DEVELOPMENT OF AN EXPERIMENTAL DIAPHRAGM VALVE USED FOR VELOCITY PROFILING OF SUCH DEVICES

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ABSTRACT

The design, manufacture and use of diaphragm valves in the minerals industry is becoming increasingly important since this sector is restricted from using excessive amounts of water for their operations. This forces a change in the flow properties of these devices from turbulent to laminar in nature and thus necessitates the characterization of these flows for future designs. Furthermore, diaphragm valves have a short service life due to a variety of reasons that includes the abrasive nature of the flow environment.

This paper describes the activities of the Adaptronics Advanced Manufacturing Technology Laboratory (AMTL) at the Cape Peninsula University of Technology in the research and development of diaphragm valves using rapid prototyping technologies. As a first step, an experimental diaphragm valve was reverse engineered and retrofitted with ultrasonic transducers used in Ultrasonic Velocity Profiling (UVP) measurements. The use of this device enables measurements of velocity profiles to gain insight into the flow structure within the valve and the increased pressure losses generated within the valve. It also showed that components fabricated using the Z-Corporation machine could withstand the working environment of diaphragm valves. Research is now conducted on ultrasonic transducer placement in the device to further enhance the velocity profiling through the device.

As a second step we produced a thin-walled stainless steel diaphragm valve using rapid prototyping technology and investment casting processes. A study of the durability of this device will be conducted and certain geometric and manufacturing aspects of this valve will be discussed.

Keywords: reverse engineering, rapid prototyping, ultrasonic velocity profiling, flow characterization, investment casting, diaphragm valve

1. INTRODUCTION

Flow patterns, also known as velocity profiles, are well documented for straight pipes displaying laminar, transitional and turbulent regimes. However, velocity profiles within diaphragm valves are absent in literature and as a result, experimental analysis is required to measure flow development in this particular valve.

Over the past three decades advances has been made in measuring detailed flow behaviour using techniques such as Magnetic Resonance Imaging (MRI), Laser Doppler Anometry (LDA) and Ultrasonic Velocity Profiling (UVP). Laser Doppler Anometry is a very accurate method and offers high time and spatial resolution, but cannot be used in opaque fluid systems, as it based on visible light techniques. Magnetic Resonance Imaging is another technique which is highly accurate and versatile, but the apparatus is too expensive and difficult to implement (Powel, 2008). UVP is inexpensive, portable, works with opaque systems and easy to implement relative to other available techniques and thus this method is ideal for studying non-Newtonian flow of opaque and highly concentrated fluids (Takeda, 1986; 1999).

A thorough literature search revealed that UVP measurements with respect to diaphragm valves are absent for Newtonian and non-Newtonian fluids.

In 2007, Material Science and Technology (MST), CPUT, commissioned the Adaptronics AMTL to develop an experimental tool using UVP to determine flow patterns in a diaphragm valve. Initial objectives for this research project included:

- the determination of whether a Z-Corp printed part could withstand the working environment of a typical diaphragm valve;
- the retrofitting of the Z-Corp printed with UVP transducer ports; and
- the use of UVP to measure flow patterns in the valve.The above mentioned objectives were achieved in that a 50mm NB commercial diaphragm valve was reverse engineered and retrofitted with UVP transducer ports for velocity profiling. The original valve body (see Fig.1, LH), was cut in half longitudinally (see Fig.2), to expose the inside form which needed to be reversed engineered.

