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Executive Summary - The Development of Thermal Spray Tooling

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Abstract

Thermal spray tooling is one of a number of technologies which have been developed to satisfy the need for low cost tooling, which is used when prototype components are required in the correct engineering material. In its current state, the technology has a number of fundamental shortcomings. The aim of this portfolio was to address these shortcomings, via a combination of experimental work and technology demonstrators - these are summarised as follows:

- An experimental programme aimed to quantify many of the problems associated with thermal spray tooling. A wide variety of tests on thermal spray surfaces was carried out, in order to compare their performance with other 'low cost' tooling techniques. For the first time, tooling shells were produced using the High Velocity Oxy-Fuel (HVOF) technique. This system is capable of producing extremely high quality tool shells, and the technique developed involves the novel use of castable ceramic patterns - the first time a releasable pattern has been developed for this spray system. In addition, it was established that 'hybrid' tooling shells could be produced - these were formed using a combination of arc spray and HVOF layers. The work proved that these hybrid shells could provide substantial performance benefits in terms of wear performance and vacuum integrity, when compared to conventional arc sprayed shells - this benefit was also achieved without significant cost penalty. The programme also investigated the effect of thermal cycling on thermal spray samples - it was shown that repeated cycling at high temperature had an adverse effect on both arc sprayed and HVOF samples - the extent of this effect was very much dependent on the material.
- The portfolio includes a technology demonstrator programme, which was carried out for Rover Group to show the potential of thermal spray tooling. The programme entailed the manufacture of a suite of 5 tools for compression moulding of Glass Mat Thermoplastic(GMT). The actual route used for the production of the tooling suite involved many unique features, which had not previously been utilised for thermal spray tooling production. One of the tools is the largest ever produced for compression moulding using thermal spraying, being approximately $4m^2$, and weighing in excess of 3 tonnes. Due to the compressive stresses involved in the moulding process, conventional resin backing systems were unsuitable for this tooling. It was therefore necessary to use a Chemically Bonded Ceramic (CBC) material, with an exceptionally high compressive strength. However, this material does not adhere to thermal spray surfaces, and it was therefore important to develop a novel fixing method at the interface of the materials. Further to this, in certain cases the use of thermal spraying was precluded by the component geometry - in these cases it was necessary to use the CBC material as the direct tool face. This was the first time that CBC tooling had been used for compression moulding GMT, and it was therefore necessary to develop new post-treatments for this inherently porous material. The moulding operation then entailed the development of specific techniques and conditions for this prototype tooling, which would not generally be used in production - normal moulding conditions for 'production' tooling were therefore inappropriate.

Further work will entail materials development, the introduction of automation and development of design rules, specifically aimed at the production of large tooling for the aerospace and automotive sectors - this will be carried out via a successful project submission under the Innovative Manufacturing Initiative (IMI).

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1.0 Introduction

The aim of this document is to summarise a portfolio of research undertaken in the field of low cost tooling. There are now many technologies available for the production of low cost tooling. These technologies are becoming increasingly important, with manufacturers under ever-increasing pressure to reduce product development costs and lead times.

One technology which is finding increasing use for the production of low cost tooling is that of thermal spraying (see Figure 1). Although thermal sprayed tooling has been in use for over 30 years [1], its use has been restricted due to lack of knowledge, and limitations in systems and materials. Increasingly, however, the technology is gradually being accepted for use in moulding applications such as blow moulding, rotational moulding, injection moulding and Resin Transfer Moulding (RTM).

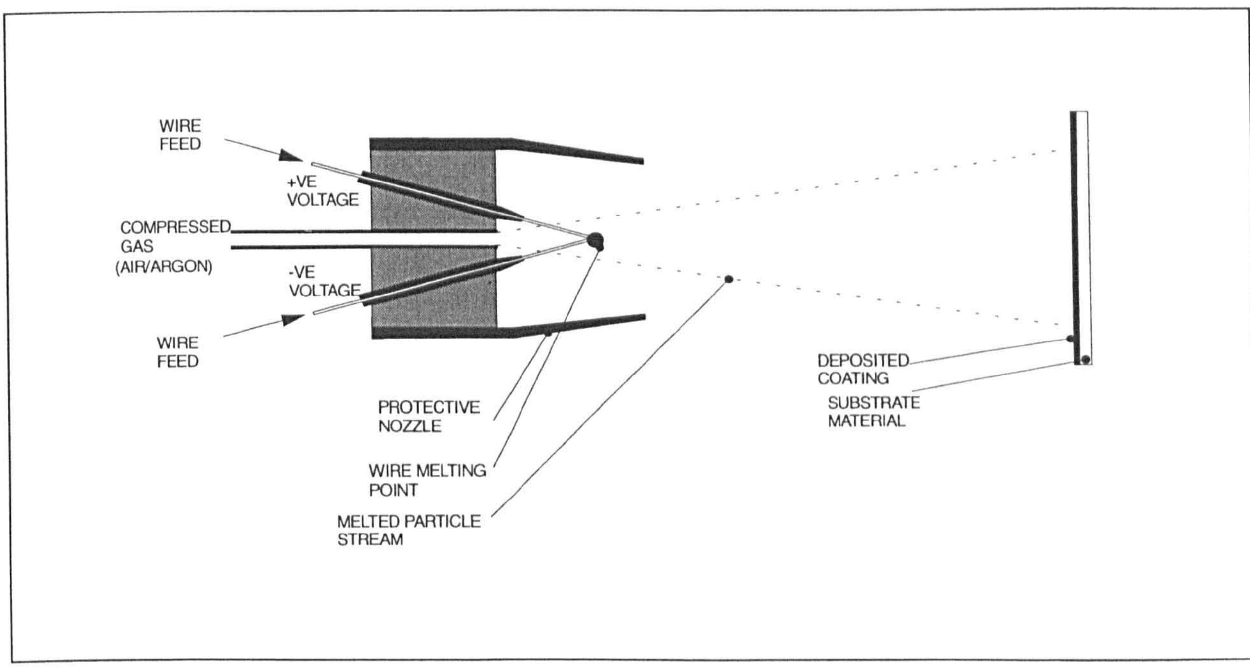

Figure 1: Electric Arc Spray System

The use of thermal spraying is still restricted, however, due to fundamental problems with the use of sprayed surfaces for tooling. These are due to the physical properties of thermal sprayed surfaces, the properties of the moulded material, the tooling geometry and many other factors. This means that generally speaking, thermal spray tooling is only viable for low pressure moulding processes, with limited component volumes and material types. The overall aim of the research portfolio is to improve the overall performance of thermal spray tooling, in order that it may be used for a broader range of applications.

The portfolio is presented as a number of discrete documents, each fulfilling a specific function. This report will summarise the contents of these documents, with particular emphasis on the innovative content of each document - the innovative contribution will be summarised in each individual project summary. Broadly speaking, the overall aims of the portfolio may be defined as follows:

- To improve the physical performance of thermal spray tooling, allowing tooling to be used in more challenging moulding environments, producing higher component volumes. This will be achieved through an experimental programme, using improved thermal spray methods and post-treatments to achieve improved tooling surfaces.
- To demonstrate the potential of thermal spray tooling as a medium for rapid component production. This will be achieved through the manufacture of tooling for a particular application, with demonstrable cost and lead time benefits.
- To define a package of work which will enable the automated production of thermal spray tools, particularly aimed at the production of large tooling for composite moulding.

2.0 Thermal Spraying Review

The intention of this section is to provide a critical review of the current state of development of thermal spraying as a group of technologies. The review will concentrate on some of the problems associated with thermal spraying, and how process improvements have alleviated these problems. Next, a section will analyse mould tool manufacture using thermal spray technologies, including current and future developments in this field, where novel methods are being used to manufacture both mould tools and metallic components using thermal spraying. Finally, a section will provide a comparison of cost between thermal spray tooling manufacture, and other tooling routes, including production tooling.

2.1 Thermal Spraying - Process Restrictions and Improvements

2.1.1 Background

Thermal spraying is a method for applying metallic and ceramic coatings to substrate materials. The use of thermal spraying as a method for the production of mould tooling has been documented for at least 35 years [1], and thermal spraying has been used for coating applications for much longer. Thermal spraying is a term which covers a wide range of technologies; these are well documented within the literature [2], and are also described elsewhere within the portfolio (see 'A Review of Rapid Tooling Technologies').

The earliest uses of thermal spraying as a tooling manufacturing route relied on electric arc or flame spraying of low melting point materials such as zinc or tin zinc. Although these materials provide a simple method of tooling production, they are relatively soft, and subject to wear and mechanical failure - their use is therefore limited to prototype tooling and low pressure moulding applications [3]. Indeed, all thermal spray surfaces generally have lower mechanical strength than their equivalent wrought material. This is mainly due to stresses which build up in the material as a result of thermal effects during the spray process [4], and increased levels of porosity and oxidation. In order to produce improved thermal spray coatings in any material, it is necessary to quantify these physical effects, and where possible modify the process to produce coatings which have improved mechanical properties, and thus improved tool life. The next sections will describe work carried out to analyse the physical properties of thermal sprayed materials, and associated process improvements.

2.1.2 Internal Stresses

It is well documented within the literature that coatings produced during thermal spraying will be subject to thermal stresses. The nature of these stresses will determine the overall mechanical performance of the sprayed material. One of the principal causes of stress within a sprayed layer is caused by what is termed 'quenching stress' [5]. Quenching stress is caused by the interaction of the sprayed particle with the substrate material. The impact of a molten spray particle onto a substrate is termed a 'splat'. As the particle impacts on the substrate, it will flatten and cool. The thermal contraction of the splat is constrained by the underlying solid; initially, this will be the substrate itself - subsequently, previous layers of the sprayed coating. As a result of this constraint, in-plane stresses develop within each splat. As the thickness of the coating increases, the stresses within the sprayed coating will increase, ultimately resulting in distortion and separation from the substrate.

The literature shows a number of studies which aimed to quantify the stresses within sprayed coatings, and to explain the causes. Harris et al [6] describe a programme to determine the heat transfer processes which take place during the arc spraying of steel coatings. Three stages of heat transfer are described; during the formation of metal particles within the arc, from the particle to the environment during flight, and from the particle to the substrate. This work concluded that the heat transfer from particle to environment is relatively small. Major changes within the structure could be affected via the use of temperature cycling of the substrate material. Previous work by Harris et al [7] demonstrated that both compressive and tensile stresses could be found in 2mm thick steel coatings, depending on the type of material sprayed. The work showed that the tensile stress caused by the interaction between coating and substrate could be counteracted by modifying the spray conditions, to induce a phase change from austenite to martensite within the material. The phase change would cause an expansion of approximately 4%, negating the contraction caused by cooling. However, this was restricted to high carbon low alloy steels; steels which did not undergo low temperature phase transformations would exhibit solely tensile stress. The use of the phase change allows shells of considerable thickness to be sprayed, without the usual problems of shell distortion caused by quench stresses.

Further work has attempted to quantify the stresses within sprayed coatings, and attempted to separate stress within the coating, and the effects of external factors, such as the stress within the substrate [8]. Gill & Clyne used an in-situ monitoring technique to determine curvature measurements of plasma sprayed coatings onto stainless steel substrates. In this case, 1mm thick samples of stainless steel were sprayed with various coatings. A video imaging technique allowed measurement of the variation of sample curvature with coating thickness. The rate of change of curvature was used to estimate the quenching stress of the coating. The programme concluded that the major cause of curvature was the quench stress, rather than residual stresses within the substrate. The programme also showed that even for thin samples, the momentum transferred to the substrate by the gas stream had little effect on the measurements, allowing the conclusion that the quench stress was the sole cause of curvature in the sample - the technique therefore allows for relatively accurate measurement of quench stresses which will be present in any given sprayed material.

2.1.3 Porosity

Further work to determine the effects of spray parameters on coating quality have been carried out by Fussell et al [9]. Rather than measuring quench stresses, this programme aimed to define the effects of changing spray parameters on the microstructure of arc sprayed shells, in materials such as type 420 stainless steel and Invar. Although quench stresses are a major cause of weakness within sprayed coatings, the coating integrity is also affected to a large degree by the spray angle, porosity and oxide content. Fussell et al state that 'orientation angles of greater than 30^0 lead to unacceptable porosity'. This is attributed to 'shadowing', which leads to entrapped porosity within the coating, although there are no experimental results to show the relationship between porosity and spray angle. Shadowing is explained as follows - "Deposited particles will act as obstructions to incoming particles; worse, the hole formed in the shadow of a previously deposited particle is large and clustered with other such holes"

Porosity will always be present in sprayed coatings to a certain degree; the very nature of spraying discrete particles dictates this. Fussell et al showed that the level of porosity within arc sprayed coatings is directly related to the kinetic energy of the particles - the higher the gas pressure and input voltage, the lower the porosity level. The standoff distance will also influence the porosity - this is reinforced by the work carried out by Harris et al [6], where it was shown that smaller standoff distances produced larger particles. Smaller standoff distances prevent a significant number of particles from adhering, giving a lower deposited mass per pass of the gun. This work determined that smaller particles produced a more dense coating, a parameter determined by standoff distance.

