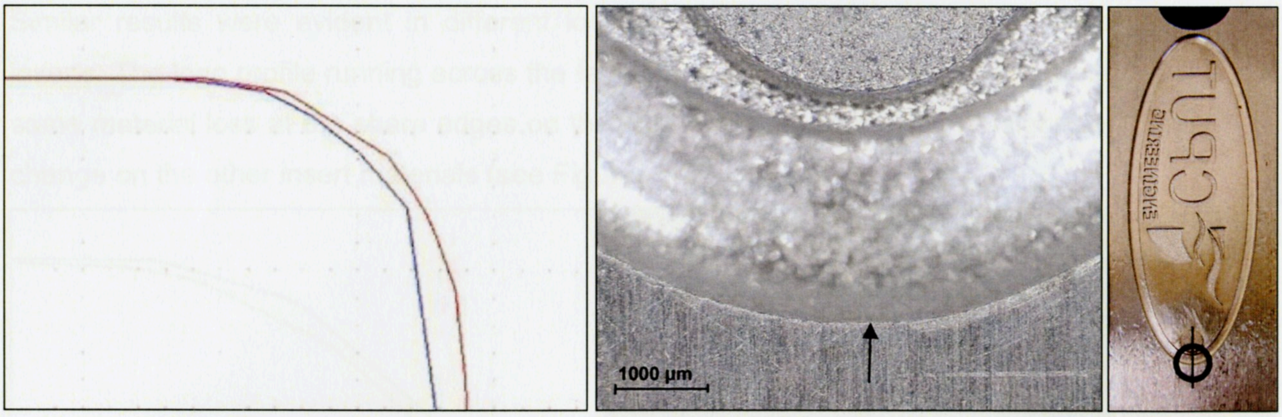

Figure 5.2: Profile of steel, injection side lower edge

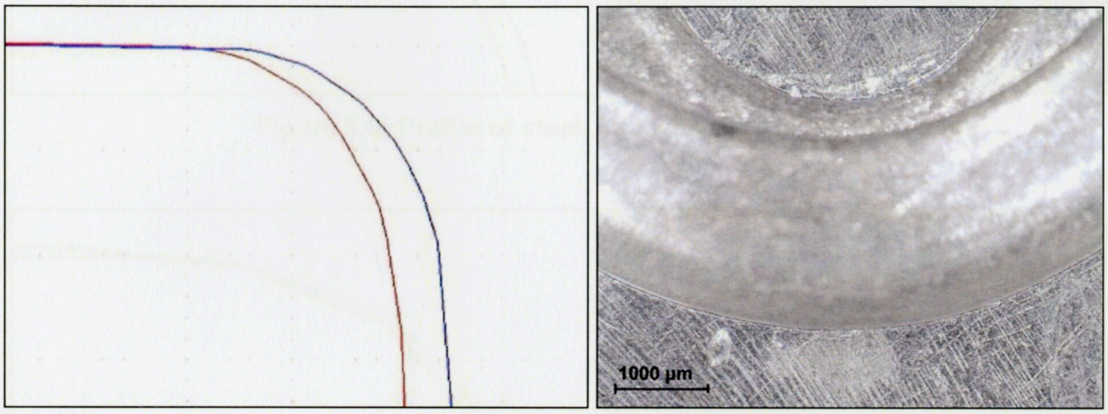

Figure 5.3: Profile of aluminium, injection side lower edge

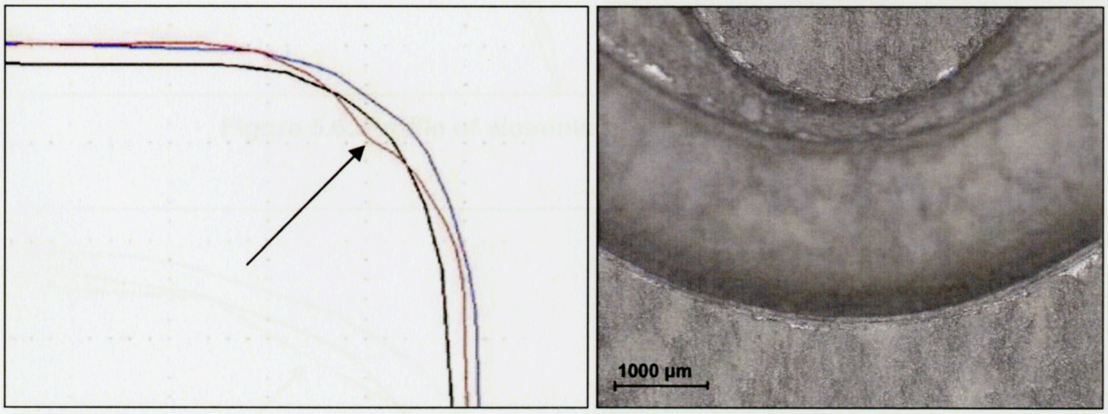

Figure 5.4: Profile of anodised, injection side lower edge
(arrow indicates material removed)

Blue = before moulding
Red = after moulding
Black = before anodising

Similar results were evident in different locations on the lower and upper halves of the inserts. The logo profile running across the face of the mould (see Figure 5.1) also shows the same material loss at the sharp edges on the hard anodised insert and no significant shape change on the other insert materials (see Figures 5.5 to 5.7).

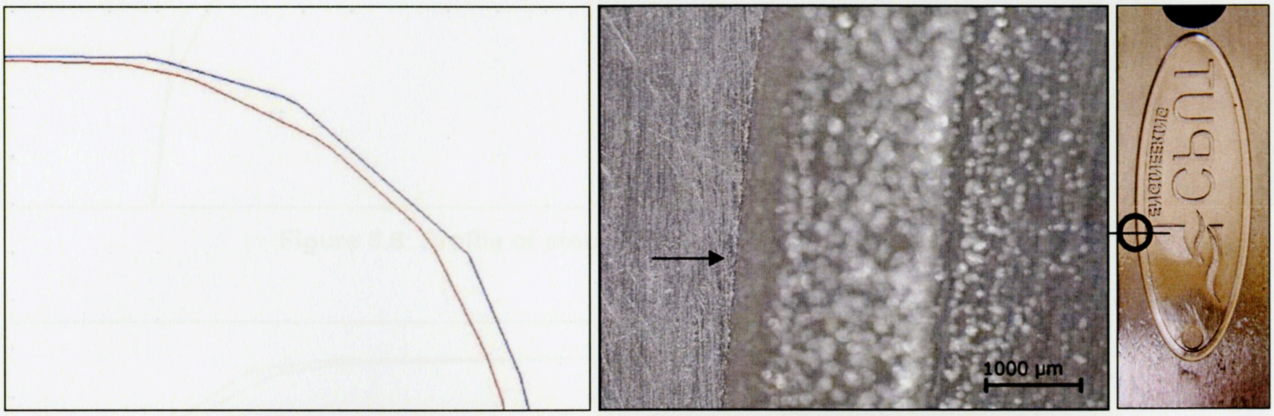

Figure 5.5: Profile of steel, injection side lower logo edge

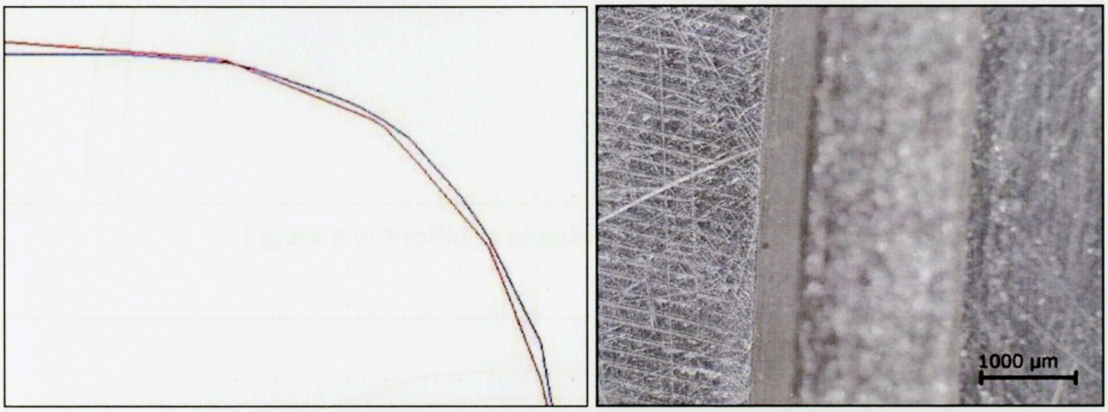

Figure 5.6: Profile of aluminium, injection side lower logo edge

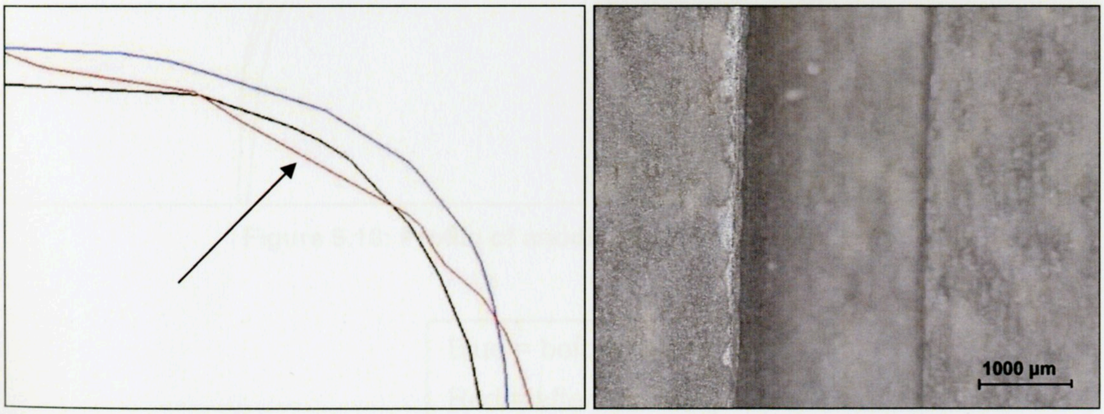

Figure 5.7: Profile of anodised, injection side lower logo edge (irregular profile produced after moulding with some material loss)