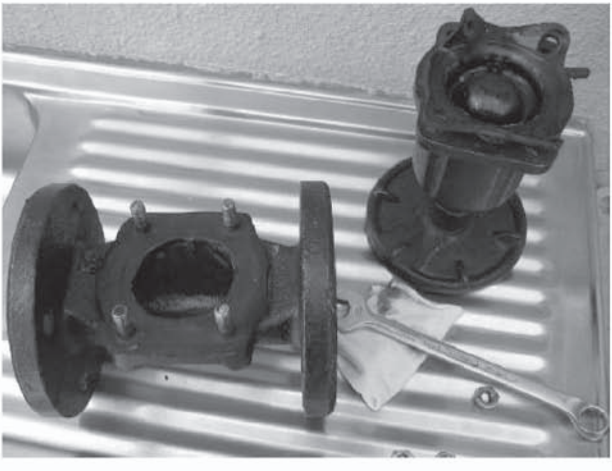

Figure 1: Original Diaphragm Valve

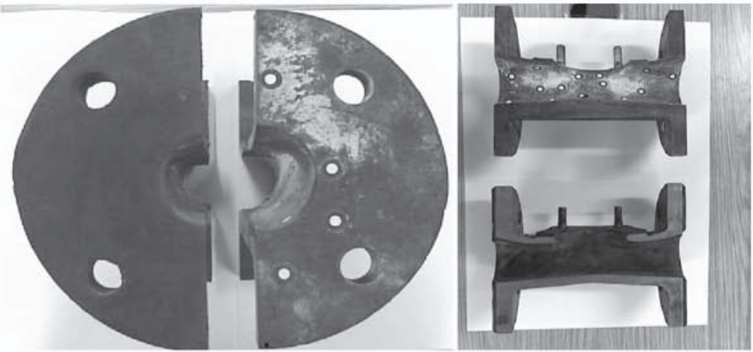

Figure 2: Sectioned Diaphragm Valve

From the sectioned valve body (see Fig.2), the half with the dots has the rubber lining removed so that we obtained the casting size as opposed to the rubber-lined size. These two halves were reverse engineered, and the form of the inside captured of both conditions in order that a comparison in the flow analysis of the two conditions could be observed. A CAD model was developed only from the unlined condition (see Figs.3a and b). The second comparison of the rubber lined part still has to be carried out.

Figure 3 a & b: CAD model of the reverse engineered diaphragm valve

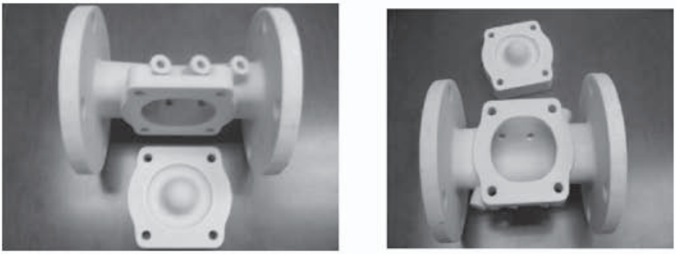

Figure 4: Micro-stone Z-Corp printed part

Figure 4 shows the micro-stone printed Z-Corp parts as captured from data generated by the reverse engineered process. The assembled valve with predetermined and printed gate mechanism was then positioned in the test rig, as depicted in Figure 5. The transducers were then fitted and connected to the flow analysis monitoring where UVP technology combined with pressure difference (PD) technology was applied in both straight pipe and diaphragm valve sections. The valve with transducer ports produced favourable readings whilst 3.3 million litres of kaolin slurry passed through it before structural collapse occurred.

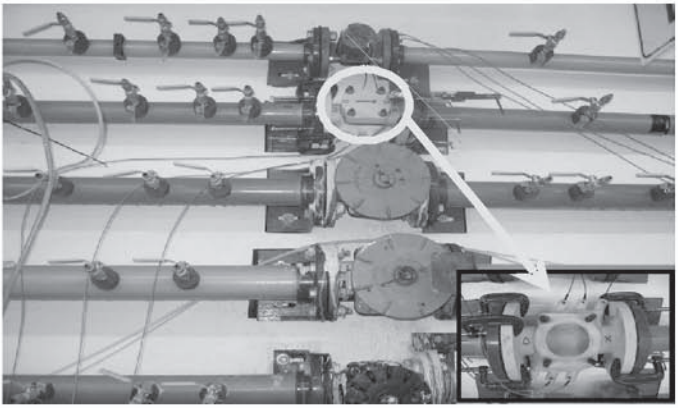

Figure 5: Z-Corp infiltrated diaphragm valve fitted and positioned in the test rig at MST

On investigation, the following collage of pictures (see Figs.6 and 7) show the defects which occurred. The conclusion of the investigation was that thick sections as copied from the original valve were problematic due to sponginess in these areas. Over-tightening of the valve when being placed in the test rig by the technician is also seen as a reason for cracking of the shell. This led to the flow medium entering the heavier sections and washing away the less infiltrated softer areas.