2.1.4 Oxidation

Another significant factor in producing good quality arc sprayed coatings is oxidation. This causes coatings to be brittle, and prone to cracking. Fussell et al attribute the level of oxidation to the large surface/volume ratio within spray particles. This supposes that the majority of oxidation takes place in the particle's flight - minimisation of the presence of oxygen within and around the spray jet should therefore significantly reduce oxidation. Fussell et al used several experimental set-ups, determining the effect of different atomising gases (air, nitrogen and argon), combined with the use of a protective shroud flushed with inert gas. These experiments showed that by using air as the atomising gas, oxide levels of around 30% (as a percentage of area, by field of view) were typical, whereas using nitrogen reduced the oxide levels to around 15%. Using argon as the atomising gas, in combination with a flushed protective shroud, reduced the level of oxidation to around 8%. Fussell et al also stated that when the experiment was repeated in a vacuum chamber back-filled with argon oxide levels of less than 2% were encountered. However, this method proved prohibitively expensive in practical terms, although the system is used in limited applications where coating quality is critical [10]. Another study showed a more cost effective method of oxidation control using nitrogen as the atomising gas for arc spraying of steels [11]. This work showed that nitrogen could be used to improve the level of retained carbon within the steel coating, whilst reducing the density of oxides present. Zurecki et al also showed that the coatings demonstrated improved wear resistance and hardness, when compared to similar materials sprayed with air as the atomising gas.

It is important to determine how the physical properties discussed will actually affect the physical performance of thermal spray materials. Many thermal spray coatings are used for improving the wear resistance of components. One of the most common methods for determining performance is therefore measuring the wear of coatings under experimental conditions. Hartfield-Wunsch et al [12] describe a programme of work to determine the wear levels within coatings sprayed by HVOF (High Velocity Oxy-Fuel), in order to assess the effectiveness of surface coatings on engine cylinders. HVOF is a spray system developed originally for producing high-quality thermal barrier coatings on aerospace components. The density of such coatings is very high, with only 1-5% porosity, compared to typical porosity values of 10-15% for arc sprayed coatings. The system can spray a number of materials, including a variety of steels, nickel-based alloys and even ceramic materials. The wear on such coatings is attributed to thin layers of oxide between splats - this oxidation will occur naturally as a result of the particles impacting at high temperature, but can be reduced by spraying in an inert atmosphere. Cracking can occur along such layers, which causes the splats to become detached and thus easily removed. The work showed that the majority of cracking initiated at the coating surface, although it was assumed that cracking would occur throughout the coating. It was suggested that the weak oxide boundaries had a cohesive strength of only 10-20% of that of the bulk material. The work also demonstrated the effect of oxidation on wear resistance. Although it had been anticipated that the harder oxide particles would stand proud of the surface, the results showed that oxides tended to crack and fall out more easily. However, the work concluded that the oxides were making some positive contribution to wear resistance, which could not be quantified using optical methods. The additional effects of porosity have a detrimental effect on coating performance; the presence of sub-surface porosity means that localised areas may collapse and become detached - this also means that cracks do not have to propagate as far in order to remove material. The key to improving coating performance appears to be increasing the tortuosity of the crack path, although the work does not suggest a method for facilitating this.

2.1.5 Summary

All of the work described above emphasises the importance of spray parameters and conditions on the performance of a given sprayed coating, whatever the spraying system used.

Various methods can be used to improve the quality of coatings, but the inherent problems of quench stresses, porosity and oxidation will mean that sprayed coatings will have poor mechanical properties in comparison to the equivalent wrought material. In terms of using thermal spray materials as tooling surfaces, this translates to poorer wear resistance, a tendency towards surface cracking, and thus limited useful life when compared to 'conventional' tooling. However, the use of thermal spraying as a tooling manufacturing route can have significant cost and lead time benefits. The next section will describe some of the important developments within thermal spray tooling, and state of the art applications.

2.2 Mould Tooling using Thermal Spray Techniques

The basic principle of thermal spray tooling is well known, and has been used for many years as a means for producing tooling for prototype and limited production applications. The most common system used for tooling production is arc spraying of low melting point alloys such as zinc and kirksite to produce a tooling shell, which is then backed with a castable reinforcement. This system is simple to use, and can produce very cost effective mould tools. However, these sprayed materials are relatively soft, and when combined with the limitations discussed in previous sections, have high wear and poor mechanical properties, limiting the lifespan of tooling. This is particularly the case when moulding more aggressive compounds such as glass-filled nylon. The aim of this section is to provide a summary of developments within thermal spray tooling, which aim to eliminate these problems, by the use of harder materials such as steel and Invar.

The use of steel as a shell material for tooling has its own problems associated. The use of pattern materials is more restrictive, as the high temperature of the particles tends to degrade softer pattern materials. Weiss et al [13] describe a method which partly eliminates the problem of pattern degradation. The method uses a sacrificial master, which is cast or sprayformed onto a pattern. The master is made from a low melting point alloy, typically tin-bismuth, which can be sprayed onto virtually any master model, including rapid prototype (RP) models. This master is then used as the pattern for arc spraying stainless steel. The master does not require a release agent, as the stainless steel particles tend to impact and adhere well to the softer tin-bismuth. A sprayed shell is then built up in the normal way. On completion of spraying, the stainless steel shell is backed up with a cast reinforcement material. The tin-bismuth backing material is then melted out, to leave a completed tool with a stainless steel face. A similar method is described by Dooley et al [14]. In this case, however, the shell is sprayed using HVOF (High Velocity Oxy-Fuel), a spraying system capable of producing dense, high quality coatings in a variety of materials. Both of these methods allow the production of steel-faced tooling. However, the use of an intermediate stage to produce the master adds complexity and time to the process. In addition, the act of melting out the master may cause dimensional distortion within the tool, due to thermal stresses. The surface finish will also reflect the impact of hard steel particles onto the softer tin-bismuth. This may tend to produce a 'pitted' finish, which would require extensive polishing to achieve an acceptable finish.

An alternative approach is taken by Gross et al [15]. In this case, a steel master pattern is used for plasma spraying of nickel-based alloys. The master models were machined and polished to a surface finish of 0.05μm, and then chrome plated (10μm thickness). The master was then heated to a temperature of 300^0C, and a plasma sprayed layer of the nickel-based alloy applied. Using this method, it is possible to produce extremely thick plasma sprayed layers in short periods of time (up to 20mm in 40 minutes). Although this technique is obviously capable of producing high quality tool shells in appropriate tooling materials, it seems to offer little commercial benefit. The use of a steel master requires that the master must be machined. In this case, the time and cost to machine the master could just as easily be used to machine a tool cavity in steel, giving a production tool in a similar timescale. This being said, there are some specialist applications where the use of a high quality machined master may be appropriate.

The aerospace industry has a requirement for low thermal mass tooling for the processing of carbon fibre composite materials. The preferred material for the tooling is Invar, due to its low coefficient of thermal expansion. The conventional method for tooling production is by machining, which is costly due to material wastage and the poor machinability of Invar relative to steel and aluminium. An alternative to this method is to produce composite tooling using carbon fibre lay-up methods. This tooling suffers from high surface wear, and restricted tool life. The ideal tooling would combine the wear resistance of Invar, with the low cost of carbon fibre. Milovich et al [16] developed a method for thermal spraying Invar tools. In this case, a master pattern was machined from graphite, in order to provide a stable pattern for spraying. Invar 36 and 42 were both arc sprayed onto these patterns. These materials were then backed up with carbon fibre composite, giving a tool with low thermal mass, with good wear resistance, at relatively low cost compared to machined Invar tooling. These tools proved eminently suitable for vacuum bagging applications, particularly when the surface was sealed with a PTFE coating. However, it would appear that it is only when specialist tooling materials such as Invar are necessary, that the use of a high quality machined master is beneficial.

The processes described in previous sections are all essentially variations on the 'basic' thermal spray tooling process used to produce low cost zinc or kirksite shells. Some work has been carried out, in order to improve the characteristics of thermal spray shells, by the means of additional operations during the spray process. In particular, Roche [17] describes a process whereby the thermal spray deposit is simultaneously peened during the spraying operation. The compressive stress caused by the peening tend to counteract the quench stresses within the material, reducing the effects of curvature described in previous sections. Although this method has been demonstrated, it has only been used to produce small test samples. The process requires an enclosed system, to prevent the escape of both spray and peening media, and is thus only really practical for the production of small tooling inserts.

Another method for coating improvement is described by Jandin et al [18]. This process employs heating and cooling simultaneous to the spray process. Initially, the pattern is heated, either by laser, oxy-acetylene torch or induction heater. This reduces the quench stress within the sprayed coating. The arc spray pass then takes place, with the sprayed material being steel. A CO_2 nozzle is placed next to the arc spray jet, so that immediately the coating is sprayed, it will be cooled, thus limiting the build-up of residual stresses within the cooling. This system is similar to that described by Creffield et al [19], although in this work HVOF was used as the spray medium. This system provides a much higher thermal input to the substrate, thus accomplishing the 'heating' operation during spraying. However, all of this work depends on the use of a pattern material which can withstand a high degree of thermal input, and in the case of HVOF, also have considerable abrasion resistance. This severely limits the choice of pattern materials, to a point where it becomes necessary to use machined metallic or graphite patterns - the cost effectiveness of these routes again becomes limited by the need to machine an expensive master.

One method which shows some promise for mould tool insert production is the Sprayform process, developed by Sprayforming Developments Ltd [20]. The system relies on the phase change in certain steels, as described by Harris et al [7], to produce a 'stress-free' coating (rather, one where the stresses counteract each other). This process is used to deposit thick steel coatings onto cheap, castable alumina patterns, which can be generated from RP master models. The system uses a robot manipulator to move up to 4 arc spray guns over the pattern, allowing thick deposits to be built up rapidly. The process also allows for the inclusion of conformal cooling channels, allowing superior mould performance through reduced cycle times.

The future of thermal spray tooling reproduction may lie with solid freeform fabrication. This is a technology similar to many commercially available RP systems, but using metallic layers deposited by thermal spraying. Weiss et al [21] describe a system known as Mask and Deposit (MD), whereby a disposable mask is laser cut and placed onto a baseplate. This mask forms a negative of the desired layer form. A layer of thermal sprayed material is deposited through the mask, and is then machined back to the level of the mask. A second mask is then applied, and the process repeated. In this way, solid metal components can be built up using thermal spraying, without the need for a master pattern. When the process is complete, the masks are removed to reveal the finished component. Although this system is only semi-automated, it could be developed to a similar level as commercial RP systems, but with the ability to produce metal prototype components directly.

All of the above technologies use variations of the basic thermal spray technology. Many described have the need for accurately machined master patterns. With this in mind, it is difficult to see how they can compete with machined prototype tooling in terms of cost. Having said this, it has been shown that certain tooling applications require the use of thermal spraying to produce cost-effective tooling. It is these niches which must be exploited, in order to make thermal spray tooling competitive with other low-cost tooling technologies. The next section will provide a cost analysis of thermal spray tooling compared with other tooling routes.

2.3 Cost Comparison for Thermal Spraying and other Tooling Routes

Although thermal spraying is an acknowledged route for the production of low cost tooling, it is difficult to provide a definitive cost comparison between this and other tooling routes, because so many variables, such as part size, complexity, material, and production volume, are involved. This section describes a case study [22] carried out by Rover Group, which allowed a direct comparison between the cost of different tooling types. It is actually relatively rare to have an actual cost comparison between different tooling techniques, as it is normally unnecessary to produce multiples of the same tool - in this case, however, particular circumstances dictated this very occurrence.

The project centred around the late delivery of a production tool, to be used for the injection moulding of a plastic component. The component was for both left and right-hand drive models, and as such, the production tool was twin cavity, to account for both components. The component was an under-bonnet cover, approximately 600x250x50mm, with a shot weight of 300g in 40% talc-filled polypropylene. In order to fulfil initial batch production requirements, it was necessary to use low-cost tooling as a stop-gap measure. It was decided to evaluate three different techniques, in order to establish a meaningful cost comparison; machined aluminium, 'conventional' thermal spray kirksite, and a tool made using the Sprayform process (see previous sections).

The cost of the fully hardened steel production tool was to be £144K, with a lead time of 16 weeks. Although this appears high, this is because the cost is for a complete mould. In order to provide a realistic comparison, it is necessary to break down this cost further, to establish the cost for the core and cavity plates. Table 1 shows the cost breakdown for a typical mould tool.