Blue = before moulding
Red = after moulding
Black = before anodising

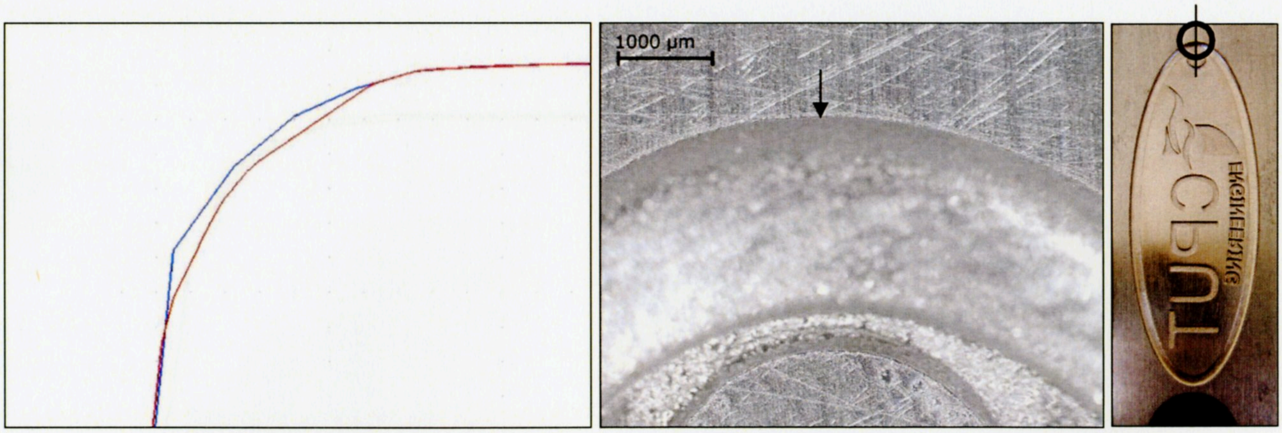

Figure 5.8: Profile of steel, injection side upper edge

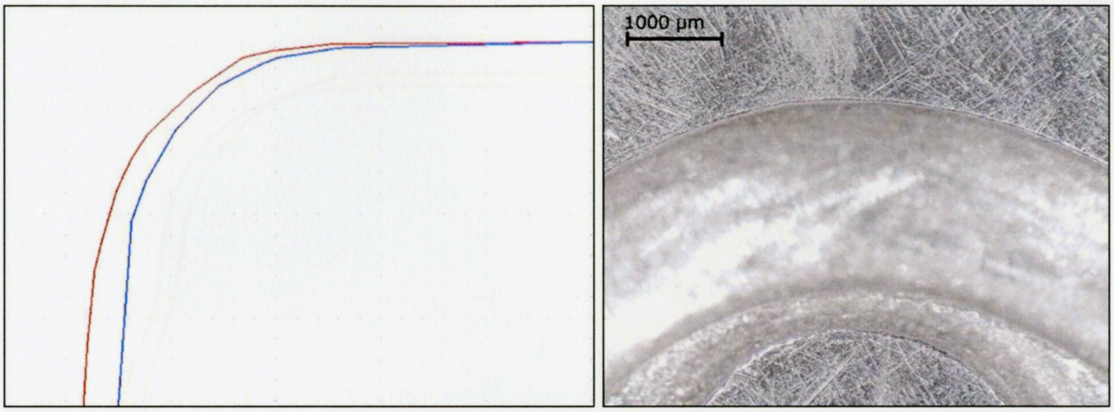

Figure 5.9: Profile of aluminium, injection side upper edge

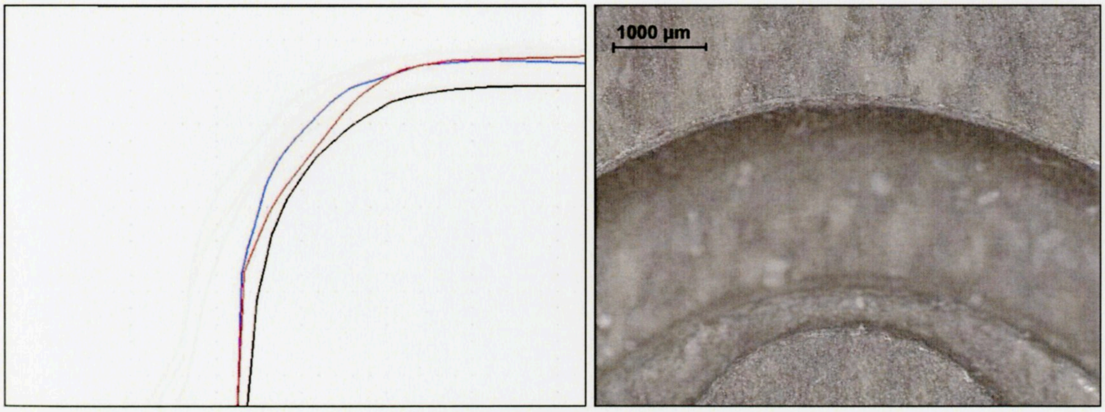

Figure 5.10: Profile of anodised, injection side upper edge

Blue = before moulding
Red = after moulding
Black = before anodising

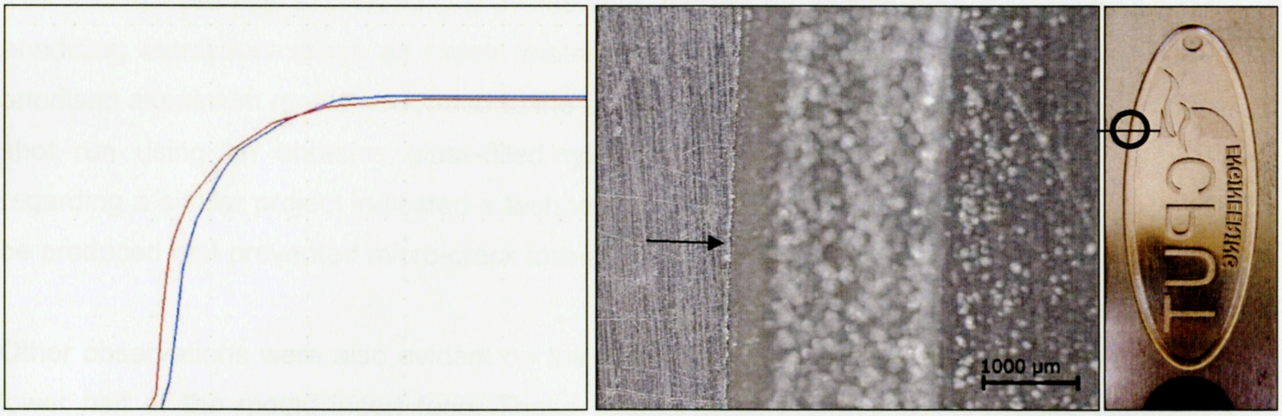

Figure 5.11 Profile of steel, injection side upper logo edge

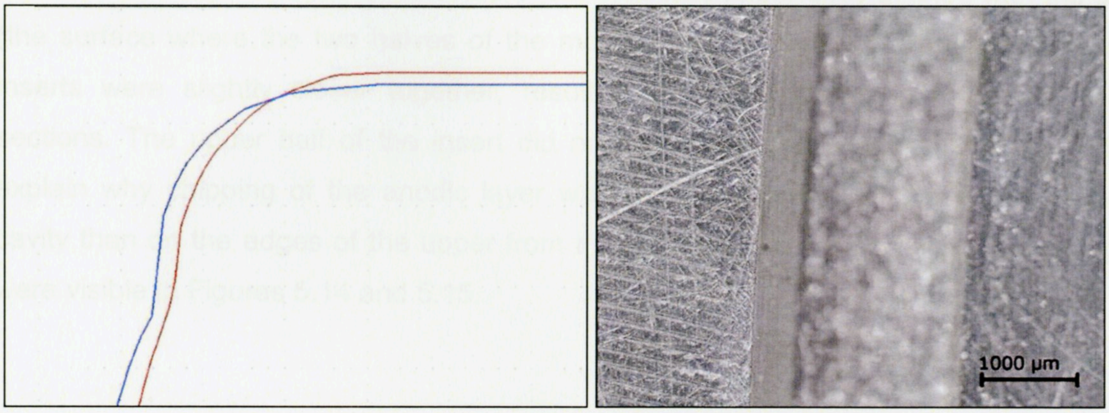

Figure 5.12: Profile of aluminium, injection side upper logo edge

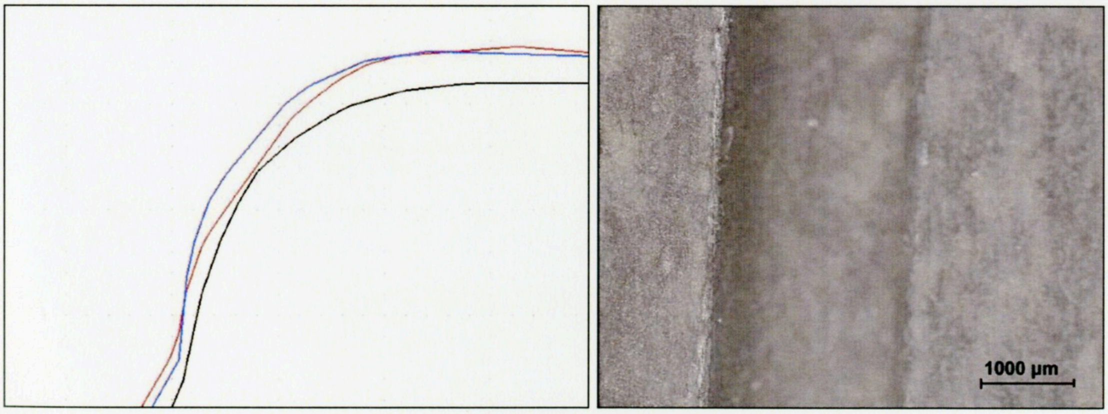

Figure 5.13: Profile of anodised, injection side upper logo edge

Blue = before moulding
Red = after moulding
Black = before anodising

The wear on the edges of the upper cavity of the mould (Figures 5.8 – 5.13) are also evident but slightly less prevalent than on the edges examined on the lower cavity (Figures 5.2 - 5.7).

The findings seemed to contradict previous work carried out in this area that involved hard anodising aluminium alloys as mould materials. The finding indicated a four-cavity, hard anodised aluminium mould performed to the standard of the P20 steel mould during a 10 000 shot run using an abrasive glass-filled-nylon polymer (Anon, 2006). Other information regarding a similar project indicated a technology developed that allowed anodised layers to be produced that prevented micro-crack formation (Rapra Technology, n.d.).

Other observations were also evident on the insert split face. Pitting marks occurred on the lower half of the mould insert face. These defects were aggravated by greater clamping forces experienced on the lower half of the inserts. It was observed after moulding the pocket of the bolster into which the inserts were fastened was imperfectly aligned with the split face (the surface where the two halves of the mould met). As a result, the lower halves of the inserts were slightly closer together, resulting in higher clamping forces on the lower sections. The upper half of the insert did not, however, show signs of pitting. This could explain why chipping of the anodic layer was more noticeable on the edges of the lower cavity than on the edges of the upper from the increased clamping force. The pitting marks were visible in Figures 5.14 and 5.15.

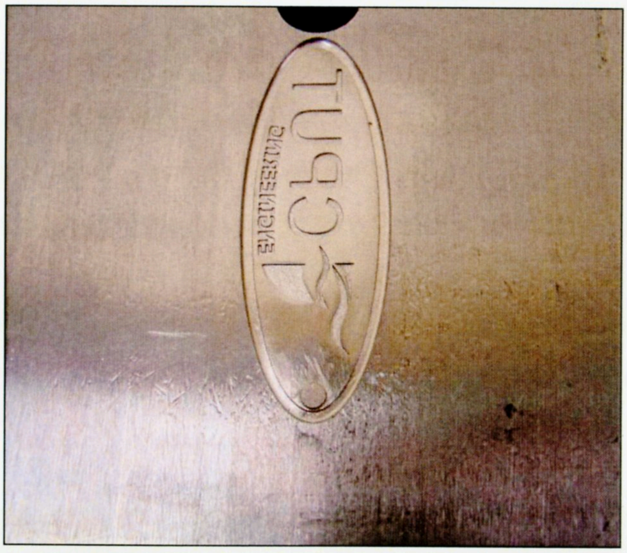

Figure 5.14: Steel injection side insert after moulding. Note the pitting marks

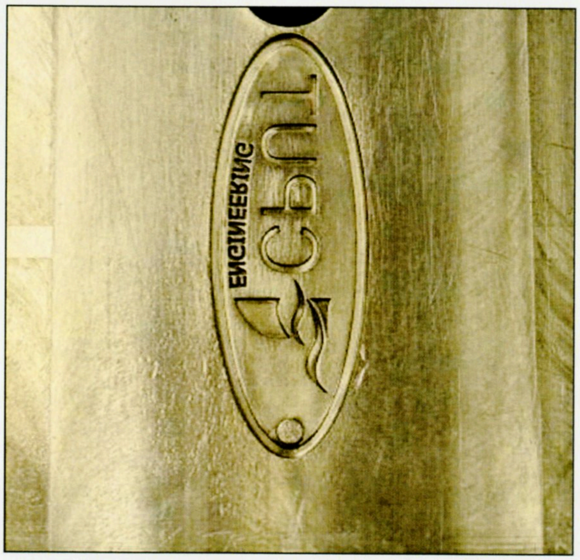

Figure 5.15: Aluminium injection side insert after moulding. Note the pitting marks

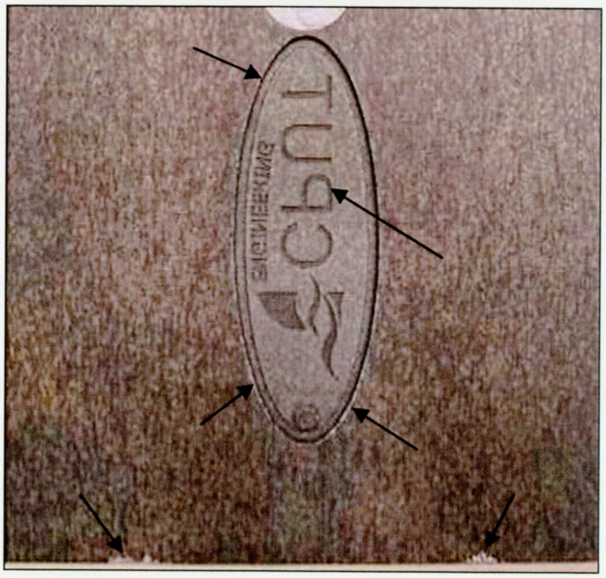

Figure 5.16: Anodised aluminium injection side insert after moulding.

When comparing the three images of the injection side of each insert, pitting marks are visible on the steel and aluminium inserts (Figure 5.14 and 5.15). When observing the hard anodised insert (Figure 5.16) it is not obvious that there are pitting marks on its surface. The base aluminium alloy is visible in the places where the hard anodised layer has chipped off. It is particularly evident on the outer edges of the cavity and the boss. These areas are the sharp edges that come in contact with the other half of the mould insert and experience the clamping force. There are, however, small areas of chipping at the edges of the letter "P" shown in Figure 5.17

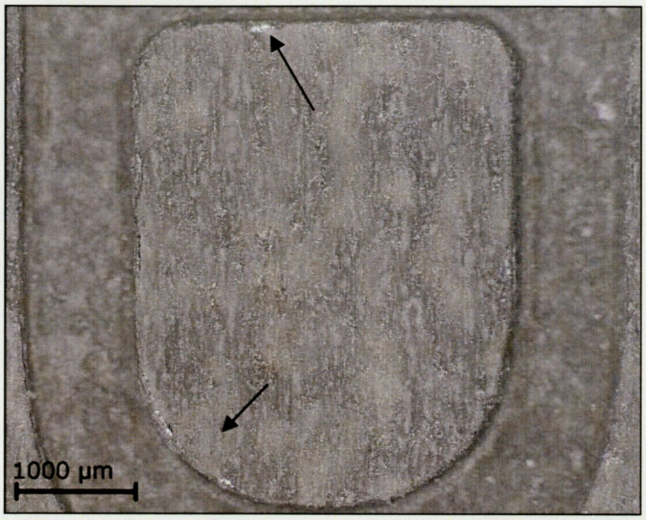

Figure 5.17: Anodic layer removal inside the cavity at the "P" of "CPUT"

The chipping therefore, is not only limited to the sharp edges that experience the clamping force but also those places in contact with the polymer The small amount of thermal expansion in the letters can aggravate the formation of micro-cracks in the anodic layer thereby weakening it in vulnerable areas. The flow of the polymer through the mould cavity can have an abrasive effect especially when the polymer has harsh fillers. This effect is normally most noticeable at the gate of the cavity where the velocity of the polymer is the greatest. Because of the product requirements of this project filler material was unnecessary and there was no noticeable wear on any of the inserts at the gates to the cavities.