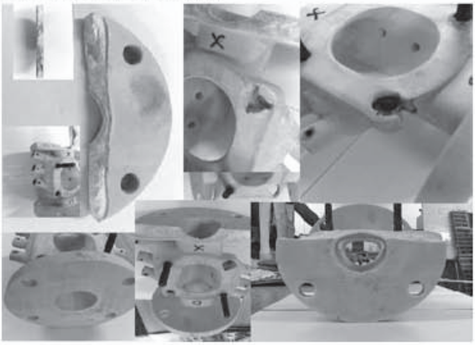

Figure 6: Collage of pictures showing the damaged Z-Corp infiltrated diaphragm valve

A case is also made here for person's using Z-Corp printed parts to understand the nature of the beast. This is to say that handling at fitment, and any subsequent handling, must be done with the utmost care by treating the part as if it were a newborn child (which in fact it is, figuratively speaking). If correct handling is carried out, then greater longevity can be expected from the Z-Corp printed part.

2. CURRENT OBJECTIVES

On observing the results and seeing the defects of the Z-Corp printed part (Valve 1), a re-design of the original valve was seen to be necessary, to obtain a more durable and longer lasting Z-Corp printed valve. This was done by reducing all wall thicknesses to a nominal 3mm section while maintaining the scanned data of the inside profile.

The original Z-Corp infiltrated part had a thicker section and therefore only the outermost regions of the shells were infiltrated. This resulted in a shell-like structure that encapsulated the inner softer core. Cracks forming in the shell-like areas caused the softer inner core to be washed away and thus weakened the entire structure, resulting in complete collapse of the device. One of the current objectives would thus be to produce a Z-Corp experimental diaphragm valve with an overall nominal wall thickness of 3mm. This would eliminate the softer inner core from the experimental diaphragm valve.

Furthermore, it was decided to develop a thin-walled stainless steel valve using the same thin-walled CAD design,and manufacturing via the investment casting process. Here the primary objectives were to reduce the amount of metal required for the casting process, thereby reducing the amount of energy required for the entire process. The benefit of this would be passed on further by a reduction of the carbon footprint, (CFP) at the casting phase. It is further envisaged that an energy saving will be achieved by improving the flow rate for optimization of energy

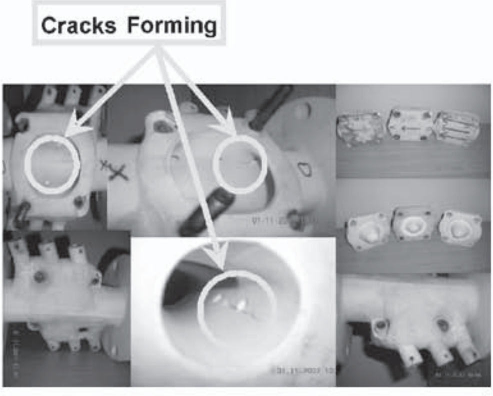

Figure 7: Pictures showing cracks on the inner valve wall leading to inner core washout

3. DESIGN AND MODELLING OF A THIN-WALLED VALVE BODY WITH MODIFIED TRANSDUCER PORTS

A second valve was CAD modelled using the same data for the internal face and then adding a 3mm conformal wall thickness. The three flanges were then added to the valve body. These flanges were also 3mm thick. The transducer ports were then added. However it was found that they had to be made longer than Valve 1, as we were informed the transducer positions needed to be further from the valve centre than previously thought (see Fig. 8, schematic section of transducer positioning).