Activity	Percentage of Cost	Actual Cost
Tooling Design	10%	£14.4K
Basic Mould Structure (Bolster, ejection, machining of cooling passages etc.)	15%	£21.6

Machining of cavity/core plates	10%	£14.4K
Electrode machining/ spark eroding	20%	£28.8K
Modification Allowance	10%	£14.4
Finishing	10%	£14.4K
Profit	25%	£36K
Total		**£144K**

Table 1: Cost breakdown for a typical production injection mould tool

The only costs associated with the core and cavity plates would be the machining operations, the electrode machining and spark erosion time, and the finishing of the core and cavity plates. This would give an overall cost for the core and cavity plates of £57.6K. It should be remembered, however, that the tool is twin cavity. All of the costs for the low cost tools described are for single cavity tools. The cost for the steel tool should therefore be adjusted accordingly. When doing this, the following assumptions are made:

- Programming and setting will account for around 30% of the machining cost. The programming and setting time will be similar for both single and twin cavity tools. The machining cost for a single cavity tool would therefore approximate to:

$$0.5(14.4-(0.3x14.4)) + (0.3x14.4) = £9.36K$$

- The electrode machining and sparking can be assumed to be 50%, as the number of electrodes required would be halved (electrodes would have to be 'mirrored' for left and right hand components) - this would give a cost of £14.4K
- Finishing of the single cavity would be 50% of the cost of the twin cavity, giving a cost of £7.2K.
- Profit is assumed to be added to the overall total i.e. it does not enter into this costing.

Using the above assumptions, this would give an overall cost for the steel core and cavity plates of:

$$9.36 + 14.4 + 7.2 = £30.96K$$

An in-house quotation was generated for the machining of aluminium core and cavity plates. These could be more easily machined, and would not require sparking or polishing, as the machined finish would be acceptable. The overall cost for these was £11.4K, with a lead time of 8 weeks.

A core and cavity set was generated using 'conventional' thermal spraying, that is a thin layer of kirksite backed with a filled epoxy resin. The overall cost of the set was £6.7K, with a lead time of 3 weeks.

Finally, a core and cavity set was generated using the Sprayform (Sprayforming Developments Ltd) process described in Section 2.2. As with the other thermal spray tooling, the cost of the core and cavity plates is incomplete. In this case, the raw cost of the plates was £6.4K. However, the plates required finish machining operations, to allow them to be fitted into the bolster. This added a further £1.5K to the cost, and 1 week to the lead time.

Table 2 shows the results of the cost comparison, along with the lead times for each technique.

Tooling type	Cost	Lead Time
Steel Production Tool (P20)	£30.96K	16 weeks
Machined Aluminium	£11.8K	8 weeks
Thermal Sprayed Kirksite	£6.7K	3 weeks
Sprayformed steel	£7.9K	4 weeks

Table 2: Adjusted Costs of Various Tooling Manufacturing Routes

When the relative costs are viewed graphically, the results are as shown in Figure 2.

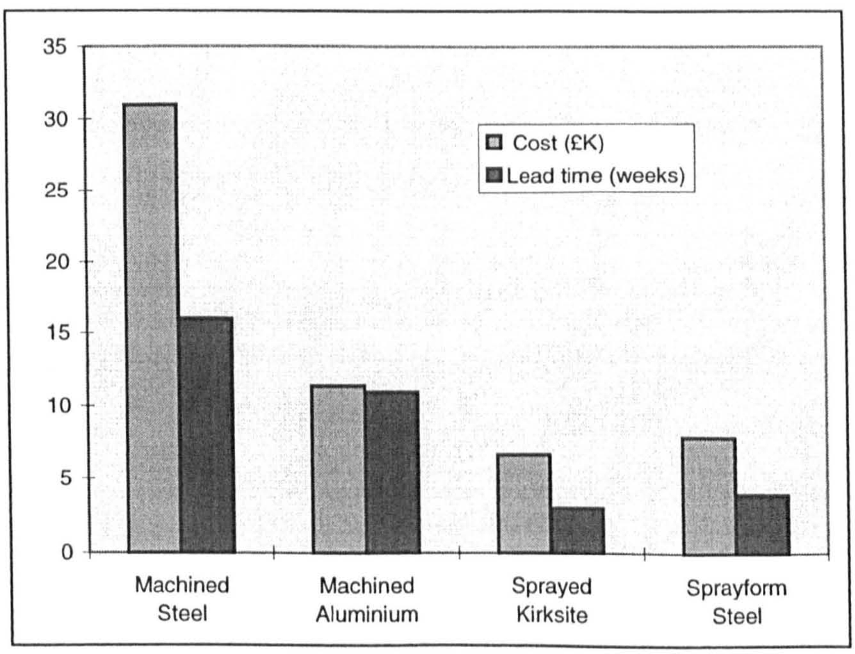

Figure 2: Relative costs and lead times for tooling using different manufacturing routes

From the graph, it can clearly be seen that both the thermal spray tools provide a considerable cost and lead time saving when compared to both steel and prototype aluminium tooling. Although the thermal spray tooling will be limited in life when compared to these other methods, for prototype components or even 'bridge to production' tooling, the use of thermal spraying can certainly be justified. This case study should only be considered as a guide, however; the relative costs will inevitably vary with the component, the volumes required, and the material to be moulded. It is, however, a good indicator of the savings which can be made using thermal spraying as a tool production route.

3.0 Physical Performance of Thermal Spray Tooling

3.1 Background

This project provides a detailed examination of the physical properties of thermal spray surfaces; particular attention is paid to those properties of thermal spray surfaces which will affect their performance in a moulding environment. In addition, the project takes an innovative approach to the production of tooling shells. Part of the programme examines the development of a route for the production of tooling shells using HVOF (High Velocity Oxy-Fuel) spraying. There is currently no proven route for the production of HVOF shells, and the use of this system involves development of new pattern materials, release agents, and spraying techniques. It is believed that this work is somewhat unique - there is currently no published evidence to suggest that HVOF is being used as a method for tooling shell production. The experimental programme aimed to improve the physical properties of thermal spray tooling; this encompassed a number of novel factors, which are summarised below:

- The development of a completely new method for the production of tooling surfaces, which aimed to provide a significant improvement in the performance of thermal spray tooling.
- The improvement of existing thermal spray tooling through post-treatment of the metal surface - this also aimed to provide a substantial improvement in the performance of existing thermal spray tooling.
- A broad investigation of the physical properties of thermal spray tooling faces, which aimed to establish comparative performance between thermal spray tooling and other 'competitor' technologies.

The whole of the programme carried out in the following paragraphs was carried out as part of the portfolio. Some of the elements, such as ceramic pattern manufacture and some post-treatment work was carried out externally. However, all the assessment of pattern materials, thermal spray shells and post-treatments was carried out at the University of Warwick by myself. More detailed information is available in the portfolio document "Physical Performance of Thermal Spray Tooling".

3.2 Pattern Materials

The selection of pattern material is important to the success of thermal spray tooling, as the material (and its processing route) will determine the dimensional accuracy, the surface finish, and the ability to release the tool from the pattern. Many materials have been used as master patterns, with varying degrees of success. The intention of this programme was to determine suitable pattern materials, particularly for the spraying of materials using HVOF, for which there was previously no readily useable pattern material.

It would appear that the choice of master pattern material has a profound effect on the success of depositing sprayed layers, particularly in the case of HVOF sprayed materials. Spraying layers of materials such as zinc and T204M using arc spraying presents little difficulty; the comparatively low melting points of these materials, combined with their relative softness and low particle velocity, means that a wide variety of pattern materials may be used. In the case of HVOF, however, the particle velocities associated with the process are considerably higher. In addition, the substrate temperatures imparted during the spraying process are considerably higher than with arc spraying. This means that the majority of pattern materials which have been traditionally used for arc spraying of low T_M materials will be unsuitable for use with HVOF. In order to provide a suitable pattern material for spraying of such materials, it is therefore necessary to take a fresh approach to the materials and processing aspects of pattern production.

In the first instance, graphite was selected as a possible candidate for pattern production. This material has been proven as a successful substrate material for *arc spraying* of materials such as Invar [16]; however, it has never before been tested as a pattern material for spraying of HVOF steels. Limited tests proved that the material was unsuitable using conventional spray parameters with Diamalloy 1003. Although the graphite surface was not significantly eroded by the spray particles, there was no adhesion to the surface, and it was not possible to form a cohesive sprayed layer. The reason for this is probably due to the low coefficient of friction of carbon, which prevents particles from splatting and sticking to the surface of the graphite. In addition to this, the surface of the graphite had a polished finish; the high surface finish probably contributed to the problem of limited adhesion. In order to test this, an area of the surface was roughened using wet & dry paper. This area was then sprayed as before. The adhesion of the sprayed layer did not improve significantly; however, abrasion of the surface did appear to increase significantly. This would therefore suggest that the graphite would be subject to significant wear, were the surface roughened to accept the HVOF layer. Despite this, it would be worthwhile to test several different grades of graphite, as only limited trials were carried out on a single type of graphite.

In terms of ceramic materials, it would appear that any potential substrate must be fired, in order to withstand the particle velocities associated with HVOF spraying. Freeze-cast alumina samples were sprayed in an unfired state, using Diamalloy 1003. The surface suffered significant degradation, with the steel particles abrading away the surface layer. Firing improves the surface cohesion of the ceramic; however, it also increases the overall mechanical strength of the material; a range of firing temperatures were tested, in order to find the optimum balance between abrasion resistance and mechanical strength. Although the firing temperature of the freeze-cast samples was optimised for the spraying of Diamalloy 1003, the firing temperature of 1050^0C meant that the ceramic pattern became difficult to remove using mechanical force. The increased mechanical strength introduced by firing at the higher temperature, would introduce a risk of damage to the tool shell during removal of the pattern. Although the use of alumina as a pattern material for spraying HVOF materials was successful enough for the production of test pieces, it would require further development for the repeatable production of tool shells.

The success of the alumina material is probably due to the fact that there is a strong mechanical bond between the HVOF sprayed material, and the surface of the ceramic. This is due to the high particle velocities; similar tests conducted with arc spray materials such as 0.8% carbon steels did not yield a cohesive sprayed layer. Although the thermal stresses are as high with HVOF particles, the higher velocity leads to a higher impact velocity at the surface, causing a higher degree of compaction. This suggests that it is only necessary to have a hardened *surface* layer on the ceramic pattern. This would allow a layer of material to be deposited, but would also allow relatively simple removal of the master pattern, due to the lower mechanical strength of the ceramic. This would reduce the risk of damage to the tool surface, and would also reduce the treatment requirements for the pattern material. This surface hardening could take the form of a flame or laser treatment, which would cause a thin layer of the surface to be locally hardened[1].

1. Subsequent work on the Spraymould programme at the University of Warwick has demonstrated the benefit of localised hardening on ceramic patterns.

Another viable solution to the problem of pattern removal would be through chemical attack. This is common enough in the casting industry, where ceramic cores are leached out using chemical attack (potassium hydroxide is most commonly used) to remove them from cast parts. Although freeze-cast alumina can be removed in this manner, there are other ceramic materials, such as silicates, which may be freeze cast with similar accuracies, and may be fired to produce similar surface hardness, but are more readily removed using a solvent such as caustic soda. This would mean that the pattern need not be subject to mechanical force, and would thus mean that the risk of damage to the tool face would be reduced.

The approach of selectively hardening the surface layer of a ceramic pattern may solve the problem of removing the bulk of the pattern on completion of the tooling; however, it still leaves the requirement for the breaking of the mechanical bond between the sprayed layer and the ceramic substrate. One possible solution to this would be to integrate a release agent *into the surface of the pattern.* Early trials with boron nitride, when painted on as a suspension, yielded little benefit in terms of release - the material was simply blown away from the ceramic surface, due to the force of the HVOF jet. An alternative approach would be to cast a surface release coat of boron nitride into the alumina pattern, which could then be fired in the conventional manner. This would mean that the boron nitride was an integral part of the alumina pattern, and would not be removed on spraying. Trials would need to be carried out to establish the required density of boron nitride in the surface layer, to obtain a balance between coating adhesion and release.

3.3 Tensile Properties

The aim of these sets of experiments was to quantify some of the important mechanical properties of thermal spray materials. The principal aim was to determine the effect of the spraying conditions and thermal effects, on the mechanical integrity of various materials. In order to do this, several trials were carried out - tensile testing, flexural testing, and an experiment to determine the effects of thermal cycling on the material strength.

3.3.1 Tensile Strength

Work carried out by Zurecki et al [11] has suggested that the properties of a steel coating could be improved by the use of an inert carrier gas, specifically nitrogen. The aim of this experiment was to determine whether the performance of arc sprayed low T_M alloys could be similarly improved for use in tooling surfaces. Samples of various materials were tested on the Lloyd tensile tester, as shown in Figure 3. The machine uses a 5kN load cell, and has a variable cross-head speed. For these purposes, a uniform cross-head speed of 1mm/min was selected. Each material and post-treatment combination was tested 5 times, to give an average result. When the specimens broke, the cross-sectional area was measured at the fracture point, allowing the true stress at fracture to be determined by calculating load/cross sectional area. The graph generated by the machine also allowed examination of the failure mechanism of each material.