The sprue bush for the inserts was interchangeable and manufactured from steel. This had an impact on the uncoated aluminium alloys as there was some mechanical damage in the form of crushing marks in the area of the runners and gates on the ejector side as shown in Figure 5.18. These marks were not visible on the tool steel or hard anodised inserts indicating that the harder material and hard surface coating resisted the crushing effect of the sprue bush. Deformation was noticed on the aluminium insert gate (arrowed in image B of Figure 5.19). It indicates the side walls of the gate deformed by the sprue bush during clamping. The deformation to the gate could lead to the product being increasingly difficult to eject as the deformed edges of the gate start obstructing ejection in a similar way that an undercut would. At this stage there was no noticeable problem with ejection as the deformation was in the order of only 0.1mm. The force of the ejector pins and their positions in respect to the gate were more than sufficient to eject the product.

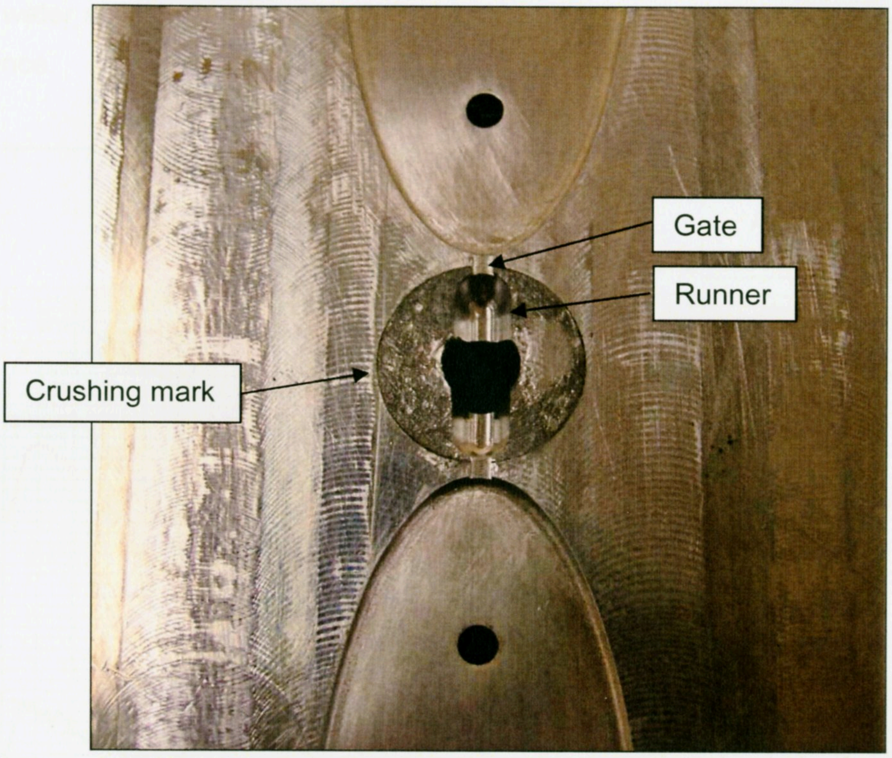

Figure 5.18: Crushing mark formed by the steel sprue bush on the aluminium insert

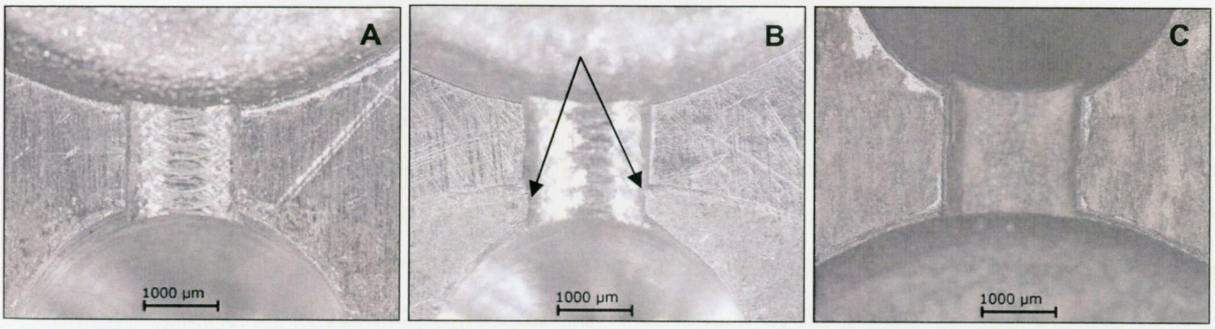

Figure 5.19: Ejector side gate of steel (A), aluminium (B) and hard anodised (C) insert

5.2 Thermal results

The thermal behaviour of the materials was measured during the moulding process as described in Section 4.7 Figure 5.20 shows a graph of the thermal profile of six shots for each mould material during production. The data was collected with a constant flow of cooling water at 12.5°C. The minimum temperature of the hard anodised insert was used as a reference.

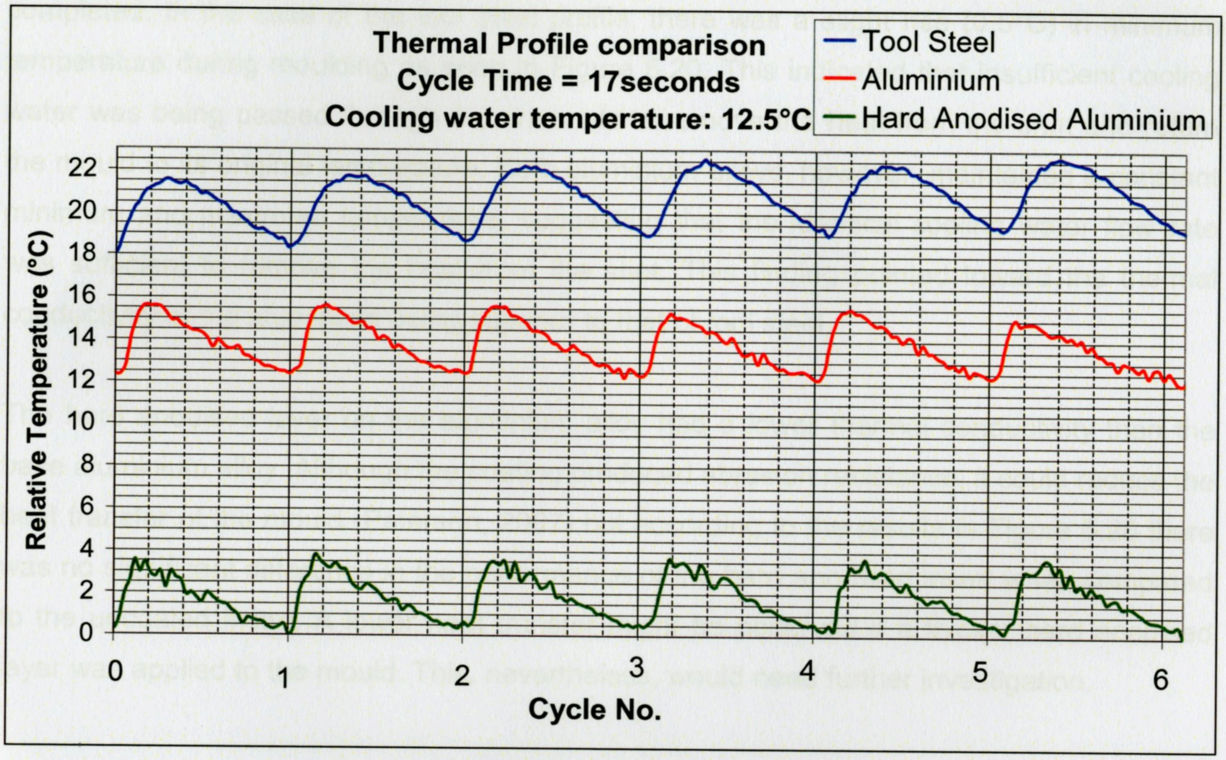
Thermal Profile comparison
Cycle Time = 17seconds
Cooling water temperature: 12.5°C

Figure 5.20: Thermal profile comparison

During the cycle molten plastic was injected in 1 7 sec into the mould cavity at a temperature in the region of 220°C. The mould was held closed for ±3.5 sec, then opened and the product ejected. During that time the mould and product were cooled by the water running through the cooling channels in the inserts. Once the product had been ejected and the mould was closed the next shot of plastic was received. The entire cycle lasted 17 sec. As the plastic was injected into the mould there was a rise in the core temperature of the mould. The temperature of the insert rose to a maximum point then began dropping until the next shot was injected.

In all the moulds the temperature rise was ±3.4°C, however, the shape of the profile was different for the various insert materials seen in Figure 5.20. The tool steel profile had a rounded shape at its apex, while both aluminium moulds were sharper The tool steel insert reached its maximum temperature at 33% of the cycle time while both aluminium alloy moulds reached their maximum at 20% of the cycle time. The sharp apex and steeper heat gain of the aluminium alloy moulds indicated that this alloy has a greater sensitivity to thermal change and a better thermal conductivity than the tool steel.

The three materials fell between different operating temperatures shown in Figure 5.20 with the minimum temperature of the hard anodised profile being used as a reference. Possible reasons for this were that the machine had operated for varying periods before readings were taken, leading to the mould material having residual heat from moulding already completed. In the case of the tool steel profile, there was a slight rise (0.5°C) in minimum temperature during moulding as seen in Figure 5.20. This indicated that insufficient cooling water was being passed through the channels to remove the heat from the shot and return the mould to its original temperature. Both aluminium alloys, however, maintained a constant minimum and maximum temperature, suggesting that the identical cooling water flow rate was sufficient to remove the heat from the shot. This finding pointed toward the thermal conductivity of the aluminium being superior to that of tool steel.

The hard anodised layer on the aluminium alloy had a lower thermal conductivity than the base aluminium alloy Although the coating produced abrasion resistance, it could reduce the heat transfer of the mould (Paterson, 2007) but according to the results in Figure 5.20 there was no significant difference in the performance of the hard anodised insert when compared to the uncoated insert. A lower heat transfer might be observed if a thicker hard anodised layer was applied to the mould. This, nevertheless, would need further investigation.

5.3 Hardness results

There were concerns that as the hot plastic was repeatedly injected into the aluminium 7075-T651 cavities a heat treatment effect might occur Aluminium alloy 7075 was solution heat treated at 120°C according to its T6 designation (Polmear, 1989:70) and the temperature of the injected plastic was to the order of 200°C. The concern was that because of prolonged exposure to high temperature from the polymer, the mould material at the cavity would become over heat treated and lose its properties during production. As explained in Section 4.1 hardness tests were done on samples of the aluminium alloy. After moulding, hardness tests were carried out on the split face and cavity of the ejector side of both aluminium and hard anodised aluminium alloy inserts; hardness readings were taken from the points indicated in Figure 5.21

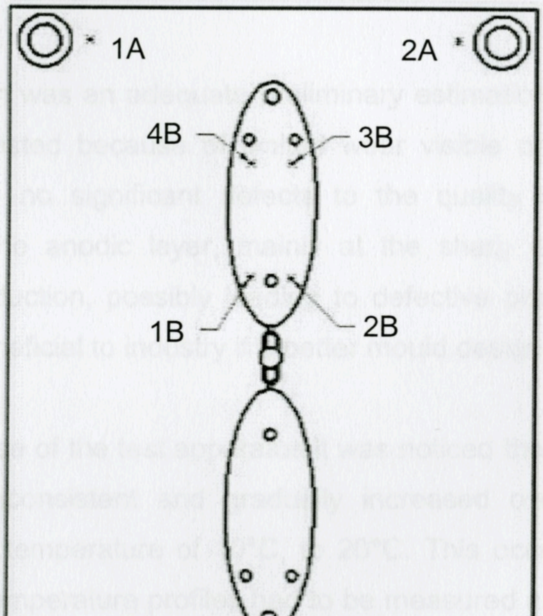

Figure 5.21: Location of hardness test points on the ejector side insert

Table 5.1: Average hardness of aluminium inserts after moulding

	Aluminium alloy	**Hard anodised aluminium alloy**
Average A	88.6 HRB	92.8 HRB
Average B	89.8 HRB	91 7 HRB
Average A and B	89.2 HRB	92.2 HRB

The average hardness of the uncoated aluminium insert on the split face (1A - 4A) was 88.6HRB and 92.8HRB for the hard anodised insert. The average hardness of the cavity (1B

– 4B) for the uncoated aluminium insert was 89.8HRB and 91 7HRB for the hard anodised inserts. From the hardness results taken before moulding, the hardness of the material was 90HRB for the uncoated aluminium and 92HRB for the hard anodised material. See Appendix L for the raw data.

From these results it was found there were no significant differences between the hardness of the cavity and the split face when compared to the same material before moulding. Therefore, the properties of the aluminium withstood the effect of the contact with the hot polymer It is probable that the material experienced temperatures above its heat treating temperature only for a short time during each shot. As a result there was insufficient exposure to temperature to alter the materials' properties.

5.4 Test apparatus review

The 10 000 test shot run was an adequate preliminary estimation to test this mould design. Further testing is suggested because of limited wear visible on the steel and aluminium inserts and there were no significant defects to the quality of the moulded products. However, chipping of the anodic layer, mainly at the sharp edges of the cavity, could escalate with more production, possibly leading to defective products. A larger amount of shots would be more beneficial to industry if a better mould design was achieved.

During production and use of the test apparatus it was noticed the cooling water temperature in the reservoir was inconsistent and gradually increased over two to three hours of production from the set temperature of 10°C, to 20°C. This occurred while the chiller was active. As a result, the temperature profiles had to be measured at a specific time - when the cooling water was at the same temperature - for all three insert sets. Production was still possible, although the chiller unit had insufficient capacity to maintain a temperature of the cooling water at 10°C. The pump that circulated the water around the system was able to pump at a reasonable flow rate. The flow meter on each of the four mould cooling channels read 1.5 units for the production of the key tags. Higher flow rates of more than 2.5 units were difficult to achieve because of restriction on the pump capacity A pump with a higher deliverable flow rate would allow for more flexibility during production and testing.