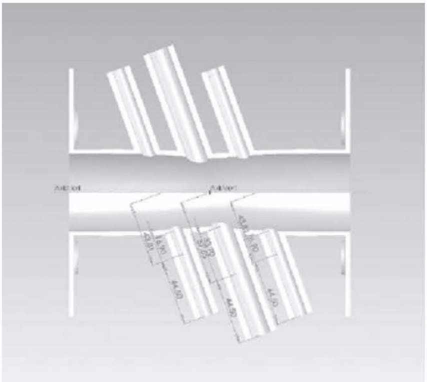

Figure 8: CAD model showing transducer positions on Valve 2

Valve 2 was successfully grown and on inspection appeared suitable for the application as perceived. This Z-Corp diaphragm valve was then infiltrated (see Fig. 9). After curing the valve was sent to the IMST for its testing protocol.

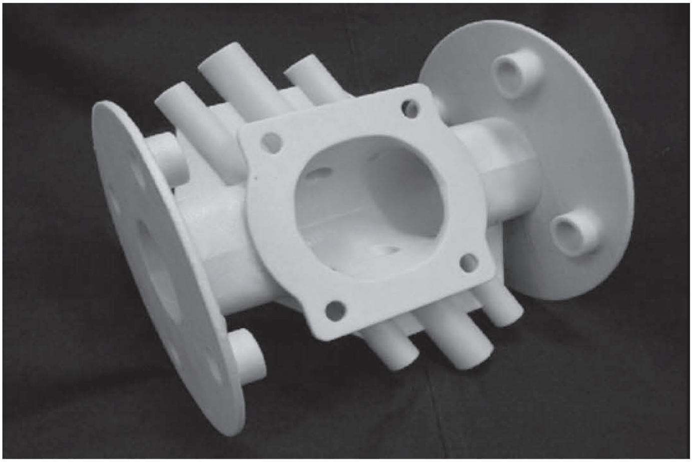

Figure 9: Thin walled infiltrated Z-Corp printed diaphragm valve (Valve 2)

4. RESULTS

The thin-walled infiltrated Z-Corp diaphragm valve was fitted and assembled in the MST test rig (see Fig. 10). The UVP sensors were then fitted and testing commenced. The mechanical properties of the redesigned 3mm conformal wall valve were vastly improved. Readings and performance of this valve proved that thin-walled Z-Corp printed parts are quite in order for such research.

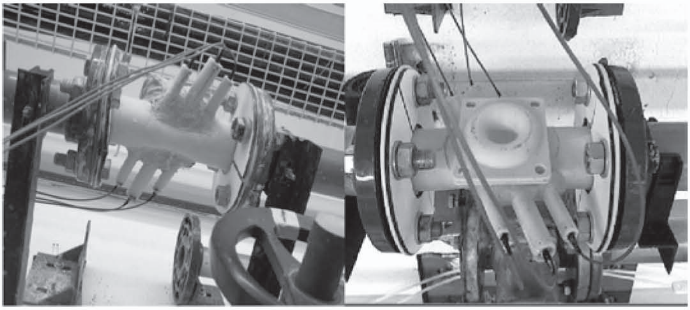

Figure 10: Valve 2 (3mm nominal wall thickness), fitted "in situ" with extended transducer ports on test-rig

The loss coefficient is defined as the non-dimensionalised difference in the overall pressure between the ends of two long straight pipes when there is a valve installed, and when there is no valve (Miller, 1990).

The head loss in a valve can be determined using the Bernoulli equation and can be expressed in terms of the velocity energy head as (Edwards *et al.*, 1985):

$$H_v = k_v \frac{V^2}{2g} \tag{1}$$

The loss coefficient of the valve k_v is given by:

$$k_v = \frac{\Delta p_v}{\frac{1}{2}\rho V^2} \tag{2}$$

In turbulent flow the loss coefficient is independent of the Reynolds number. In laminar flow however, a hyperbolic relationship exists between the loss coefficient and the Reynolds number (Edwards *et al.*, 1985) and is given by:

$$C_v = k_v \mathrm{Re} \tag{3}$$

where C_v is a characteristic of a specific valve including its dimensions (Edwards *et al.*, 1985). An initial experimental investigation was conducted comparing a commercially available diaphragm valve with the thin-walled infiltrated Z-Corp diaphragm valve. The loss coefficients for these two valves were determined using the hydraulic grade-line approach (Fester *et al.*, 2007). For these tests, the maximum static pressure in the pipe was 53 kPa, the maximum pressure drop across the valve was 1.5 kPa and a maximum velocity of 1.9 m/s (4.2 l/s) was measured. There was agreement between the loss coefficient data for the two valves (see Fig. 12), a good indication that geometric, kinematic and dynamic similarity was achieved (Slatter & Pienaar, 1999).

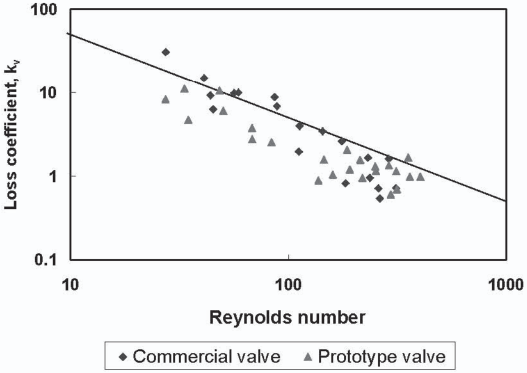

Figure 11: Loss coefficient data for the Commercial and Infiltrated Z-Corp printed diaphragm valves

A second experiment was now conducted utilizing the UVP system. Velocity profiles measured in the straight pipe were integrated and the resulting flow rate was compared to the flow rate measured by the in-line flow meter. Differences of the order of 9-10% were obtained and considered acceptable, validating both the procedure and the profiles. A comparison of the theoretical velocity profile and the measured one is shown in Fig. 12. Agreement within less than 10% was obtained which is a very good indication that the UVP measurements were credible. The velocity profile in the valve was thus measured.

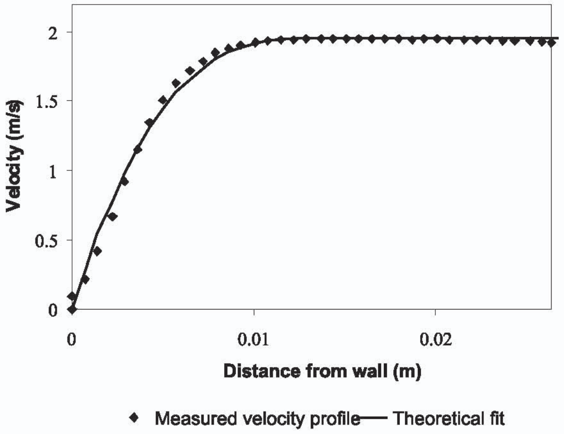

Figure 12: Velocity profile in a pipe as obtained with the UVP system and compared to a theoretical fit

Figure 13 shows a comparison of the velocity profiles obtained in the straight pipe and the centreline of the thin-walled infiltrated Z-Corp printed diaphragm valve. It is expected that the velocity will be higher in the valve, and this is demonstrated by the results obtained. The first measurements of velocity profiles in the valve are encouraging. Further work needs to be done on measurements in different planes through the valve, since the flow in the valve is three-dimensional.

Twelve (12) million litres of slurry passed through this valve, although repairs had to be made due to the mishandling.