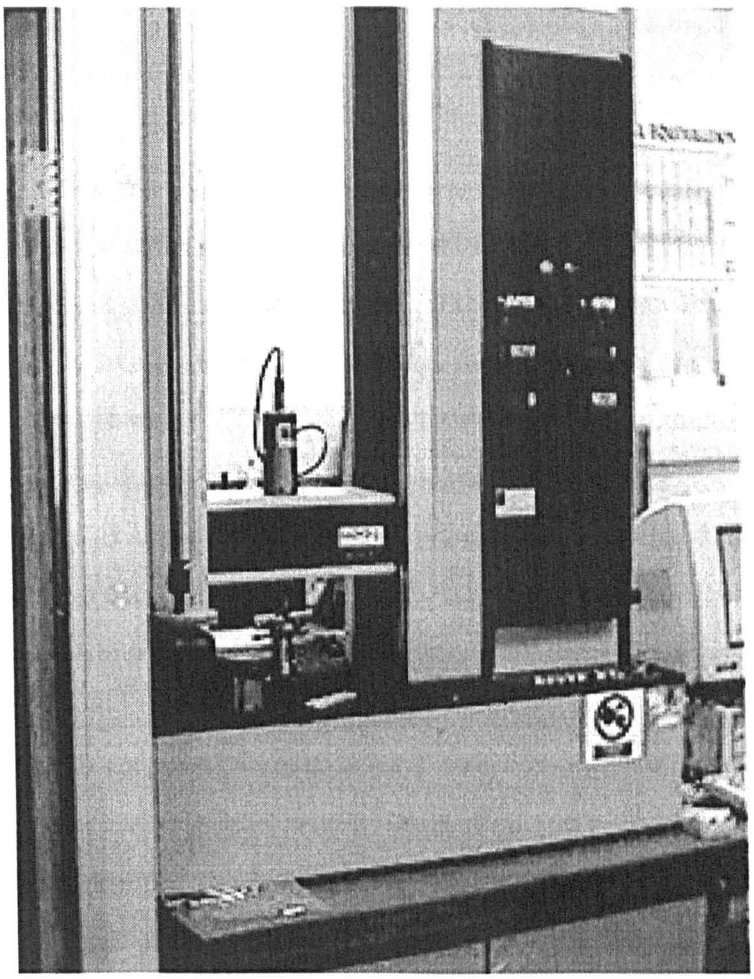

Figure 3: Machine used for tensile & flexural testing

The results showed a clear improvement in the performance of zinc when arc sprayed with nitrogen as a carrier gas. The failure stress of the tensile test specimens increased by an average of 12% over air-sprayed zinc. This would indicate that under air-sprayed conditions, zinc is severely affected by oxidation, which is largely caused by the action of the carrier gas on the molten particles. Use of the inert carrier gas inhibits the oxidation level, improving the mechanical properties of the zinc. These results are summarised in Table 3.

Sample Number	Zinc (air carrier gas)	Zinc (nitrogen carrier gas)	T204M (air carrier gas)	T204M (nitrogen carrier gas)
	Failure Stress (MPa)			
1	0.36	0.41	0.54	0.54
2	0.36	0.42	0.53	0.54
3	0.36	0.42	0.55	0.54
4	0.36	0.42	0.52	0.54
5	0.35	0.39	0.52	0.54
AVERAGE	**0.36**	**0.41**	**0.53**	**0.54**

Table 3: Effects of Inert Carrier Gas on Tensile Strength

In the case of Tafa T204M, the only change which was noticeable was that the samples arc sprayed with nitrogen as a carrier gas exhibited more uniformity in their tensile properties; the actual average failure stress only increases by 2%. This would seem to suggest that T204M is not uniformly affected by oxidation during spraying, to the same degree as pure zinc. The material is a kirksite-type material specifically developed for tooling applications, and it may be that certain alloying elements within the material inhibit oxidation. The results also suggest that the inconsistencies with air-sprayed T204M may be due to localised oxidation which causes small inclusions in the sprayed layer, which may cause crack propagation under stress - the use of nitrogen appears to remove any inconsistencies within the sprayed layer.

The results for the HVOF sprayed Diamalloy 1003 were extremely significant, as they showed that the failure stress was lower than expected. Diamalloy 1003 is a stainless steel coating supplied by Sulzer-Metco in powder form, specifically for HVOF spraying. The coating is relatively low cost, but produces a hard, dense coating, making it an ideal coating for tool surfaces. The HVOF sprayed tensile test samples were only approximately 0.6mm thick, whilst the arc sprayed samples were around 2mm thick. Although the failure *stress* of the Diamalloy 1003 was much higher than the arc sprayed materials, the maximum failure *loads* were somewhat similar between arc spray and HVOF. It had been anticipated that HVOF would provide significant benefits in tensile properties, allowing a thinner sprayed shell to be used, as opposed to a thicker, weaker arc spray shell. The results, however, indicate that use of a thinner Diamalloy 1003 shell would result in a weaker thermal spray layer, which would be more prone to cracking under stress. The lower failure load of the HVOF samples may be in part due to the process parameters used, and may also be due to the spraying conditions. In normal spraying, HVOF coatings are applied to substrates which are heated to around 150-200^{0}C. The fact that these samples were sprayed onto cold samples may cause thermal shock in the sprayed coating. In addition, the coatings were sprayed using propane as the combustion gas. This is now known to produce inferior quality coatings, due to the variability of the propane supply [19]. Propylene is now the recommended choice of combustion gas, due to its more consistent quality of supply. Both of the above factors may have affected the quality of the HVOF samples. However, based on the above results, a coating thickness of above 0.95mm would provide significant benefits over arc sprayed coatings, although the shell cost would be somewhat higher.

3.3.2 Flexural Strength

The purpose of this experiment was to determine the effect of different carrier gases on the flexural strength of thermal spray materials. Although tensile strength is an important test of a material's mechanical properties, flexural strength is more indicative of the type of stress which will be encountered in moulding environments. Zinc was tested, with air and nitrogen as carrier gases. This was done in order to assess the effects of reduced oxidation on the failure mode of the material. This experiment used the Lloyds tensile test machine, as shown in Figure 3. The machine was set up to perform a compression test, with a cross-head speed of 1mm/min, using a 5kN load cell. A special fixture was fitted to the machine heads, as shown in Figure 4. The samples were placed with the 'tool' face downwards in the fixture.

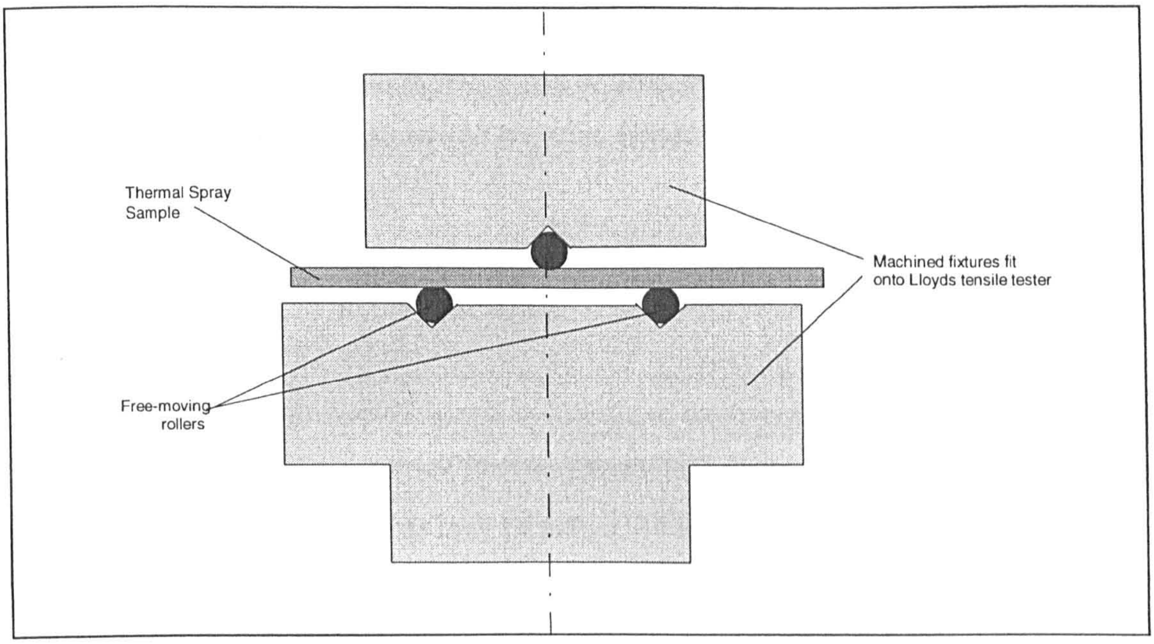

Figure 4 : Flexural testing fixture

The results showed that the choice of carrier gas had a considerable effect on the flexural properties of arc sprayed zinc. When air was used as a carrier gas, the overall flexural strength appeared to be higher, but the material was more susceptible to brittle failure. With nitrogen as a carrier gas, the overall failure load was reduced slightly, but the material appeared to be more ductile - this is demonstrated by the higher displacement before fracture, and the overall area of the load/displacement curve.

The experiment showed that the choice of carrier gas had a profound effect on the Modulus of Elasticity of the zinc. This is important, as the Modulus of Elasticity (E) will determine the way in which a material behaves under loads. The modulus of zinc with air as a carrier gas (10.37GPa) is more than twice that of the nitrogen-sprayed samples (4.86GPa). In addition, as would be expected, the elongation to failure of the inert sprayed samples is far higher than for the air-sprayed sample. In application terms the higher oxide content associated with the air-sprayed samples gives a higher stiffness but significantly reduced ductility. These figures are extremely low, when compared to the figures for wrought materials. For example, the E of pure aluminium is 70GPa, whilst steel is 190-210GPa, depending on the composition. The sprayed samples have Moduli of Elasticity more akin to non-metallic materials; the figures are similar to wood, with an E of 11-14GPa, or nylon, with 2.1-2.8GPa. As with many of the other properties of sprayed materials, this is most probably due to the levels of porosity in the material, and the levels of oxidation. It can be seen that the use of inert carrier gas is beneficial in improving the ability of the material to flex without damage, but also reduces the overall failure stress of the material.

3.3.3 Thermal Fatigue

This set of experiments was designed to determine the overall effect of thermal cycling on the mechanical strength of a material. Previous work [28] showed that under rotational moulding conditions, arc sprayed surfaces may be subject to a reduction in their mechanical properties due to repeated cycling at elevated temperatures. In this benchtop test, the programme included HVOF sprayed Diamalloy 1003, and arc sprayed zinc and Tafa 204M.

In order to simulate the environment in which the materials would be expected to operate, they were subjected to 300 cycles from room temperature to 200^0C, in a bath of low T_M alloy. The materials were then removed, and allowed to cool to room temperature. After this, their tensile strength was tested using the same test conditions as the untreated samples. The results clearly show that the thermal cycling has an effect on the tensile strength of the materials, although the results are more pronounced for arc sprayed materials.

In the case of Tafa 204M, the average tensile strength dropped by a considerable amount; around 23% of the original tensile strength was lost after 200 heat cycles. Whilst the zinc had a lower initial tensile strength, the loss after heat cycling was only 14%. This would suggest that both sprayed samples suffered some degree of oxidation, which was exaggerated by the elevated temperature.

In the case of HVOF sprayed Diamalloy 1003, there is very little reduction in the overall performance of the material, in terms of mechanical properties. The material only suffered an average 4% deterioration in tensile strength, after 200 heat cycles. This is to be expected; stainless steel is specifically oxidation resistant, particularly at comparatively low operating temperatures as in this experiment. Although the tensile strength of the Diamalloy 1003 was lower than expected in the initial (untreated) experiment, this may well be due to oxidation which occurred at the spraying stage. The high temperatures would mean that the spray particles would be prone to oxidation, which would explain why the samples were more brittle than expected. However, this experiment shows that steels would not be significantly affected by thermal fatigue at temperatures such as this. These results are summarised in Table 4.

Sample Number	Zinc (untreated)	Zinc (after 200 heat cycles)	T204M (untreated)	T204M (after 200 heat cycles)	Diamalloy 1003 (untreated)	D1003 (after 200 heat cycles)
	Failure Stress (MPa)					
1	0.36	0.31	0.54	0.42	0.86	0.83
2	0.36	0.30	0.53	0.39	0.84	0.82
3	0.36	0.33	0.55	0.42	0.83	0.80
4	0.36	0.31	0.52	0.40	0.85	0.79
5	0.35	0.32	0.52	0.40	0.83	0.81
AVERAGE	**0.36**	**0.31**	**0.53**	**0.41**	**0.84**	**0.81**

Table 4: Effect of Thermal Fatigue on Tensile Strength

3.4 Wear Resistance

The intention behind this set of experiments, was to provide comparative wear data, showing the effects of a standard abrador on various materials and post treatments. Although not strictly representing in-mould performance, this would give an idea of how each material would perform under the same conditions. Several thermal spray materials and post-treatments were tested. In order to provide a benchmark, other 'low cost' tooling materials were also tested. A rig was constructed as shown in Figure 5 for the purpose of providing consistent wear test data. In order to provide accelerated wear conditions, the wear test samples were moved in a reciprocal motion against a sheet of 400 grit wet & dry paper. The tests were conducted without any lubricant; in order to prevent damage to the abrasive sheet, it was indexed after every 10 cycles - a linear actuator being used to move the sheet along 1 axis after a set number of cycles. Another important aspect of the indexing was to maintain a constant level of abrasion. The height the sample was measured before testing, and the rig was then programmed to carry out 500 cycles, at a constant rate of 2 strokes per second, with a constant load of 2kg on the sample. Readings were taken at 50 cycles, then 100, 200, 300, 400 and 500 cycles, to determine the levels of wear at each stage. At the end of 500 cycles, the sample was measured to determine the overall level of material removal.