While first setting the injection moulding machine with the steel mould insert in place, it was found that the mould had to be opened extremely slowly to permit the lettering detail of the key tag to be loosened from the injection side insert (see Figure 4.14). Ideally, during the mould opening stage, the sprue would be pulled with the ejection side along with the two key tag products. Inaccurate machining of the mould insert, such as insufficient draft angles being machined, caused the lettering to offer resistance to the ejection process. This then resulted in the key tags being held to the injection side while the sprue was pulled by the ejection side as the mould was opened. The result was that the product would break at the gate (the weakest part), the sprue being ejected and the two key tags held onto the injection side of the mould. This behaviour was also present with the aluminium insert, but the products were held to the stationary side more aggressively The gates were breaking irrespective of how slowly the mould was opened. A non-silicon mould lubricant, "Mould Release" by Spanjaard (trade name) was used to assist the product to peel off from the stationary side. During the production of the hard anodised aluminium insert it was found the products were held onto the injector side even more aggressively, to a point where the release agent did not improve ejection. As a result, each product had to be removed by hand, thus significantly slowing production - normally unacceptable in an industrial environment. The insert could not be modified as the anodised layer would have been damaged.

When considering how to measure the mould insert temperature during production, the intention was to record a temperature measurement every 0.1 sec. It was later found that the fastest period of measurement was 0.5 sec with Labview software and a data acquisition card. To obtain accurate readings the period needed to be fast, but 0.5 sec was satisfactory for the testing. Other observations were the temperature profiles recorded were jagged. This was particularly evident with the lower cavity recordings. The cause of the jagged pattern of the profiles was not fully understood as there was no sign of outside interference and the lower thermocouple was replaced without alteration to the shape of readings. A different channel on the data acquisition card was also used to find the fault, but to no success. The data received from the upper thermocouple was, however, acceptable and used to draw conclusions as shown in Figure 5.20.

The wear comparisons using the 3D scanner indicated that the method of orientation was inconsistent because of the high degree of accuracy required when placing the insert into the scanner (see Sections 4.4 and 5.1). The results were profiles that were not perfectly aligned and, therefore, analytical data was unreliable. However, the shapes of the surfaces and edges were still useful to draw conclusions. The addition of using a microscope to observe the edges in questions was valuable to confirm findings from the profile.

6 Conclusions

All mould inserts completed the 10 000 shot run without noticeable defects to the moulded product. There was no significant wear on the tool steel and uncoated aluminium insert. However, there was chipping of the anodic layer on the hard anodised insert at the sharp edges of the cavity, particularly on the outer edges.

The anodic layer chipped for several reasons, such as the formation and propagation of micro-cracks at the stress concentrated areas and the abrasive effect of the polymer flow through the cavity The slight thermal expansion might also have aggravated the formation of micro-cracks. The thermal expansion of the anodic layer is differed from that of the base aluminium alloy Other chipping was noticed at the areas where the extension pipes screwed into the insert (see Figures 4.18, 4.21 and 5.16). This thin area between the split face and the threaded hole experienced a small amount of deflection, indicating the anodic layer's sensitivity to deflection as it was hard and brittle. There were no significant defects in the moulded product of the hard anodised insert, however, continued use could render the insert unsuitable in production. The hard anodised layer was unsuitable because of the chipping effect observed, but further developments in mould design or improvements to hard anodised layers to prevent chipping could be beneficial. However, the layer did prevent the pitting marks observed on the uncoated aluminium and tool steel inserts making hard anodising a promising method to reduce wear in injection moulds - maybe not for the mould cavities, but for other moving parts in an advanced mould such as sliding components and rotating cores.

The uncoated aluminium alloy insert did show signs of mechanical damage caused by crushing of the sprue bush. However, this did not influence the moulded product or production.

The pitting marks visible on the steel and aluminium inserts were not evident on the hard anodised unit. The hard anodised coating resisted the pitting damage caused by the greater clamping forces seen on other inserts. This was because the hardness of the hard anodised layer being in the order of 39HRC - slightly higher than the tool steel material used.

There was concern the hot polymer would produce a heat treatment effect on the aluminium alloys during production. The heat treatment could have deteriorated the metals' properties by over-treating it while in contact with the molten plastic. The after-moulding hardness test indicated no significant difference in hardness on the cavity and the split face when compared to hardness tests conducted on the material before moulding. The negligible hardness difference on the split face indicated that for the given production run and injection moulding machine settings no work hardening took place. The uncoated aluminium alloy held its properties after the moulding of the 10 000 shot production run; this was true also for the hard anodised insert.

The superior thermal conductivity of the aluminium alloy compared to the tool steel could lead to more efficient and even cooling of the product shown by the faster rate of heating observed in Figure 5.20. Both aluminium inserts reached their maximum temperature 13% faster than did the steel insert, indicating the plausibility of the cycle time being decreased. The hard anodised insert had a similar thermal profile to the uncoated aluminium, therefore, the anodic layer did not have a significant effect on the thermal behaviour of the insert.

The hard anodised aluminium insert had a rough texture making the key tag not as polished and smooth as in the other inserts. A polished cavity will not only give the product a smooth surface, but will aid the flow of polymer as it is injected into a mould. The anodic layer can be polished to a smooth surface, but this extra process can be time-consuming, thus increasing mould cost. Hard anodising could, however, be a good surface treatment to consider if the product required a textured or matt finish.

The mould design and manufacture of the three test inserts was unsatisfactory for an industrial application. This was because of difficulties experienced during ejection of the product. The key tag would break away from the sprue at the gate, if the mould was opened too rapidly This resulted in the sprue being ejected properly, but leaving the key tags on the injection side of the mould. The key tags then had to be manually removed, thereby reducing production efficiency The tool steel inserts performed to a satisfactory standard if the mould was opened at a low speed, however, both aluminium insert sets experienced the difficulties mentioned earlier The mould was, however, suitable to test purposes.

During recording of the thermal profile of each insert material, the operation range of the mould was inconsistent as seen in Figure 5.20. The main reason for this was that the cooling water could not be maintained at a constant temperature and during production the water temperature in the reservoir would increase gradually The tool steel insert showed signs that it could not emit all the heat generated from the injected polymer fast enough, thereby the core temperature of the insert increased. Because of the temperature of the cooling water not being constant it was difficult to determine if the inserts were operating at different temperature ranges because of their thermal properties, or because of the varying cooling water conditions or other factors, such as the length of production before readings were taken.

7 Recommendations

The mould design of an aluminium alloy injection mould is of utmost importance and, therefore, certain design changes should be investigated if this project is to be continued. The aluminium injection mould (AIM) design (Kirkland, 2003 & Goldsberry, 2003) should be investigated as an improved alternative to an insert-and-bolster design. The large bolster was a good starting point but if it was to be manufactured it would be more expensive than rather having a mould manufactured largely from aluminium alloy. The weight saving would also be beneficial to mould handling as the entire bolster with inserts weighed a little more than 100kg. With the present design the insert experiences all the clamping force and from knowledge learned from the AIM design it would be advantageous to have tool steel pillars bear the force of the clamping action. To prevent the crushing of the ejector side of the uncoated aluminium alloy insert caused by the steel sprue, an aluminium sprue might be investigated for use with this insert.

The current mould design should be modified if more inserts are to be manufactured. To improve ejection from the mould, the orientation of the product should be swapped around so that the ejection side insert contains the front half (lettering) cavity and the injection side is the back (flat) half cavity of the key tag. By having the lettering detail of the product on the ejector side of the mould, the product will have little to hold it to the injector side, thus avoiding the difficulties explained in Section 5.4. Another option would be to manufacture shallower lettering with special attention paid to the draft angles.

Further investigation using the current inserts can be undertaken to determine the point of mould failure for the aluminium alloy and hard anodised aluminium alloy inserts. The condition of the inserts after another 10 000 shots would be necessary to investigate the expected life span of an aluminium mould of similar design.

Further investigation could involve a medium strength aluminium alloy as a mould material, such as the 6xxx series. Aluminium alloy 6082 is manufactured in South Africa and is readily available and more affordable than the 7075 alloy This alloy could prove to be more wear-resistant than harder 7075 aluminium alloys. According to Paterson (2007), the relationship between hardness and wear resistance is not correlated. If a soft material were used, abrasion would plough into the metal and so remove material. If a hard material were used, then abrasion would be resisted for some time until the material surface failed in a brittle manner, again losing material. Once failure is initiated the surface degrades rapidly However, if the material is of medium strength the metal is neither ploughed nor fails initially in a brittle fashion. The effect of applied stresses by a clamping force could deform the metal, but without loss. This applies cold working to the material making it harder and more brittle (cold working is applied to some aluminium alloys to increase their strength). In due course brittle failure will result in metal loss of the medium strength alloy but long after either a soft or hard alloy

Further investigation can be conducted to observe wear resistance of hard anodised layers when using an abrasive polymer Abrasive polymers usually contain a filler material such as glass fibre to increase the strength of the moulded product. The anodic layer formed when hard anodising has good chemical resistance, therefore, corrosive polymers can be used to investigate this behaviour when moulding with plastics such as polyvinyl chloride (PVC). The key tag designed for this project was manufactured using polypropylene as the moulding material which is neither corrosive nor abrasive. The choice of plastic was dictated by the product demands as explained in Section 4.5 and thus an abrasive or corrosive plastic was unnecessary The use of an abrasive or corrosive polymer could be investigated further to assess the wear behaviour of the hard anodised insert with particular attention to the gate area of the cavity, were wear is most likely to occur with such a polymer

Currently for the tool steel insert, the mould has to be opened slowly to allow the lettering detail to come away from the injection side of the insert. If the mould was opened too rapidly the sprue broke from the product at the gates and the key tags required manually removal from the injection side. During the moulding of the aluminium insert the products required manual ejection because of the key tags being held on to the injection side even when the mould was opened at low speed. An aerosol mould release agent was used to aid ejection. During production with the hard anodised insert the key tags were vigorously held onto the injection side even when the mould release agent was used. Manual ejection was required for the entire production run with the hard anodised insert. Manufacturing inaccuracies were the cause of improper ejection.

Hard anodising is known to increase wear resistance of aluminium, but as noticed during the mould testing, the anodic layer chipped off at the sharp edges of the cavity Development of the hard anodising process could be investigated further to prevent micro-cracks and their propagation in the anodic layer Because the thermal expansion of aluminium is different from that of a hard anodised layer, aggravated formation of micro-cracks could occur If the anodic layer (or another surface coating) had a thermal expansion coefficient similar to the base aluminium alloy the amount of cracking and chipping could be reduced.

The effect of thicker anodic layers can be investigated to assess the relationship between wear resistance and the anodic layer thickness.

The chiller unit was unable to maintain the cooling water at 10°C. The installation of a larger capacity chiller unit would be beneficial to maintain constant cooling water temperature. This would allow for a more constant cooling water temperature and thus a stable testing and production environment.

For further flexibility during future use of the injection moulding machine a higher flow rate pump would be favourable to allow for higher flow through the mould cooling channels.

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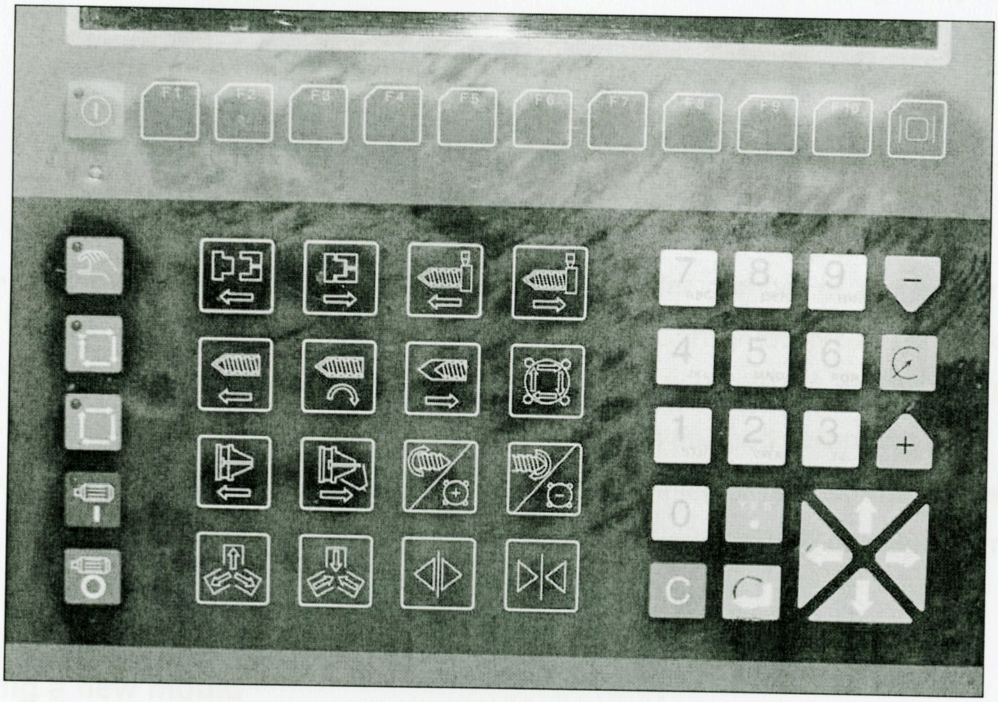
9 Appendices

9.1 Appendix A: Injection moulding machine setup

Setting of the injection moulding machine is a time consuming operation to the untrained person. Often artisans (injection mould setters) are employed to set up moulds for production. Slight changes in machine settings can affect production time and product quality The following is a guide to setting up the SM 90 injection moulding machine. This guide should be used with the operation manual for the machine.