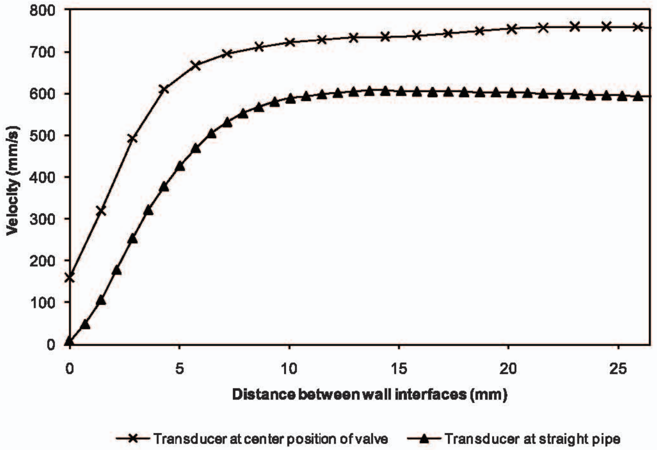

Figure 13: Velocity profiles along the centreline of the thin-walled infiltrated Z-Corp diaphragm valve (x's) and a straight pipe

5. DEVELOPMENT OF A THIN-WALLED STAINLESS STEEL DIAPHRAGM VALVE BODY

As discussed previously, it was also decided to produce a thin-walled stainless steel prototype valve (Valve 3). The CAD data of the thin-walled Z-Corp diaphragm valve was used for this procedure minus the UVP transducer ports. The actual stainless steel components were manufactured using the lost wax process, also known as the precision investment casting process.

The production process (see Fig. 14) involves making a disposable wax pattern by injecting wax into a metal die. The resulting wax patterns are then assembled onto a runner system to form a cluster (assembly). A ceramic shell is built around the wax patterns by application of a series of ceramic coatings. The ceramic shell is de-waxed and fired at a high temperature to sinter. Casting then takes place by filling the ceramic shell with molten metal. The metal solidifies in the shape of the original wax pattern(s). After the casting has cooled, the shell is broken away and the casting exposed. It is then sent to the finishing area, where the gates, rises, flashing and any left over runner or vent sections are removed through grinding and the product is then finished. The resulting castings have very fine surface finishes and accurate dimensions.

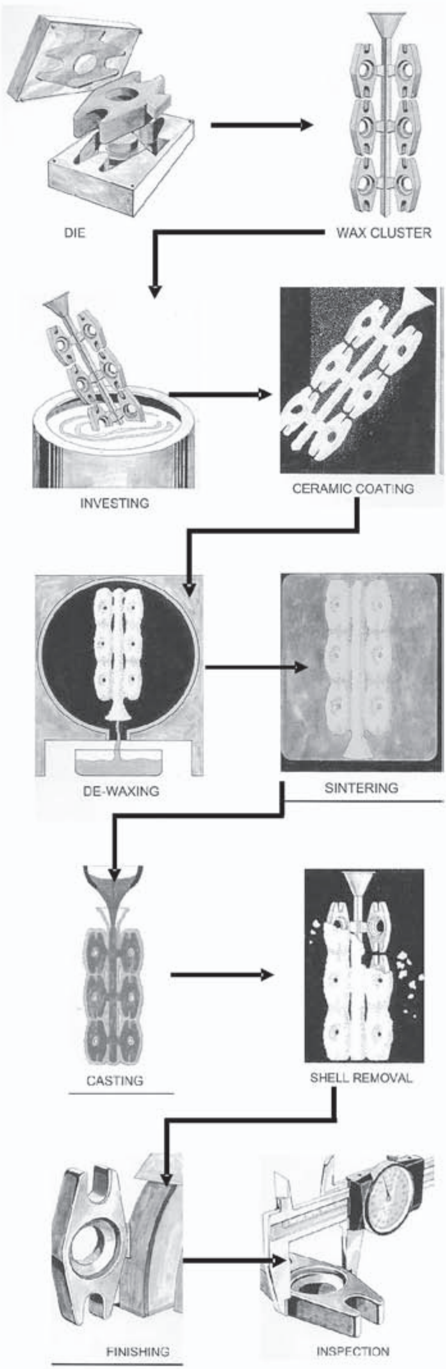

Figure 14: Process chain for the precision investment casting process

6. CASTING PROCESS FOLLOWED IN PRODUCING THE STAINLESS STEEL PROTOYPE

The CAD model of the thin-walled Z-Corp diaphragm valve was used with the original scan data of the inner valve surface (see Fig. 15a). In this model however, the transducer ports were omitted since the resulting product will be tested in the field to study the wear properties of stainless steel castings for this particular working environment. A contraction allowance was included to compensate for the behaviour of stainless steel during cooling. Furthermore, a machining allowance was included on the three flange surfaces (see Figs. 15 b & c). The part was printed in starch powder using the Z-Corp machine. The resulting component/pattern (Valve 3) was then infiltrated with wax to produce a starch/wax pattern (see Fig. 16). The precision investment casting process as described above was then followed until the final stainless steel castings were produced (see Fig. 17).