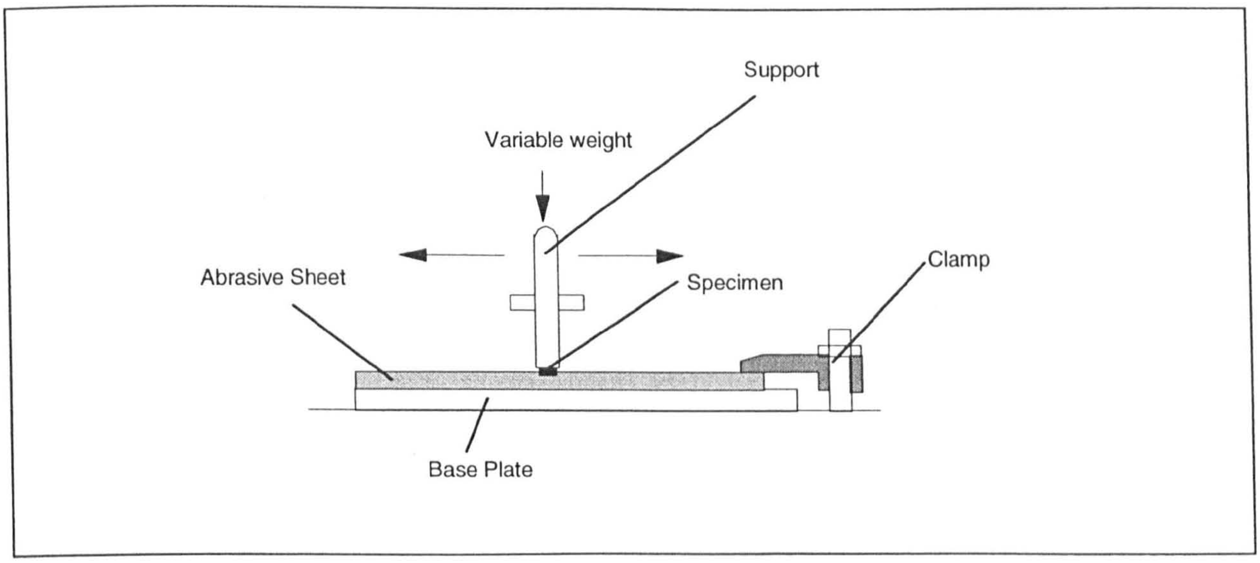

Figure 5 : Wear test rig

It was clearly shown that there was a wide variation between the wear resistance of thermal sprayed materials in an untreated state, particularly when compared with the 'benchmark' materials, electroformed nickel and carbon fibre composite, two materials commonly used for aerospace tooling. Out of all the materials tested, the carbon fibre showed the poorest abrasive resistance - this reflects many of the durability problems associated with tooling made from this material; as it is relatively soft, it is prone to abrasion and damage in the moulding environment. Pure zinc sprayed with air as a carrier gas showed an improvement of 33% in abrasion resistance compared with carbon fibre, although its performance was relatively poor in comparison to other materials. Surprisingly, the T204M did not show significantly better wear resistance than zinc, despite the fact that it is specially formulated to improve wear resistance. The HVOF material performed well in the abrasion tests, with Diamalloy 1003 improving abrasion resistance by 42% compared to electroformed nickel, and a 68% improvement over zinc. The hardness of the material, coupled with the fact that the surface is extremely dense, mean that the material is far more wear-resistant compared to arc sprayed surfaces. This implies that a thin shell of HVOF-applied steel could be used to the same effect as a much thicker arc sprayed layer of material. All of the above results are summarised in Graph 1.

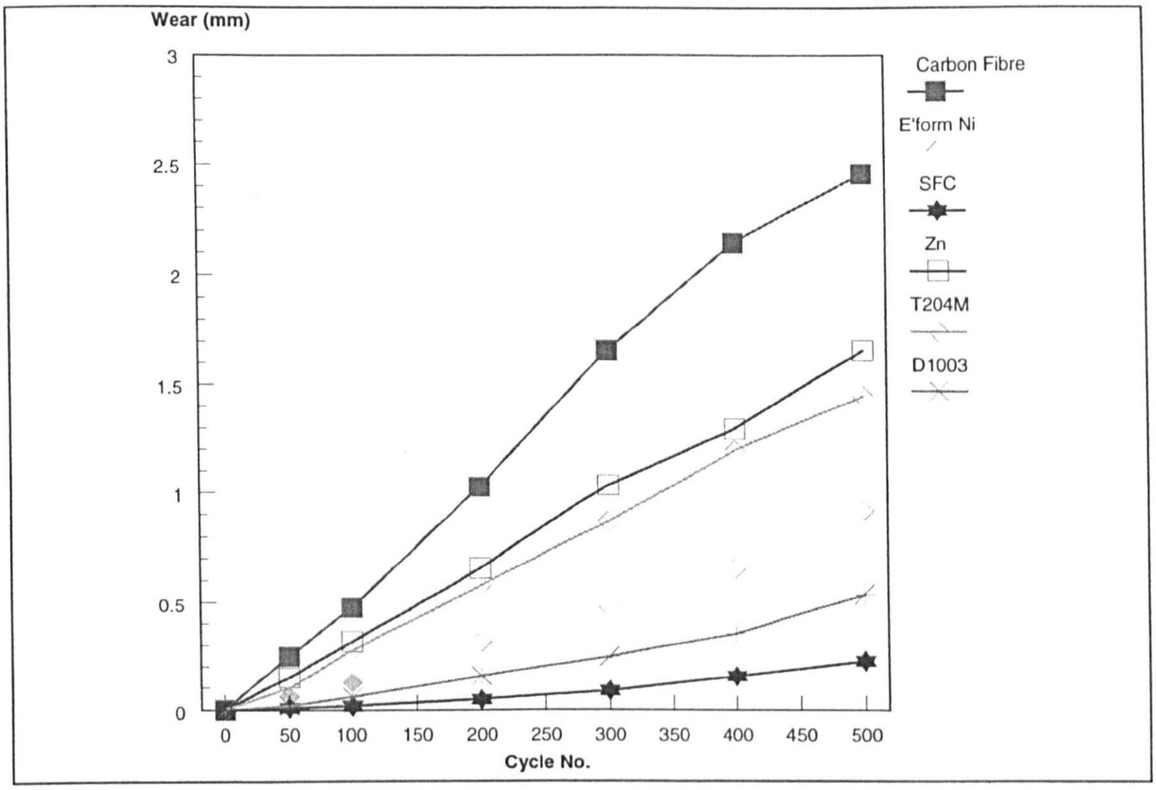

Figure 6: Comparative wear results for various materials

The best performer in this group of untreated samples was the martensitic steel deposited by Stress Free Coating (i.e. deposited by the Sprayform process, as described in Section 2.2). The material is obviously extremely hard, and therefore abrasion resistant. Although the material performed better than HVOF coatings in this test, the coating is extremely porous, due to the spraying parameters which are used. The abrasion test is more suited to testing the hardness of materials, rather than their resistance to abrasion during moulding. It may be that the more porous materials do not perform to the same level in a moulding environment, as molten plastic may be able to enter the porosity, and remove localised areas. In order to provide a fuller assessment of the wear performance of thermal spray surfaces, it would be necessary to make a number of tools, each using a different material. Although this would provide a more accurate picture of the wear performance, it would be difficult to extract quantitative data. Although empirical, this set of tests at least provides comparative data for the materials, without the expense of a mould trial programme.

3.5 Vacuum Integrity

One important application of thermal spray tooling will be for vacuum forming of composites. This is a relatively low-stress tooling application, ideal for thermal spray. The intention behind this set of experiments was to test the ability of thermal spray surfaces to hold a vacuum over a period of time - a critical attribute for this type of tooling. Various sprayed materials were tested, along with post-treatments and benchmark materials. The materials were tested using the actual vacuum bagging technique which would be used in production moulding.

The results of these experiments were interesting, as they clearly showed the difference in vacuum integrity between arc sprayed and HVOF sprayed materials. In addition, it is possible to assess tests concentrated on comparing the 'benchmark' materials, electroformed nickel and carbon fibre composite, with untreated thermal spray samples. Over the 4 hour test period, both benchmark materials performed well. In both cases, a slight loss of vacuum was evident. As both materials are relatively dense, this may indicate a slight leakage of air into the vacuum system - however, this did not affect the overall integrity of these materials. By comparison, unbacked, untreated thermal spray samples performed poorly. In the case of both arc spray materials, zinc and Tafa 204M, the vacuum loss after 4 hours was 100%. The porous nature of the materials is clearly unsuited to use for vacuum purposes in their untreated state. The untreated Diamalloy 1003 performed better than arc spray materials, but also suffered a vacuum loss of 52%. Although this would not be suitable for autoclave applications, the thickness of the material may also play a part in the vacuum integrity. In the case of this test, the HVOF sample was 0.6mm thick, compared to the arc spray material thickness of 2mm. Thus the HVOF material displayed a marked improvement over the arc spray samples despite being less than a third of the thickness. Figure 7 shows the results for zinc sprayed samples, with various post treatments, including PTFE, Poly-Fluoro Alkyl and HVOF-sprayed Diamalloy 1003. The results of these post-treatments are summarised in subsequent sections.

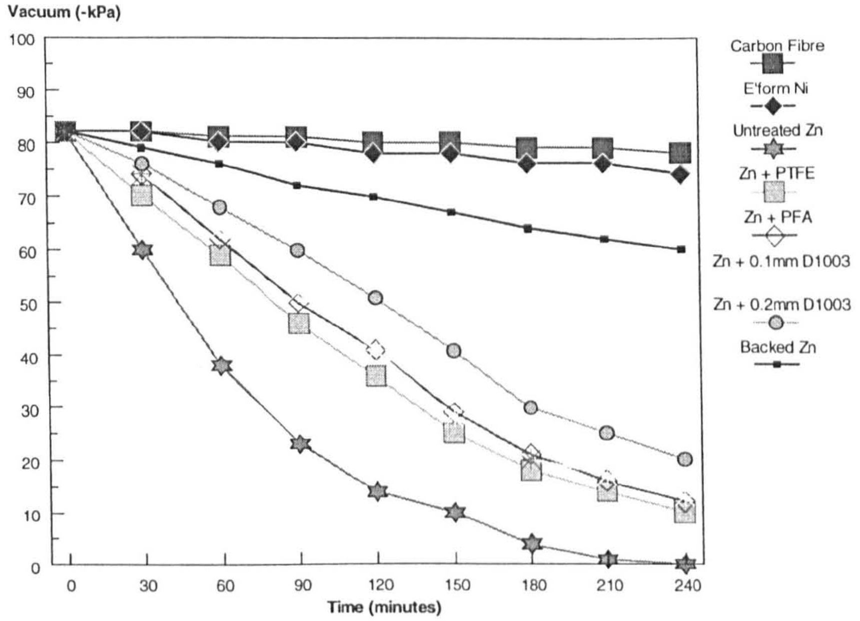

Figure 7: Loss of vacuum vs. time for thermal spray samples & benchmark materials

3.5.1 Effects of Post-Treatment

In terms of the post-treatments which were applied to the arc sprayed surfaces, the results were somewhat disappointing. Both zinc and T204M were treated with PTFE, and also with PFA. These coatings were applied on the recommendation of Poetons, as the optimal coatings for the material type and anticipated operating conditions of the tooling surfaces. The effect of the coatings on improving vacuum integrity was minimal; this would suggest that the porosity levels within the arc sprayed coatings are so high, that it was impossible for the post-treatments to totally in-fill all surface porosity. Although the coatings had little effect on vacuum integrity, they may well prove extremely invaluable as release coats; however, it would appear that their use as vacuum sealing coats is limited.

The problems with the polymeric post-treatments is borne out to some extent by the results of treating zinc and T204M with a thin layer of Diamalloy 1003. However, this thin layer did have some effect on the overall vacuum integrity. This may be because the steel particles actually alter the physical profile of the arc sprayed surface on impact. The harder HVOF particles will impact onto the softer zinc, which may cause some degree of localised compaction of zinc splats. In addition, the thin layer of HVOF will also be relatively dense compared to the zinc. This may explain why there was some slight improvement in vacuum integrity when compared with the polymeric post-treatments. This initial test was carried out with a 0.1mm layer of Diamalloy 1003. A second test with a 0.2mm layer of the same material produced a considerable improvement in vacuum integrity. This would suggest that the thicker the layer of HVOF material, the higher the vacuum integrity. This is to be expected; the HVOF layer will have a considerably lower level of porosity, and will allow less leakage.