Machine start up

- Switch the machine ON at the wall;
- on the control panel press the emergency stop button in and release it again;
- at this point the ON button can be pressed to start up the machine. It will take a few moments to boot. In that time a diagram of the machine and manufacturer image will appear on the screen and,
- once at the menu screen the machine settings can be loaded. There is a library of saved settings used for past moulds used in the machine . It

is advisable when setting up a new mould to load a similar mould setting from the library Once the settings are loaded save the new mould settings under a different name (so not to overwrite the other settings) and modifying them to suit the new mould.

Calibrating the machine

When the power is turned off, the rotary encoders lose their calibration. The encoders tell the machine's software the position of the injector screw, the mould and the ejector ram. When the encoders are un-calibrated the settings used will not appear to be working correctly, or the mould will not close completely

- With the machine ON and the barrel inside the set working temperature settings go to the calibration page in manual mode. For manual mode, for interface output settings and then for the calibration page. Switch the hydraulic motor on;
- for mould position calibration, select the smaller number of the two (mould open and closed). Once the small number is highlighted press and hold the mould closed button. The red bar will read "calibrating" as the mould is closed. The bar will read "complete" when it has finished calibrating and,
- similarly do the same for ejector backward and injector forward (be aware that this will push the screw forward and any shot ready will be expelled from the barrel).

Fitting a new mould

- When the mould is out of the machine, measure the mould height and fasten it in the closed position with straps. Have the fastening bolts and equipment ready to fasten it to the platens as well as the block and tackle to hoist the mould and a suitable eye bolt fastened into the mould. Predetermine as to where and how the mould is to be fastened onto the platens of the machine;
- calibrate the mould position as described in the previous section;
- with the machine ON, open the platens in manual mode and set the mould height of the machine to a number about 5mm or so smaller than the

measurement taken. For mould thickness (height) adjustments settings. One can only access the mould thickness adjustment page when the mould is fully open;

- turn the machine OFF at the wall to ensure a safe working environment;
- hoist the mould up with a block and tackle attached to the overhead arm and lower into the machine between the platens;
- fix the injection side of the mould first. One will have removed the strap and allow the hoist to support the ejector side as one locates the retaining ring into the hole on the injector side and fasten the backing plate of the mould to the platen;
- while the hoist is still supporting the ejector side (to retain mould alignment), close the guard doors and switch the machine ON;
- In manual mode close the mould by pressing the mould close button until the ejector side platen is in contact with the ejector side of the mould. Be careful not to clamp the mould at high pressure hence the smaller than normal mould height. Change the mould height if needed to bring the ejector side platen to the mould back plate;
- switch the machine OFF at the wall;
- fasten the ejector side of the mould so the platen. Ensure the mould alignment is satisfactory;
- release the hoist and remove from the clamping side of the machine.
- switch the machine ON;
- fine tune the mould height so that the toggles lock when the mould is completely closed and,
- when the mould height is set correctly and calibrate the mould position as described on the previous page.

Barrel temperature

Press for the temperature settings page. This page allows the user to set the barrel temperature for the polymer in use. Upper and lower temperature limits can also be set. There is a library on screen beneath the barrel diagram with frequently used barrel temperatures for various polymers (or resins).

The barrel heaters have three modes namely: Off, Standby and Heat. Move the highlighted cell with the arrow buttons to the “SELECT” option. Select the desired mode by pressing the + or − buttons. The “OFF OR UNDER TIMER SETTING MODE” switches the barrel heaters off but can be set to automatically switch ON if the machine is not off Timer settings page can be viewed by pressing from the temperature settings page.

Injector settings

The injection settings page controls the injection of the molten polymer into the closed mould. Parameters to be set on this page include the injection pressures and speed of the various injection phases, injection time as well as shot size. The holding pressures and their phases as well as nozzle leakage and choke positions can also be set.

- Be sure to allow enough time for the injector to complete the injection cycle (start with too much time);
- the position as labelled on the screen is the distance the screw will move forward to inject the polymer When setting up a new mould begin with a small value and increase until a fully filled mould is achieved;
- the leakage position is the machine’s method of determining a leak. It is the position the screw is in if a leak is present where too much material was injected. If the nozzle is not properly sealed with the sprue bush then polymer will leak at the join causing the machine to move within its cushion. Leakage could also happen if the mould height or clamping force is not sufficient and,
- the choke position is the machines method of determining a blockage or when not enough material is able to be injected. This can be caused by a product that has not been ejected properly

In manual mode the injector screw can be moved forward (inject), rotated (feeding) and retracted (decompression) with the following buttons.

In manual mode the injector carriage can be moved forward and backward with the following buttons.

Dosing and decompression settings

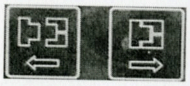
The feed or dosing and decompression settings control how the machine feeds the next shot as well as the cooling time. This takes place after injection. The key considerations for these setting are to:

- Supply enough pressure and speed to feed the next shot;
- the cooling time must be enough for the machine to feed the next shot. Otherwise a “No material” alarm will be sounded and,
- decompression retracts the screw to avoid drooling of the nozzle.

Mould opening and closing

The mould opening page controls the manner in which the mould opens and closes, as well as mould protection. The speed and pressure of the mould opening and closing can be set. In a situation where the product has not been ejected properly and remains between the closing mould, the machine detects this during the low pressure phase of closing (LOW-PR). If the machine cannot close the mould to the set distance with the set speed and pressure in the given time then an alarm will sound. The unit “p” is a pulse and is equivalent to about 0.4 sec.

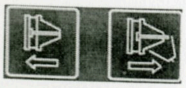
In manual mode the mould can be opened and closed with the following buttons.



Ejector settings

The ejector settings control the pressure, speed and position of the ejector cylinder The ejector cylinder pushes the ejector plate of the mould in turn pushing the ejector pins out.

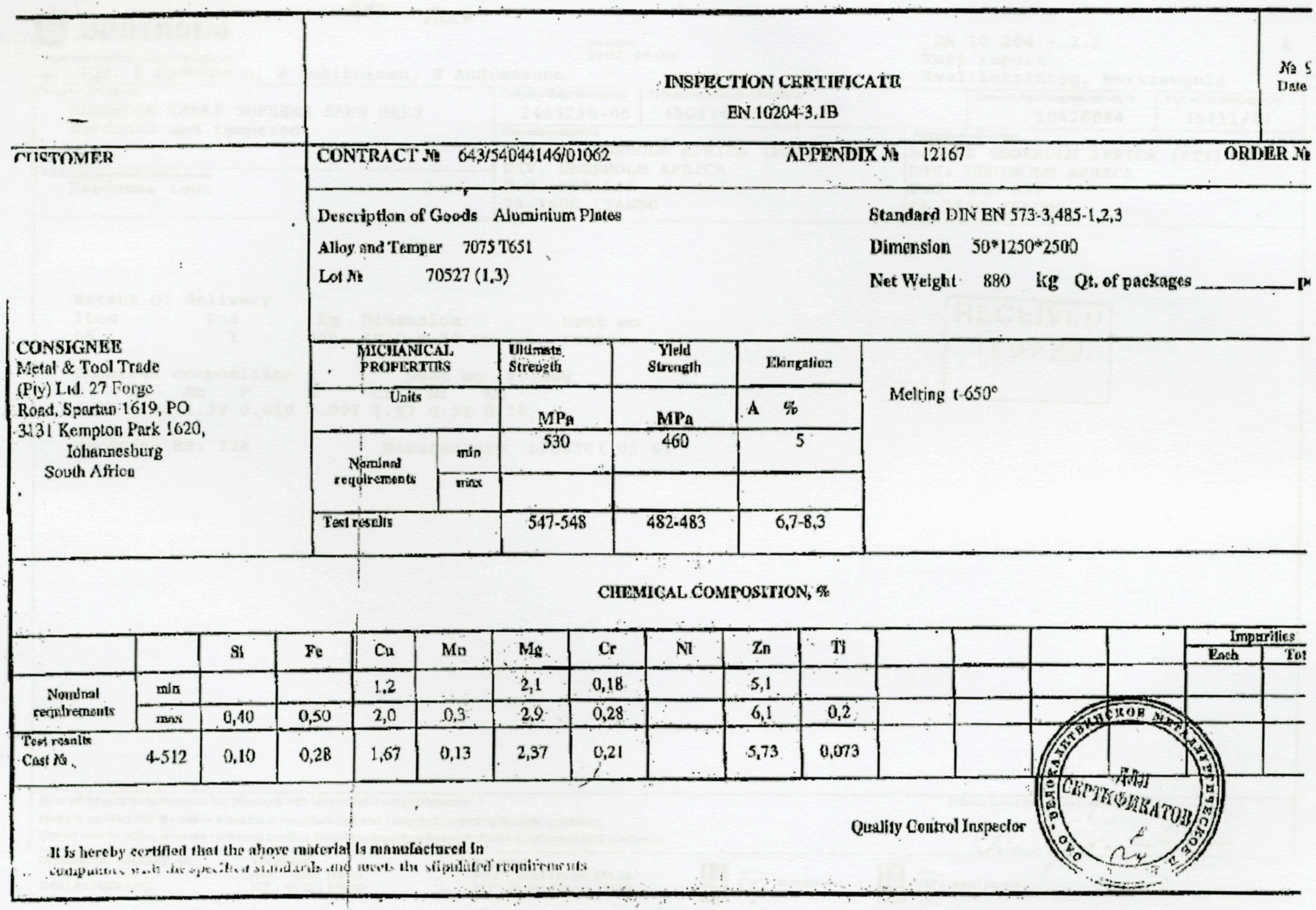
In manual mode the ejector cylinder can be moved forward and backward with the following buttons.



Other operation notes

- When the machine is not operational put the barrel heaters in "OFF OR UNDER TIMER SETTING MODE" and make sure the timer settings are as they should be, see the barrel temperature section. After a few minutes the screen will switch off This prevents the machine from having to be turned off at the wall and so retaining the calibration of the encoders;
- during manual mode the functions can be carried out independently using the key pad as indicated in the previous sections;
- semi automatic mode will carry out one cycle before waiting for the operator to open and close the guard door before carrying out another and,
- Automatic mode will produce cycles continuously without intervention from the operator

9.2 Appendix B: Material certificate for aluminium alloy 7075-T651



№ S
Date

INSPECTION CERTIFICATE
EN 10204-3,1B

CUSTOMER

CONTRACT № 643/54044146/01062 APPENDIX № 12167 ORDER №

Description of Goods Aluminium Plates
Alloy and Tamper 7075 T651
Lot № 70527 (1,3)

Standard DIN EN 573-3,485-1,2,3
Dimension 50*1250*2500
Net Weight 880 kg Qt. of packages ______ p

CONSIGNEE
Metal & Tool Trade
(Pty) Ltd. 27 Forge
Road, Spartan 1619, PO
3131 Kempton Park 1620,
Johannesburg
South Africa

MICHANICAL PROPERTIES		Ultimate Strength	Yield Strength	Elongation
Units		MPa	MPa	A %
Nominal requirements	min	530	460	5
	max			
Test results		547-548	482-483	6,7-8,3

Melting t-650°

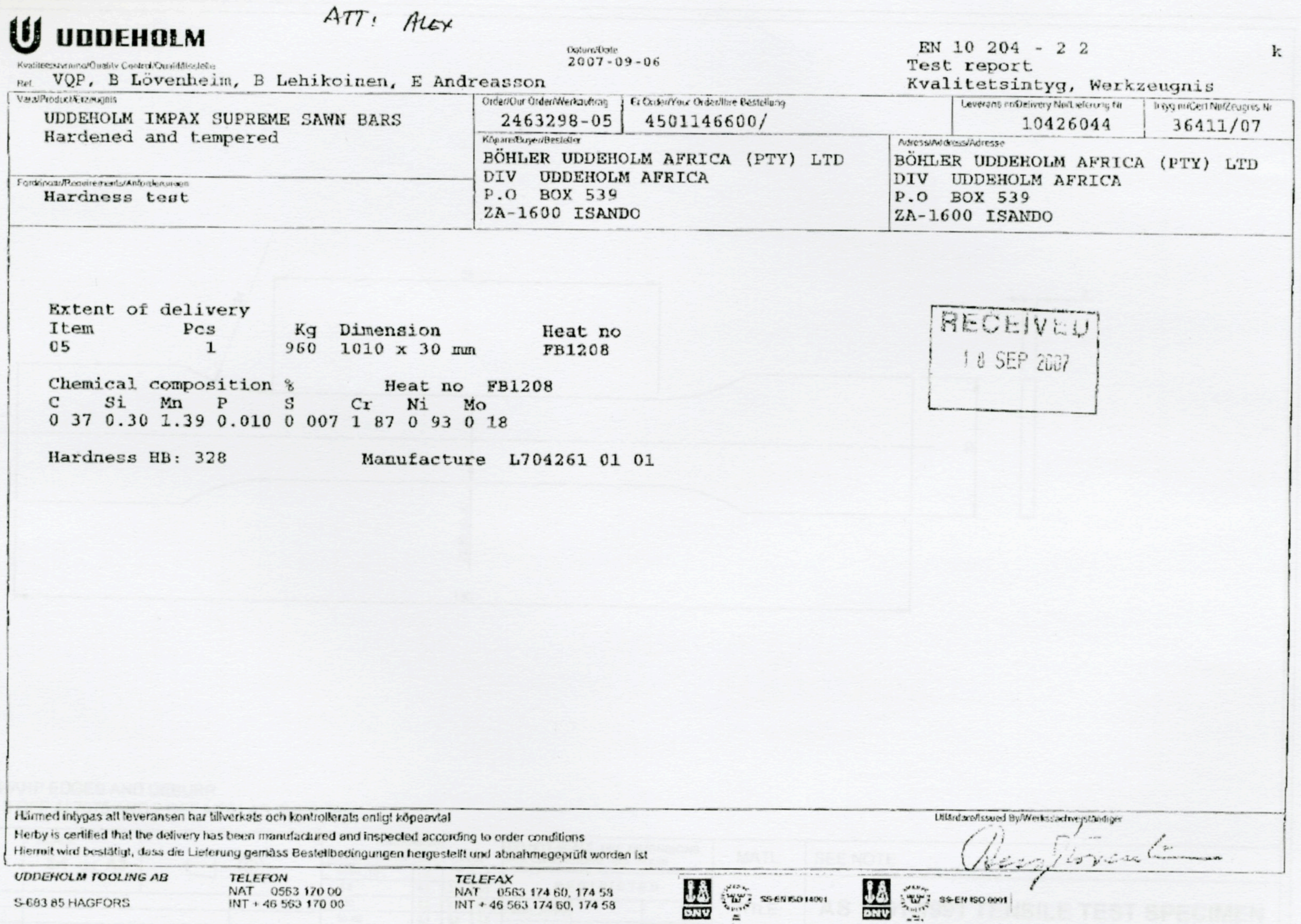
CHEMICAL COMPOSITION, %

		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti					Impurities Each	Impurities Tot
Nominal requirements	min			1,2		2,1	0,18		5,1							
	max	0,40	0,50	2,0	0,3	2,9	0,28		6,1	0,2						
Test results Cast №	4-512	0,10	0,28	1,67	0,13	2,37	0,21		5,73	0,073						