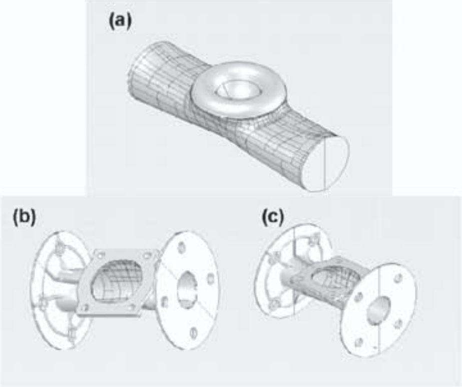

Figure 15: (a) Scan data of the inner surface of the original diaphragm valve. (b) & (c) Different views of the CAD Model produced

Figure 16: A collage of pictures showing the wax infiltrated Z-Corp starch printed patterns

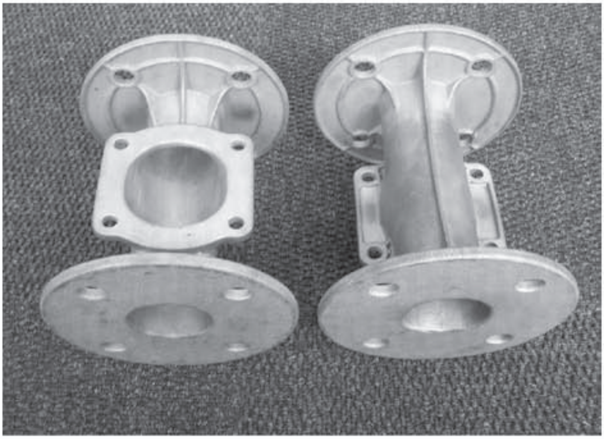

Figure 17: Thin-walled stainless steel casting as produced from the wax infiltrated Z-Corp starch printed pattern

CASTINGS BY CASTCO PRECISION CASTINGS (PTY) LTD

7. CONCLUSIONS

This paper described the activities of the Adaptronics Advanced Manufacturing Technology Laboratory (AMTL) at the Cape Peninsula University of Technology in the research and development of diaphragm valves using rapid prototyping technologies. An experimental diaphragm valve was reverse engineered and retrofitted with ultrasonic transducer ports used in Ultrasonic Velocity Profiling (UVP) measurements. The use of this device enabled more realistic measurements of friction losses through such devices and enhanced the process of flow characterization. It also showed that components fabricated using the Z-Corporation machine could withstand the working environment of diaphragm valves.

Continued experiments with this device will be conducted to describe flow patterns inside a straight pipe and diaphragm valve so that the flow behaviour responsible for the energy loss can be made available for practical re-design purposes. Additional research and development will be carried out, with further Z-Corp printed valve bodies being manufactured. These future valve bodies will have transducer ports added at varying angles, offset positions and internal forms, to assess which forms will result in a more efficient valve body. These variations will be scientifically assessed with UVP technology to achieve an energy saving by improving the flow rate for optimization of energy.

A thin-walled stainless steel diaphragm valve was also produced successfully using rapid prototyping technology and the precision investment casting process. The combination of scientific research conducted at the Adaptronics AMTL & MST and the process chain development of thin-walled stainless steel valves at CASTCO PRECISION CASTINGS (PTY) LTD will ultimately lead to a considerable energy saving in both the operation and the manufacturing of these valves. The long term benefit of these processes will ultimately be the reduction of their carbon footprint.

9. ACKNOWLEDGEMENT

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