3.5.2 Effects of Backing Material

The addition of a backing material to all of the thermal spray samples provided a considerable improvement to the vacuum integrity of the samples. The samples had an CY149 aluminium-filled epoxy backing added, which gave a total sample thickness of 5mm. The results clearly showed that the backed samples provided approximately 80% improvement in vacuum integrity over the test period. This suggests that the vast majority of leakage was through the thermal spray sample, and that addition of a backing material reduces leakage to a large degree. However, the backed samples still did not perform as well as the benchmark materials. One possible cause of this was that the porosity of the thermal spray layer allowed ingress of air under the vacuum tape - the average levels of porosity in arc sprayed samples would not preclude this. To test this assumption another experiment was performed, to determine the level of 'side leakage' which occurs through the thermal spray sample.

3.5.3 Elimination of Side Leakage

An experiment was conducted, in order to assess the effects of 'side leakage' on the overall vacuum integrity of thermal spray samples. The experiment first determined the vacuum integrity of unbacked zinc, which as discussed previously has been shown to be very poor. A backed sample of zinc was also tested - this provided considerably better results. This led to the assumption that some of the losses suffered by the backed sample may be due to air seeping around the vacuum tape. In order to test this theory, layers of vacuum tape were progressively added to the sample as shown in Figure 8 - the vacuum loss at each stage was measured. The vacuum loss after 4 hours was taken to be the final reading.

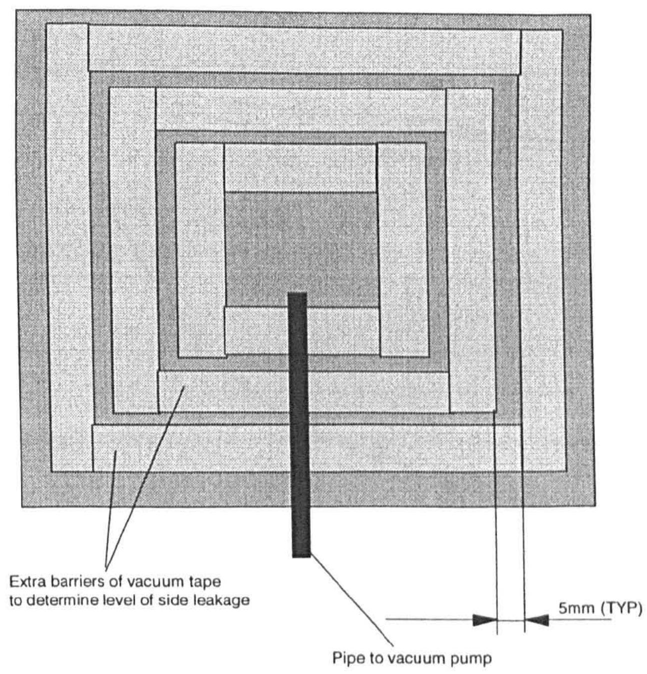

Figure 8: Positioning of extra vacuum tape layers

The results clearly showed that there was some vacuum loss due to side leakage, which occurred in the area of thermal spray directly under the first layer of vacuum tape. The loss then rapidly fell away, and at a distance of 50mm from the inside of the first vacuum tape layer, became relatively constant. This would suggest that the porosity of the thermal spray surface *external* to the vacuum environment is also important in determining vacuum integrity. Post treatment could possibly reduce the porosity of this external area - a more comprehensive solution would be to mount a second layer of vacuum tape, approximately 35mm from the first - this would contain the vast majority of the leakage. These results are summarised in Figure 9.

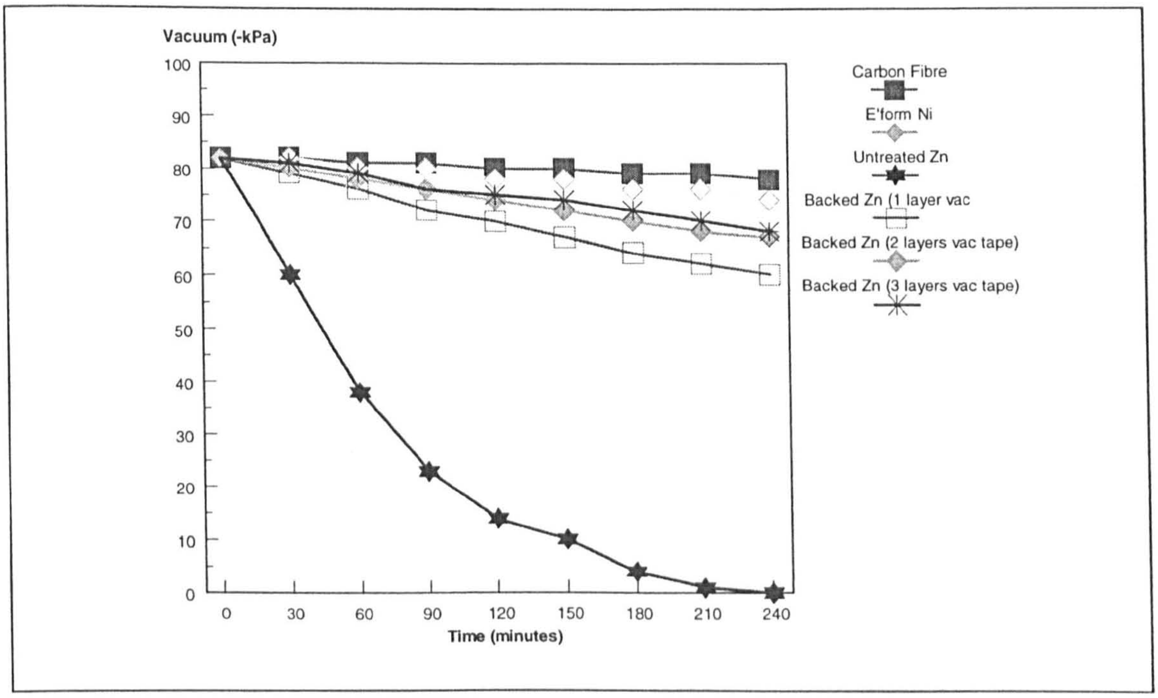

Figure 9: Effect of 'side leakage' on vacuum integrity of zinc samples

3.5.4 HVOF Material Thickness

Some of the results were used to determine the thickness of Diamalloy 1003 which would provide full vacuum integrity, without any backing material. In the case of zinc, thin coats of Diamalloy 1003 were applied to the surface, to see what effect they had on the vacuum integrity of the overall shell.

The results showed that as the material thickness increased, the vacuum integrity improved, and that this relationship is linear. The minimum material thickness for holding complete vacuum integrity was around 1.4mm. However, backing the thermal spray surface has already been shown to have a profound effect on the vacuum performance - the minimum backed HVOF material thickness for holding vacuum is around 0.8mm. In a tooling situation, it would therefore be necessary to spray a layer of HVOF material to around 0.8mm thickness, and then back it with a carbon fibre composite material to provide complete vacuum integrity. It may be possible to reduce the thickness of the HVOF layer still further by the provision of post-treatments, as described in previous sections.

4.0 Compression Moulding Project

4.1 Background

The compression moulding project was important for Rover Group, as it proved the ability of thermal spray tooling, as a method for the production of large prototype tools for the production of 'technical prototype' components. These are components which are manufactured in the correct engineering material, which may then be used for testing and evaluation. In this case, the required components were an important part of the vehicle structure (details of the components may not be released for reasons of confidentiality). The selected method of manufacture for these components was compression moulding, using a GMT (Glass Mat Thermoplastic) material.

In selecting an appropriate material for the components, a number of materials were evaluated, including SMC (Sheet Moulding Compound), and GMT (Glass Mat Thermoplastic). GMT was determined to be more desirable, as it was polypropylene-based, and thus more recyclable than the thermoset SMC - SMC components of this type had also been manufactured. In addition, Rover Group had no previous experience of producing this type of components in GMT - their current experience of GMT moulding is limited to battery boxes. It was thus deemed important to evaluate the effectiveness of using GMT as a potential material. Compared with aluminium, GMT offered the following advantages:

- Cheaper and more readily recyclable than aluminium.
- The possibility of producing a one-piece moulding; the current aluminium assembly consists of a number of individual pressings.
- Greater accuracy of part - improved dimensional repeatability due to absence of component springback, as seen with pressed aluminium/steel components
- No requirement for painting
- Lower part cost

Although the GMT component was calculated to have a lower stiffness than existing steel or aluminium assemblies, which are traditionally used in a monocoque construction, this was not deemed to be a major disadvantage, as the GMT assembly would be fully supported by an aluminium spaceframe. In addition, the required angle of draw on the component precluded

the use of a single piece, pressed aluminium component. The assembly would therefore consist of a number of joined sections, increasing complexity, weight and cost. Although the ultimate aim is a single component, the initial design consisted of a five-piece assembly.
In order to manufacture these components, it was necessary to produce a set of tooling capable of moulding approximately 30 component assemblies in GMT, using the compression moulding process. Although the use of thermal spraying is widespread as a route for prototype tooling, there is no literature to suggest that the technique has been previously used for compression moulding of GMT, and certainly not for components the size of the components required (up to approximately $4m^2$). However, research has been carried out, notably at the Advanced Technology Centre, into the performance of a range of tooling methods, including thermal sprayed surfaces, for the compression moulding of GMT [23]. This work took samples of various materials, including thermal spray materials, and subjected them to tests to establish the wear resistance under benchtop test conditions, and also under moulding conditions. Based on the results of these tests, it was decided that Tafa 204M would be an appropriate material to use for the thermal sprayed tool shell, in order to provide good surface wear resistance. However, as this material is expensive, it was decided that a thin surface layer (~1mm) of T204M would be backed up with a thicker layer (~2mm) of pure zinc, a considerably cheaper material. Thus the tool surface would retain good wear resistance, whilst keeping cost as low as possible.

In terms of the backing material for the tooling, it was critical that an appropriate material was selected, given the particular nature of the moulding process. During moulding, the tools are maintained at a constant temperature of around 80^0C. The GMT is heated to around 250^0C, and placed in the mould, which is then closed under pressure - this may be up to $450kg/cm^2$. The material then flows to fill the mould, which will subject the mould to a hydrostatic pressure of around $150kg/cm^2$. The tooling is thus subject to considerable compressive and shear stresses. The backing material must thus be capable of withstanding these forces without damage. The normal backing material for thermal spray shells is an aluminium-filled epoxy resin, which is post-treated to 150^0C to encourage cross-linking and improve strength. However, due to the size of the tools, they could not be heated in an oven. The epoxy backing would therefore have been unacceptably brittle. As a substitute, Densit was selected as a backing material. This is a Chemically Bonded Ceramic (CBC), with an extremely high compressive strength (~200MPa). This material did not require any post-treatment, and could be cast in much the same way as the epoxy resin. However, from previous sample tests it had been shown that Densit did not adhere to thermal spray surfaces, and in addition the zinc sprayed surface reacted with the alkaline Densit. It was therefore necessary to develop a novel method for fixing the two components together. After some investigation, a system was developed combining a mechanical fixing with a resin barrier/adhesive.

In order to provide a mechanical bond between the two materials, it was necessary to attach mechanical fixings into the thermal spray material. This was to be accomplished by overspraying the fixings. An investigation was carried out, in order to find the most appropriate fixing. The most appropriate fixing turned out to be a galvanised roofing tack, as the galvanising produced a roughened surface, which encouraged adhesion of the thermal spray. The tacks were first bent through a 90^0 angle, to provide the mechanical key into the Densit. The first 2mm of zinc was then sprayed in the normal fashion. The tacks were then fixed to the surface of the thermal spray using a two-part quick-cure epoxy adhesive. Once all the tacks had been applied, a further 1mm layer of zinc was sprayed over the tacks. This arrangement is shown in Figure 10.