Quality Control Inspector

It is hereby certified that the above material is manufactured in compliance with the specified standards and meets the stipulated requirements

9.3 Appendix C: Material certificate for tool steel M201



UDDEHOLM

ATT: Alex

Datum/Date
2007-09-06

EN 10 204 - 2 2
Test report
Kvalitetsintyg, Werkzeugnis

k

Kvalitetsavdelning/Quality Control/Qualitätsstelle
Ref. VQP, B Lövenheim, B Lehikoinen, E Andreasson

Vara/Product/Erzeugnis UDDEHOLM IMPAX SUPREME SAWN BARS Hardened and tempered	Order/Our Order/Werkauftrag 2463298-05	Er Order/Your Order/Ihre Bestellung 4501146600/	Leverans nr/Delivery No/Lieferung Nr 10426044	Intyg nr/Cert No/Zeugnis Nr 36411/07
Fordringar/Requirements/Anforderungen Hardness test	Köpare/Buyer/Besteller BÖHLER UDDEHOLM AFRICA (PTY) LTD DIV UDDEHOLM AFRICA P.O BOX 539 ZA-1600 ISANDO		Adress/Address/Adresse BÖHLER UDDEHOLM AFRICA (PTY) LTD DIV UDDEHOLM AFRICA P.O BOX 539 ZA-1600 ISANDO	

Extent of delivery

Item	Pcs	Kg	Dimension	Heat no
05	1	960	1010 x 30 mm	FB1208

Chemical composition % Heat no FB1208

C	Si	Mn	P	S	Cr	Ni	Mo
0 37	0.30	1.39	0.010	0 007	1 87	0 93	0 18

Hardness HB: 328 Manufacture L704261 01 01

RECEIVED
18 SEP 2007

Härmed intygas att leveransen har tillverkats och kontrollerats enligt köpeavtal
Herby is certified that the delivery has been manufactured and inspected according to order conditions
Hiermit wird bestätigt, dass die Lieferung gemäss Bestellbedingungen hergestellt und abnahmegeprüft worden ist

Utfärdare/Issued By/Werkssachverständiger

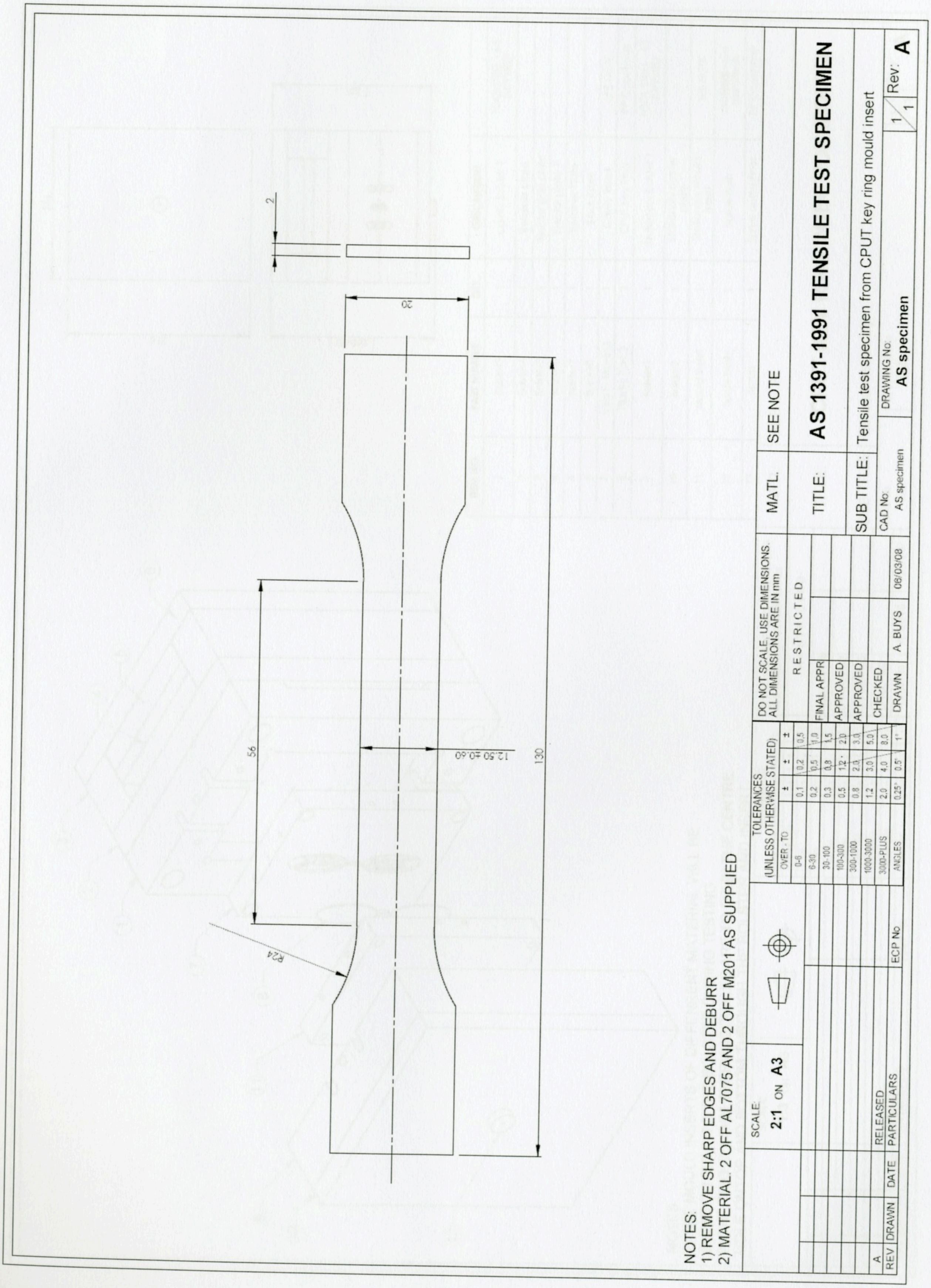
UDDEHOLM TOOLING AB
S-683 85 HAGFORS

TELEFON
NAT 0563 170 00
INT + 46 563 170 00

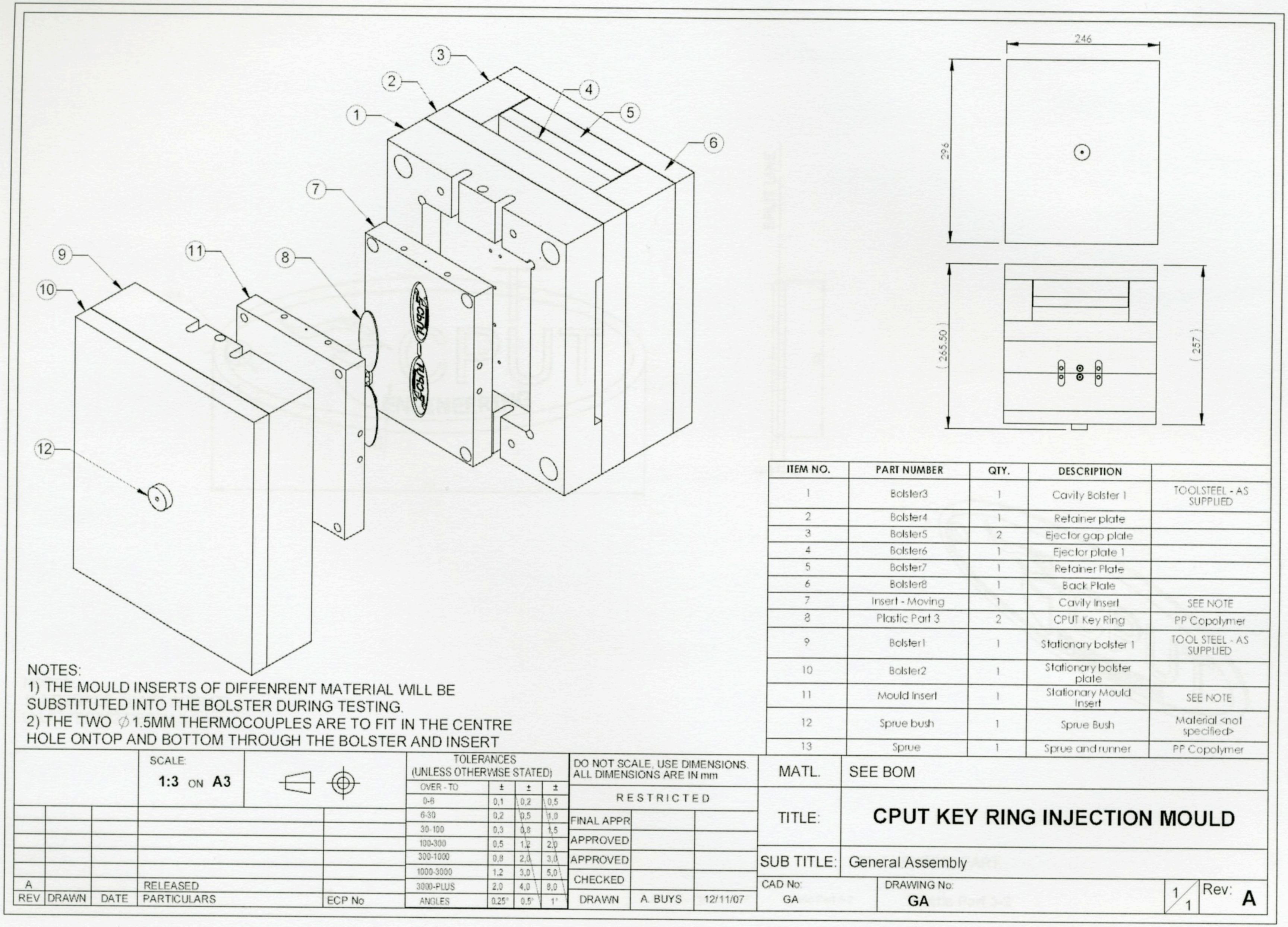
TELEFAX
NAT 0563 174 60, 174 58
INT + 46 563 174 60, 174 58

DNV SS-EN ISO 14001 DNV SS-EN ISO 9001

9.4 Appendix D: Tensile test specimen drawing



9.5 Appendix E: Injection mould assembly drawing



ITEM NO.	PART NUMBER	QTY.	DESCRIPTION	
1	Bolster3	1	Cavity Bolster 1	TOOLSTEEL - AS SUPPLIED
2	Bolster4	1	Retainer plate	
3	Bolster5	2	Ejector gap plate	
4	Bolster6	1	Ejector plate 1	
5	Bolster7	1	Retainer Plate	
6	Bolster8	1	Back Plate	
7	Insert - Moving	1	Cavity Insert	SEE NOTE
8	Plastic Part 3	2	CPUT Key Ring	PP Copolymer
9	Bolster1	1	Stationary bolster 1	TOOL STEEL - AS SUPPLIED
10	Bolster2	1	Stationary bolster plate	
11	Mould Insert	1	Stationary Mould Insert	SEE NOTE
12	Sprue bush	1	Sprue Bush	Material <not specified>
13	Sprue	1	Sprue and runner	PP Copolymer

NOTES:
1) THE MOULD INSERTS OF DIFFENRENT MATERIAL WILL BE SUBSTITUTED INTO THE BOLSTER DURING TESTING.
2) THE TWO ∅1.5MM THERMOCOUPLES ARE TO FIT IN THE CENTRE HOLE ONTOP AND BOTTOM THROUGH THE BOLSTER AND INSERT

SCALE: 1:3 ON A3

TOLERANCES (UNLESS OTHERWISE STATED)			
OVER - TO	±	±	±
0-6	0,1	0,2	0,5
6-30	0,2	0,5	1,0
30-100	0,3	0,8	1,5
100-300	0,5	1,2	2,0
300-1000	0,8	2,0	3,0
1000-3000	1,2	3,0	5,0
3000-PLUS	2,0	4,0	8,0
ANGLES	0,25°	0,5°	1°

DO NOT SCALE, USE DIMENSIONS. ALL DIMENSIONS ARE IN mm

RESTRICTED

FINAL APPR		
APPROVED		
APPROVED		
CHECKED		
DRAWN	A. BUYS	12/11/07

REV	DRAWN	DATE	PARTICULARS	ECP No
A			RELEASED	

MATL. SEE BOM

TITLE: **CPUT KEY RING INJECTION MOULD**

SUB TITLE: General Assembly

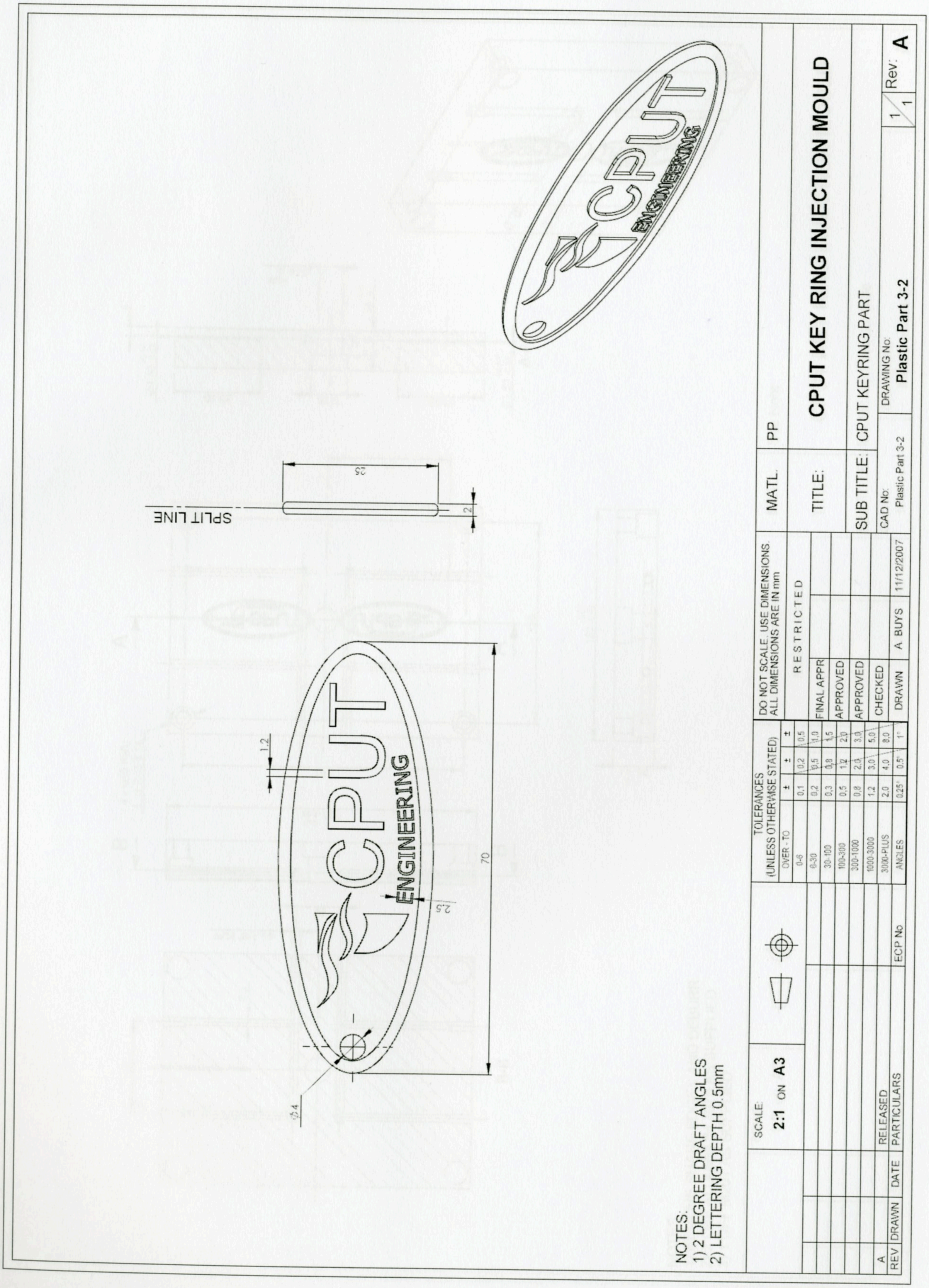
CAD No: GA

DRAWING No: GA

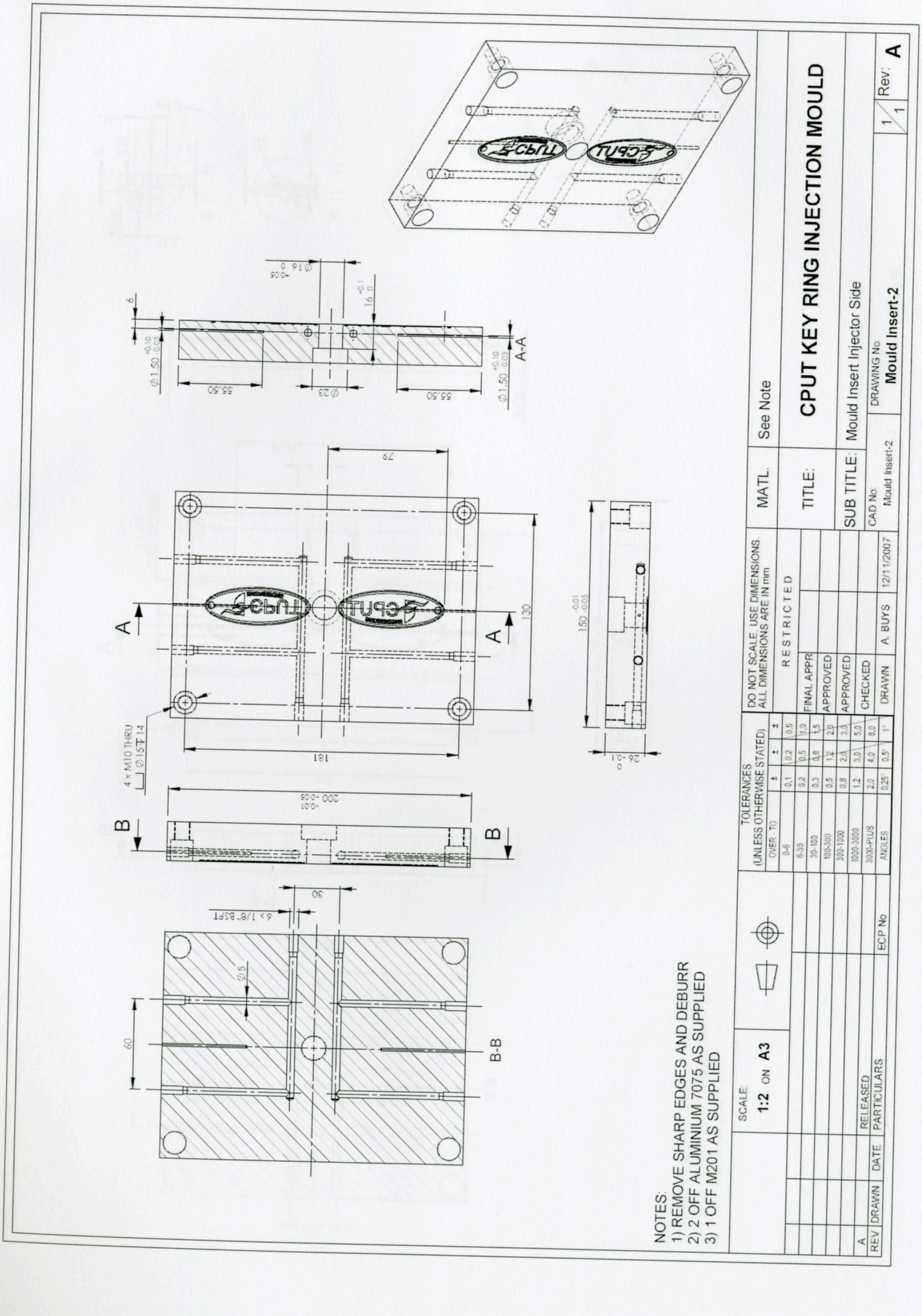
1/1

Rev: A

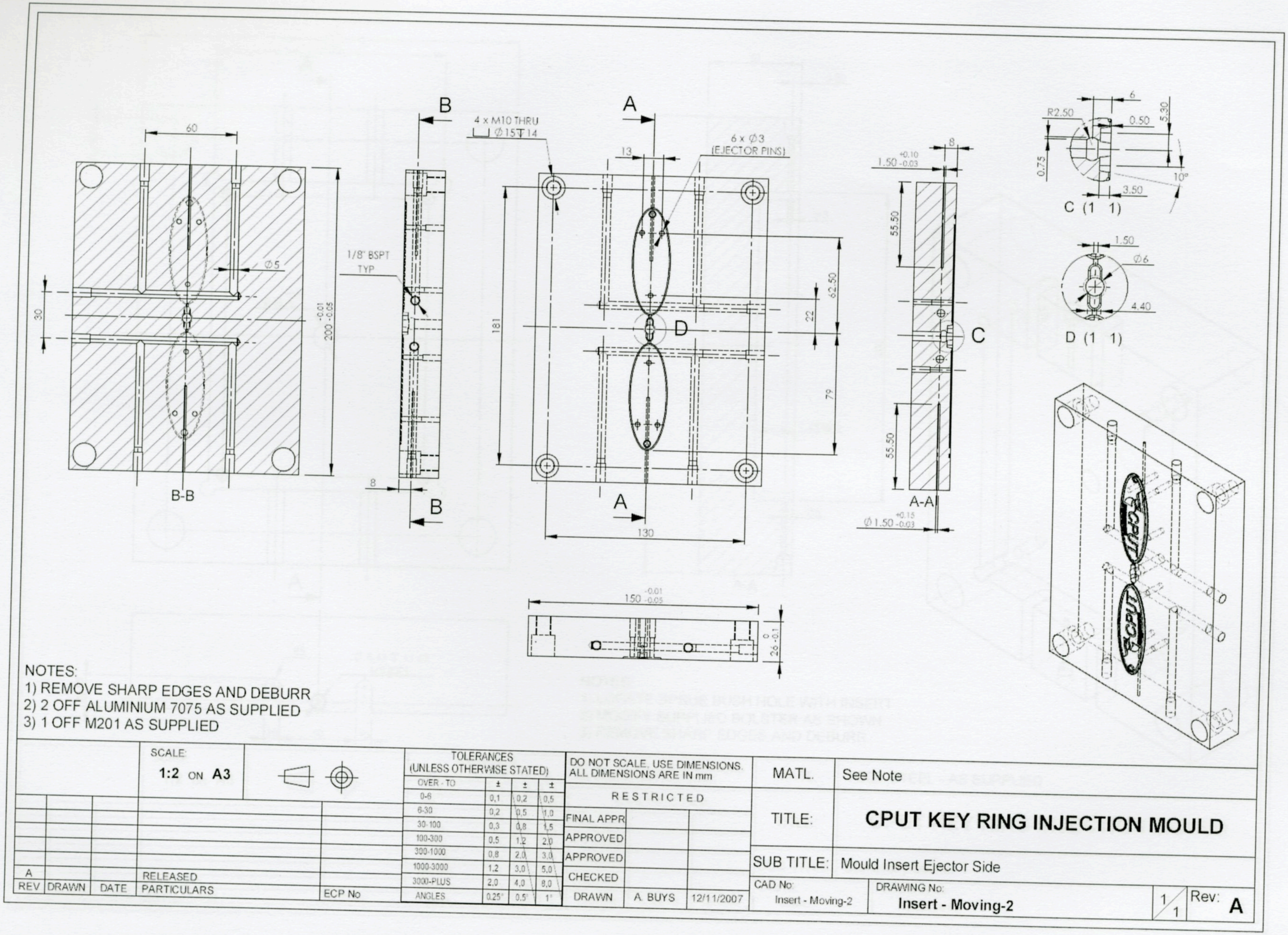
9.6 Appendix F: CPUT key tag design



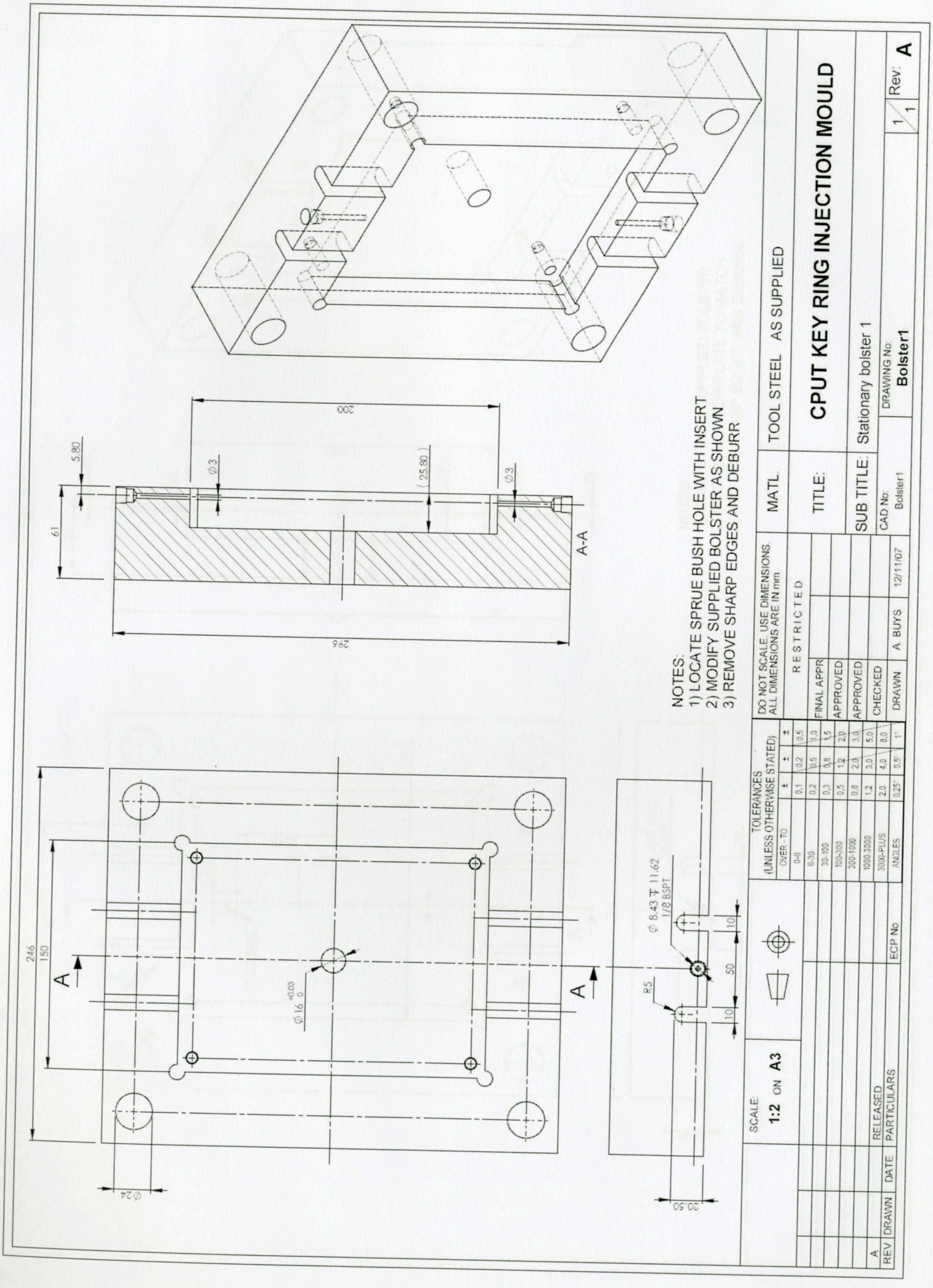
9.7 Appendix G: Injector side insert drawing



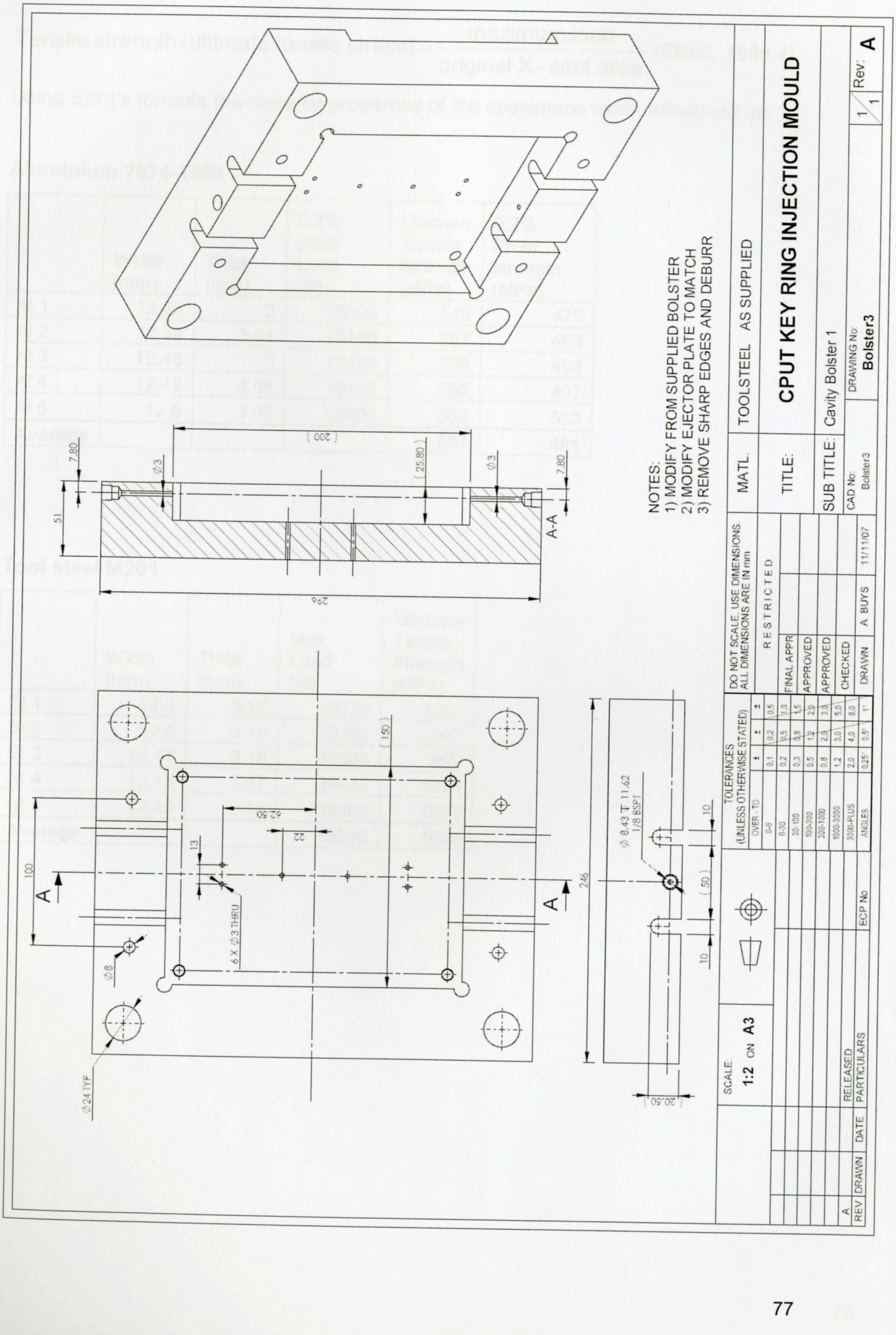
9.8 Appendix H: Ejector Insert drawing



9.9 Appendix I: Injector bolster drawing



9.10 Appendix J: Ejector bolster drawing



9.11 Appendix K: Tensile test data

$$\text{Tensile strength (ultimate tensile stress)} = \frac{\text{maximum load}}{\text{original X - sect area}}$$ (Elliott, 1988:4)

Using Elliot's formula the material properties of the specimens were calculated as:

Aluminium 7075-T651

	Width (mm)	Thick (mm)	0.2% proof Load (N)	Ultimate Tensile Strength (MPa)	0.2% Proof strength (MPa)
Al 1	12.52	3	18000	549	479
Al 2	12.44	3.01	18100	557	483
Al 3	12.45	3	18400	556	493
Al 4	12.48	3.08	19100	562	497
Al 5	12.5	3.02	19000	562	503
Average				**557**	**491**

Tool steel M201

	Width (mm)	Thick (mm)	Max Load (N)	Ultimate Tensile Strength (MPa)
St 1	12.5	3.12	39222	1006
St 2	12.5	3.16	39369	997
St 3	12.47	3.18	39605	999
St 4	12.15	3.17	39423	1024
St 5	12.45	3.14	39362	1007
Average			**39396**	**1006**

9.12 Appendix L: Hardness test data

Hardness results of material samples

Tool Steel M201 Hardness Brale with 150 kg mass **HRC**		**Aluminium 7075 T651** Hardness 1 16" ball with 100 kg mass **HRB**		**Aluminium 7075 T651 hard anodised 70 micron** Hardness 1 16" ball with 100 kg mass **HRB**	
33		92.1		90	
32.9		88.8		92.5	
30.5		91		92	
29		90.5		91.5	