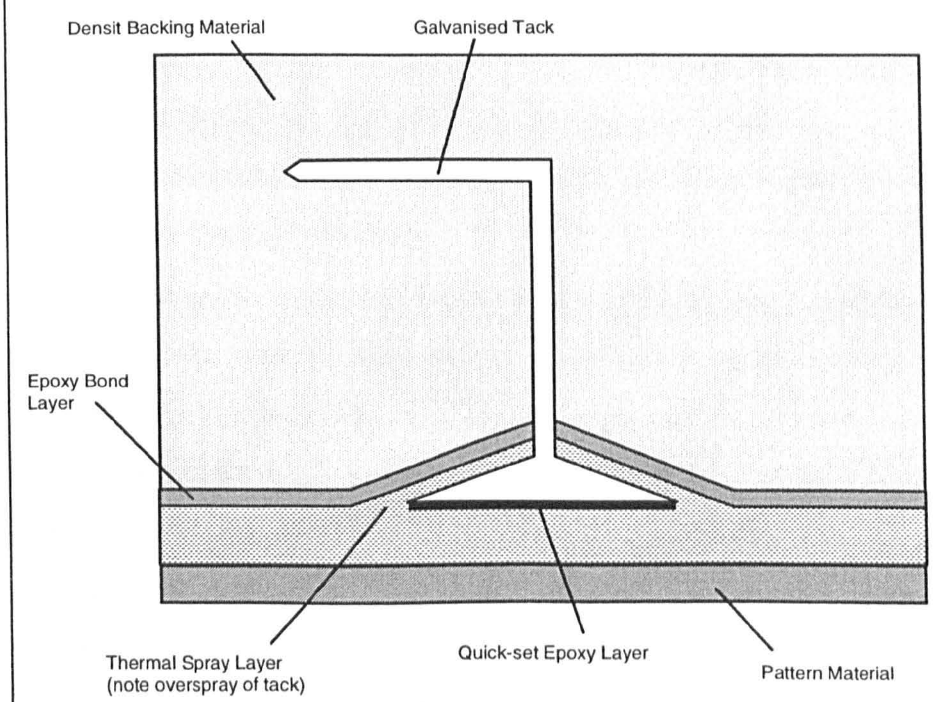

Figure 10: Novel fixing method between Thermal Spray & Densit

In order to prevent corrosion of the thermal spray surface, it was necessary to use a protective barrier between the zinc and Densit. A joint research programme between WMG and Express Plastics Ltd (a manufacturer of electroformed nickel shell tooling), had established an epoxy resin as the optimum barrier coating. The epoxy is capable of curing when completely submerged in Densit, and may be post-cured to give an ultimate temperature resistance in excess of 120^0C. The formulation is as follows:

CIBA CY219	100 parts
Ancamid 1704	40 parts
Ancamid 503	10 parts

The Ancamid amine curing agents are mixed together before addition to the CY219, giving a pot-life of 30-40 minutes. This epoxy resin was painted onto the back face of the thermal spray, and casting commenced when the coating attained a tacky, viscous consistency.

4.2 Tooling Manufacture

The tooling was manufactured in a way common with many thermal spray tools, and may be summarised as follows:

- A master pattern was manufactured in Ureol. This pattern was generated by taking the component CAD geometry, adding all the relevant tooling features such as shut-off and material shrinkage allowances, and generating a CNC programme. This programme was used to produce an accurate model of the component 'A' surface.
- The pattern was coated with a PVA release agent, and sprayed with the Tafa 204M/ zinc combination to a thickness of 3mm.
- A reinforcing bolster was applied to the outside of the tool shell, and the backing material cast into the bolster, onto the back surface of the thermal spray layer.
- Once the backing material had cured, the master pattern was removed to reveal the 'female' tool half (cavity).
- This tool half was then coated with a special high temperature wax, to form the component thickness and shut-off profile. This meant that it was not necessary to produce a separate pattern for each tool half, thus considerably reducing the overall cost.
- The above steps were then repeated to form the 'male' tool half (core).

Figure 11 shows the large tool during manufacture. At this stage, the female half of the tool has been sprayed, and the reinforcing frame placed on the pattern. At this stage, the cooling system and reinforcement are being fitted. The figure gives some idea of the overall size of the tool.

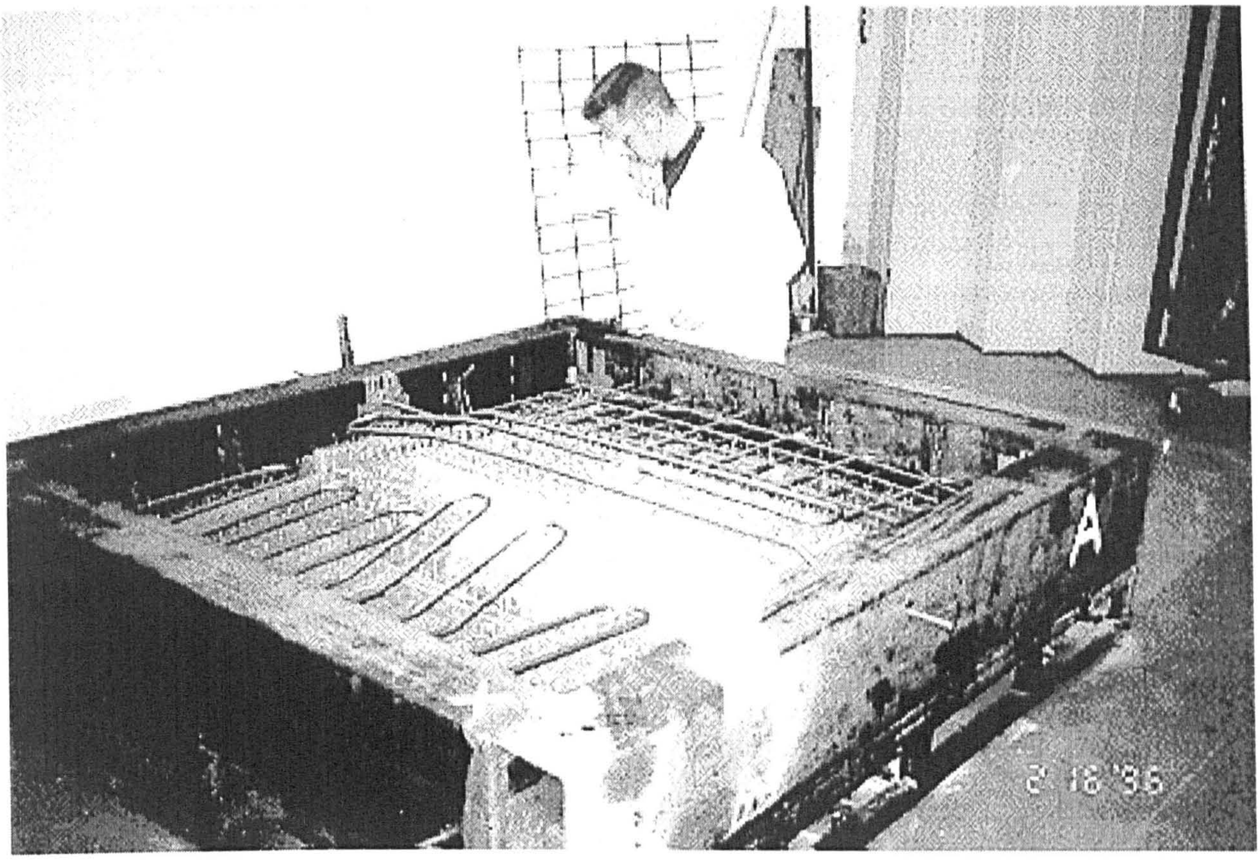

Figure 11: Large tool (female half) during manufacture

The manufacturing route was proven to be successful throughout the manufacture of the five tool sets, although slight modifications were necessary to suit individual component geometries. The overall manufacturing route is summarised in Figure 12.

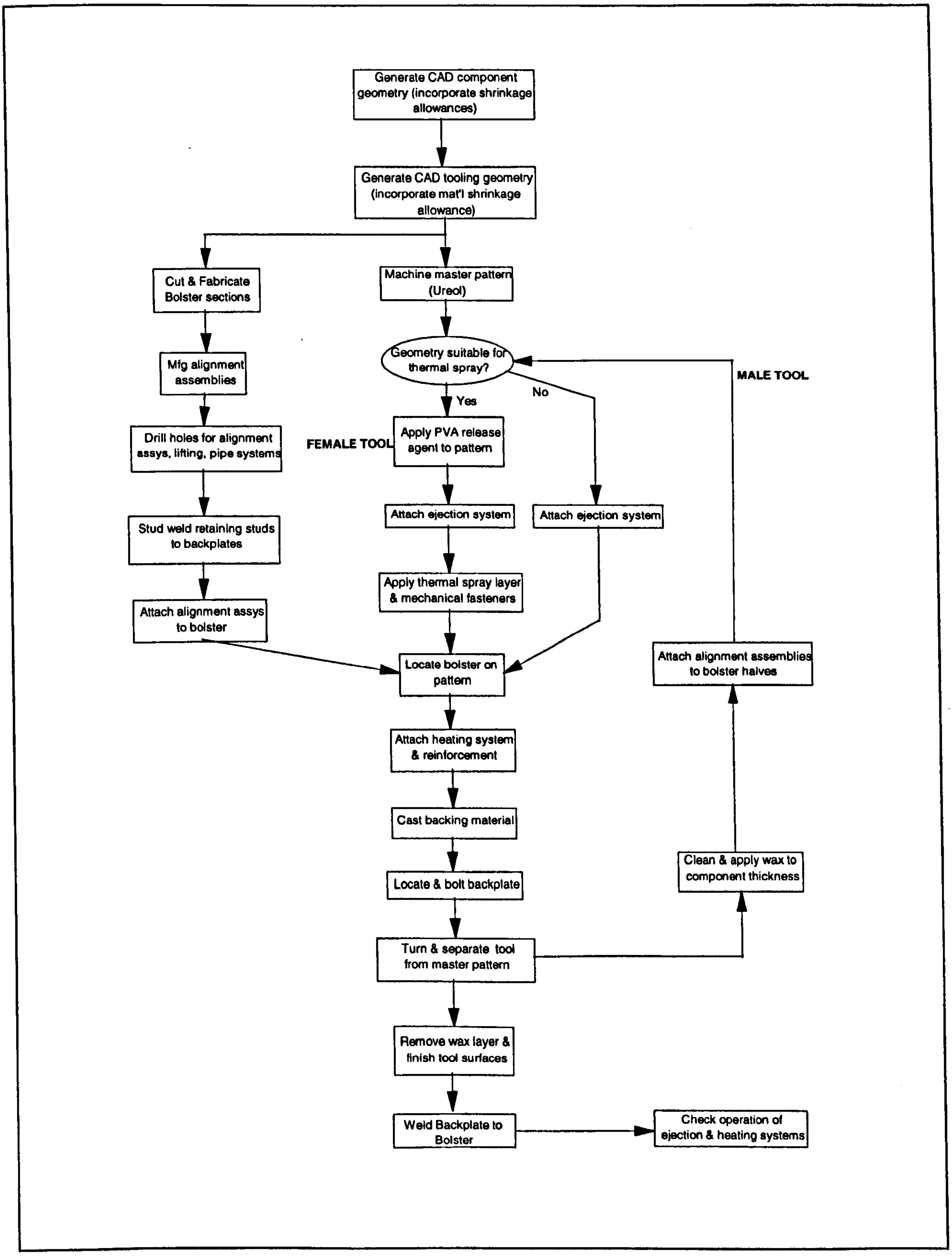

Figure 12 : Flow chart showing tooling manufacturing route

The project resulted in considerable cost savings on tooling manufacture, when compared to the conventional route for tooling production. This would normally be done by using machined aluminium tooling, in a cast iron bolster. The overall cost savings are detailed below - the figures shown are for the five sets of tooling:

Tooling Type	Total Cost	Total lead time
Machined Aluminium	£227K	36 weeks
Thermal Spraying	£82K	17 weeks
Total Saving	**£145K**	**19 weeks**

In addition to the considerable cost and lead time savings, a wealth of information was generated on the manufacture and use of thermal spray prototype tooling in the production of composite components. This is the first time that thermal spraying has been used as 'live' tooling for the compression moulding of GMT, and was an important step forward for Rover Group. A number of important conclusions were drawn from the work, which may be summarised as follows:

- Tooling design - although the tooling performed adequately for the required component volume, stresses due to moulding caused damage to the tools. In order to produce higher component volumes, the overall design philosophy for thermal sprayed tooling needs to accommodate the possibility of higher component volumes - this will necessitate the development of more robust tooling manufacturing techniques. Many possible improvements to the actual thermal spray shells were described in Section 3, but the overall repeatability of the process requires improvement. .
- Tooling handling/manipulation - The manufacture of the tooling exposed a number of problems with the way in which large tools like this are handled during the manufacturing process. Manipulation of the pattern during spraying operations, the spraying operation itself, and subsequent pattern handling, all proved to be problematic. The overall way in which the tools are manufactured needs to be revised, in order to maximise repeatability, and reduce risk.
- Thermal spray materials - The materials used for producing the thermal spray shells proved to be unsuitable for anything other than prototype volumes in the moulding environment

encountered. Future iterations need to build on research already undertaken in treating thermal spray surfaces [24], and extend the programme to ensure that thermal spray surfaces are suitable for higher component volumes. This may include the use of alternative thermal spray systems, such as HVOF.

- Thermal Spray Optimisation - The project highlighted a number of areas for improvement in the use of thermal spraying for shell production. This included restrictions in the process itself, pattern materials and backing materials which are used, and the physical act of spraying itself. In order to 'productionise' this type of tooling for large components, all of these areas must be fully addressed.
- Automation - The current thermal spray facility uses an operator for controlling the arc spray gun. For larger tools, operator fatigue becomes a significant problem. In addition, the sprayed shell's quality is dependent on the operator's experience, and variable results can reduce the tooling integrity. Automation of the spraying operation would allow large patterns to be sprayed more consistently reducing the variability due to operator error.