30.1		88		90.5	
32.7		90.2		91.5	
31.5		89		94	
31.8		90.3		94	
31.2		91.6		92	
30.9		94.5		91	
31.8		90.2		91	
31	**Average**	82.9		92	
		90	**Average**	**92**	**Average**

Hardness results after moulding of ejector side inserts.

Aluminium 7075 T651 Hardness 1 16" ball with 100 kg mass **HRB**		**Aluminium 7075 T651 hard anodised 70 micron** Hardness 1 16" ball with 100 kg mass **HRB**	
1A	84	1A	91
2A	89	2A	91.5
3A	91	3A	95.5
4A	90.5	4A	93
Average A	**88.6**	**Average A**	**92.8**
1B	88.2	1B	92.5
2B	86.5	2B	91.8
3B	92	3B	91
4B	92.5	4B	91.5
Average B	**89.8**	**Average B**	**91.7**
Average All	**89.2**	**Average All**	**92.2**

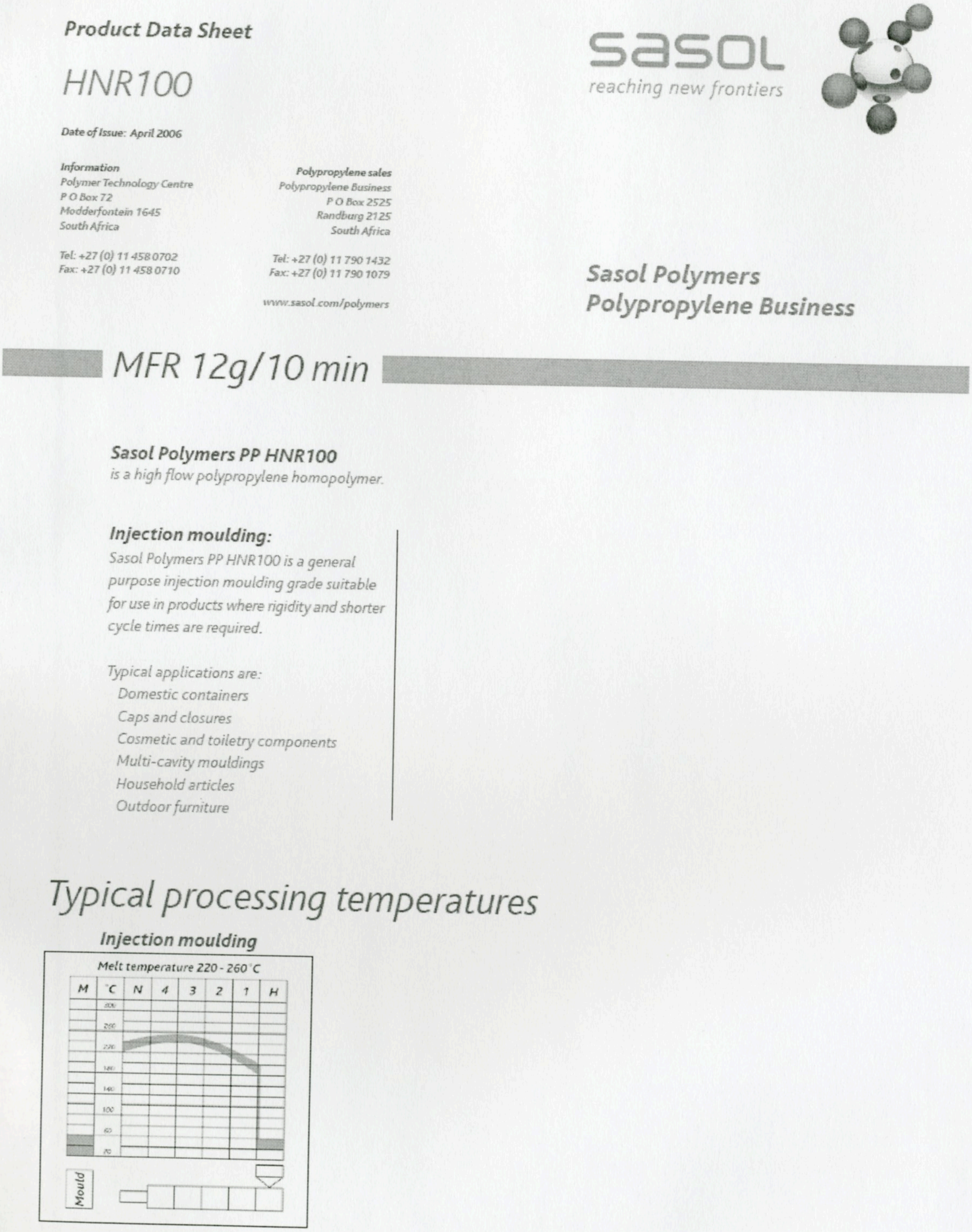
9.13 Appendix M: Micro-hardness data

Micro-hardness test of hard anodised aluminium alloy 7075-T651 specimen.

	Standard test with 704.2 Vickers hardness (HV) test piece 200gram force	**Hard anodised layer Vickers hardness (HV) 100 gram force**	
		Area A (HV)	**Area B (HV)**
1	689.0	371.2	324.6
2	710.3	391.9	335.7
3	701.0	383.1	300.2
4	719.7	390.2	317.9
5	698.0	371.2	352.0
Average	**703.6**	**381.5**	**326.1**
Standard deviation	**10.5**	**10.0**	**19.4**
Rockwell C equivalent	**60HRC**	**39HRC**	**33HRC**

9.14 Appendix N: Polypropylene data sheet

(Sasol polymer, 2006)



Product Data Sheet

HNR100

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Polypropylene Business

MFR 12g/10 min

Sasol Polymers PP HNR100
is a high flow polypropylene homopolymer.

Injection moulding:

Sasol Polymers PP HNR100 is a general purpose injection moulding grade suitable for use in products where rigidity and shorter cycle times are required.

Typical applications are:
- Domestic containers
- Caps and closures
- Cosmetic and toiletry components
- Multi-cavity mouldings
- Household articles
- Outdoor furniture

Typical processing temperatures

Injection moulding

Melt temperature 220 - 260°C