The project was innovative in a number of aspects, which may be summarised as follows:

- This was the first time that Rover Group had used thermal spray tooling for the production of GMT components. In addition, the overall size of the tooling presented considerable challenges (the largest tool was approximately $4m^2$ in projected area). This meant that the manufacture of this tooling required a new approach in terms of the logistics of tooling manufacture, as well as in the design and manufacture of the tooling itself.
- Although small test components had previously been produced using thermal spray tooling, this was the first time that thermal spray tooling had been exposed to a normal compression moulding environment. It was therefore necessary to determine an appropriate moulding regime, in order that the tooling would successfully produce the required component volumes. The tooling could not be treated in the same way as conventional tooling, as this would have resulted in irreparable damage to the tooling. This required some flexibility in terms of the moulding pressures, material placement, and other moulding parameters. The moulding conditions are described in detail in Appendix A of the portfolio document "Compression Moulding of the LCV Floor Assembly".

- In some cases, it proved impractical to use thermal spray tooling, due to the geometry restrictions of the components. It was therefore necessary to use cast CBC tools without any thermal spray face. It is believed that this is the first such use of CBC tooling for compression moulding of GMT, and required the development of surface protection for the Densit tools, to prevent damage during moulding.

Based on the success of this project, Rover have committed to investing in a thermal spray facility, solely for the production of large prototype tooling for moulding similar components. This will constitute a capital spend of over £100K, and is anticipated to save an estimated £2M from Rover's prototype tooling cost.

4.3 Personal Contribution

In addition to the overall benefits to Rover Group gained from the project, there were a number of innovative areas which arose from the project. I was personally responsible for the overall management of the tooling, from tooling design through to component moulding. This involved liaison between the customer team within Rover, a large number of sub-contract suppliers, the moulding company, as well as co-ordination of the tooling team. In addition, I was responsible for parts of the tooling manufacture, including all of the thermal spraying, much of the pattern preparation, and co-ordination of all manufacturing stages. The innovative areas which arose from the project may be summarised as follows:

- The development of a novel method for fixing thermal spray surfaces to backing materials, involving the use of oversprayed mechanical fixings - the optimum fixing type was found via a test programme. In addition, the use of a resin bond coat between a thermal spray layer and backing material is believed to be unique.
- The project highlighted a number of shortcomings with tooling design unique to thermal spraying. A number of tooling design modifications are suggested which would significantly improve tool life for any future projects - these findings could not have been made without the practical moulding knowledge gained with this type of tooling, and are unique to this project.
- The moulding conditions for prototype tooling are considerably different to those for production tooling. The project provides unique information on the moulding conditions required for this type of tooling/material combination, which will prove useful for future projects.

5.0 Further Work - Strategic Tooling Requirements for Moulding Composite Structures

5.1 Background

The compression moulding project described in the previous section clearly demonstrated that thermal spraying had much promise as a tooling production route. However, the project highlighted a number of problem areas which would require addressing, in order that the technique could be used repeatably. This was particularly the case in the production of the largest tool, which introduced a number of problems which had not previously been encountered. In order to overcome these problems, and in order to provide an assured development route for the technique, it was decided that a structured research path was required. The success of the projects described in previous sections led to a desire from several companies to fund further research into thermal spray tooling, particularly aimed at the production of large tooling for limited production runs. A proposal was therefore submitted under the Innovative Manufacturing Initiative (IMI) - Aerospace Sector, in conjunction with a number of partners. This application was successful, and became the Spraymould project. This is a 3 year project, which will provide a structured development route for large tooling. This section will provide a summary of the project, which effectively describes the further work required in this area.

The development of low cost tooling for moulding of composite structures, has been identified as a particularly strong requirement by the aerospace sector in general [25]. Component volumes are low (as few as 500 for a production run), and current tooling methods constitute an extremely high capital cost. Typical applications for tooling are in Resin Transfer Moulding (RTM), and also in autoclave applications, as shown in Figure 13. The tool face is made up of a thin layer of material, and backed up with an 'egg box' structure. This allows the tool to have a low thermal mass, improving the heat transfer to the tool, and thus reducing moulding cycle times. There is no need for a matched die set, as the component is formed under vacuum against the tool face. Higher pressure moulding operations such as RTM and compression moulding would require the use of a matched die set, which would normally be machined from solid billet.

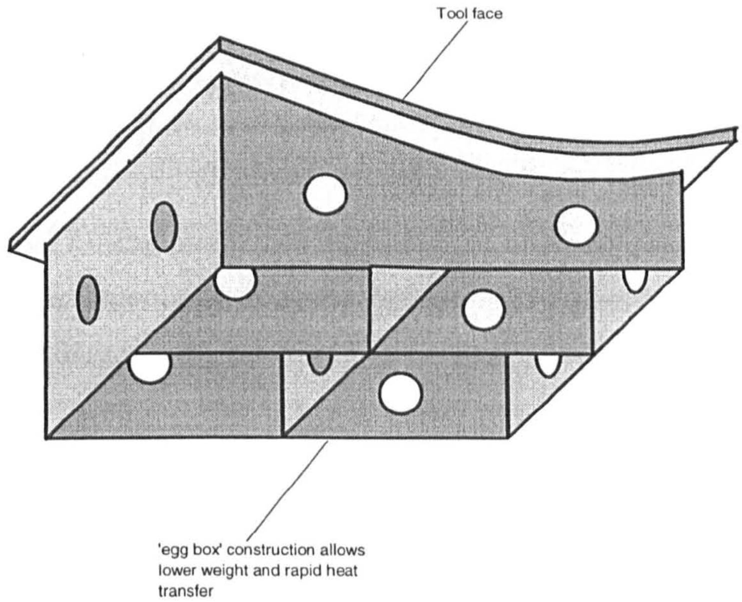

Figure 13 : Typical aerospace composite mould tool [26]

There are a number of materials available for the fabrication of tooling, but the most commonly used are aluminium, steel and Invar (36 or 42). Invar is a specialist tooling material, and is a low-carbon, austenitic steel alloy, with a high nickel content (36-42%). The material is primarily used because of its low CTE ($0.8\text{-}9\times10^{-5}$mm/mm/^{o}C) [26]. Each of the above materials has benefits and drawbacks, which are summarised in Table 5.

Material	Advantages	Disadvantages
Aluminium	Low Cost Easily Machined Good Thermal Conductivity Low Weight Easily Repaired	Unsuitable for compound curve parts due to high CTE Unsuitable for use above 200°C or consolidation of thermoplastics
Steel	High Durability Weldable (use in fabrications) Easily Repaired Good Vacuum Integrity	High Cost Difficult to form complex shapes High Weight
Invar	Low CTE High durability Weldable Easily Repaired Good Vacuum Integrity	Very High Cost Low Thermal Conductivity High weight Difficult to weld Vacuum fittings must also be Invar to prevent leaks

Table 5: Advantages & disadvantages of materials for aerospace tooling

The current methods for tooling production are extremely expensive and time consuming; it is not uncommon for tooling to cost in excess of £1M, and have a lead time of 6 months. It was felt that thermal spraying could provide an ideal solution for aerospace tooling. Initial work by Milovich et al had demonstrated the potential of using arc sprayed Invar as a tooling material - however, this work had only been demonstrated in small samples [16]. Discussion with the industrial partners revealed that existing research programmes required carbon fibre composite test components of up to 3m x 2m in projected area; it was felt that the Spraymould programme would provide an ideal opportunity to develop tooling capable of moulding components of this size.

5.2 Programme of Work

Previous sections have outlined a requirement for the production of large scale tooling for the moulding of composite structures. This tooling must be produced at significantly reduced cost and lead time (compared to conventional tooling methods), without sacrificing accuracy, durability or performance. The compression moulding project provided evidence that thermal spraying could be used to produce tooling for relatively high pressure moulding applications, with a 60% cost saving and a 50% lead time saving over machined aluminium *prototype* tooling. The aim of the IMI Spraymould project is to extend the life of this tooling, making it suitable for low volume production, for both aerospace and automotive sectors.

In order to provide a means of producing repeatable tooling shells, the limitations of the tooling used for the compression moulding project must be eliminated. The programme of work will concentrate on these areas, with specific research designed to optimise thermal sprayed tooling for composite moulding applications. In order to provide a comparison, the resulting tools will be evaluated against existing tooling technologies. Thermal sprayed tools must be competitive with these technologies, in order to provide a viable solution to the problems of moulding large composite components. The future performance of the tooling will be determined by a number of key work areas. Subsequent sections will describe these areas, along with the need for the work.

5.2.1 Thermal Spray Surfaces & Backing Materials

The most common system for producing thermal spray surfaces for thermal spray tooling is electric arc spraying. Whilst this has the advantage of having a high deposition rate, coupled with low cost [2], the surfaces produced typically include porosity of between 15-20%. The surface is prone to rapid degradation under moulding conditions, due to the ingress of polymer into porous areas. An important part of the project will be to develop surface treatments which improve the quality of the sprayed tool face, eliminating porosity and thus extending the tool life. A T Poeton will have prime responsibility for developing the treatments, which may include plating, infiltration and other costing techniques. These will then be evaluated to determine the optimum surface treatment for a given moulding process.

In addition to this, other methods of thermal spraying will be evaluated for tooling production. Although the arc spray system is currently the most widely used, it is only suitable for spraying low melting point materials (one exception to this is the Stress-Free Coating system, as developed by Spray Forming Developments Ltd). The project will investigate the use of other spraying technologies, in particular High Velocity Oxy-Fuel (HVOF). Originally developed for applying thermal barrier coatings to aerospace components, this system produces high integrity coatings in a variety of materials, with very low porosity (as low as 1%). The project will evaluate this system in terms of materials and spray parameters, as a possible route for tool shell production. This work will concentrate particularly on the ability to spray steels, and specialist aerospace tooling materials such as Invar.

Another area for research is that of backing materials for the thermal spray shell. Although the compression mould tooling described in the previous section was successful, the Densit backing material proved exceptionally expensive, making up virtually 50% of the overall consumable cost. In addition, the material did not adhere well to thermal spray surfaces, entailing the use of mechanical fixings, which increased the overall complexity of the tooling. The project will evaluate backing materials in terms of tooling performance (mechanical strength, thermal conductivity etc.), cost and ease of use. This will provide a guide to the best backing material for a given moulding application - this will particularly be the case for autoclave tooling, where various backing options will be explored.

5.2.2 Component & Tool Design

Although a general guide has been produced for the design and manufacture of thermal spray tooling (see 'Design and Manufacturing Criteria for Metal Spray Tooling - portfolio document), this does not provide specific guidelines for the design of components of this size, or for composite moulding tooling. The compression moulding project showed that the design of such tooling is not a simple matter, and requires specialist knowledge to design optimised tooling. Spraymould will therefore develop a comprehensive design philosophy for thermal spray tooling, eliminating many of the mistakes which became apparent during the project. This should further extend tool life, by the elimination of unsuitable design features, giving higher mechanical strength and improved wear characteristics - this will also influence component design.

It is intended that the design philosophy will be produced in the form of a set of design rules, which may be used by the industrial partners to programme a Knowledge Based System for component and tooling design. This will allow the 'customer' partners to correctly define component and tooling design, without requiring specific experience of thermal spray tooling. This will also mean that the tooling design will be available in CAD format, which will form an integral part of the system automation strategy (see Section 5.2.5).

5.2.3 Pattern Materials

Although a wide variety of pattern materials have been used for thermal spraying, there is currently little understanding of the best pattern material for large tooling. The factors to be assessed must include cost, production requirements, accuracy, thermal stability and surface finish. The programme will assess a number of potential pattern materials using these criteria, allowing selection of the optimum material.

The use of pattern materials becomes a critical issue when using the HVOF spray system. Whilst arc sprayed materials may be deposited onto a wide variety of pattern materials, the HVOF system has a high temperature, high pressure flame, which causes most pattern materials to degrade and/or melt. Although sacrificial patterns using a lower melting point thermal sprayed metal have been tried [13], this will probably prove impractical, particularly in the case of large tools. An important aspect of the research will therefore be finding a suitable pattern material for use with HVOF, in order to produce high integrity shells in an accurate and cost-effective manner. Another aspect of pattern production will be the manipulation of the pattern for spraying. During the compression moulding project, it was found that moving the pattern was cumbersome and difficult, particularly in the confined space of the thermal spray booth. It is probable that future projects will require a specially-designed transport system, allowing easy movement of the pattern, as well as variable positioning for spraying various areas of the pattern.

5.2.4 Hardware Development

Although the use of both arc spraying and HVOF are well-proven for a number of applications, the production of tooling shells may require some development of the thermal spraying hardware. In particular, thermal spraying is a 'line of sight' process - this means that the thermal spray particles are emitted from the gun in a straight line. The minimum angle of attack for particles is 45° when hitting the substrate (see Section 1). Below this angle, a weakened coating will result. Certain features, such as deep pockets, are currently impractical for spraying, as the particle jet cannot produce a good coating at the base of the pocket. The aim of this work will be to modify the thermal spray hardware to allow access to deep features.

5.2.5 Process Automation & Simulation

In its current state, thermal spraying has been proven as a method for the production of large prototype tooling, particularly for compression moulding. However, some of the major problems experienced with the tooling arose from variability of the sprayed shell, and also overheating of the pattern material due to excessive dwell time when spraying. The current method of production relies on manually spraying the shell, which introduces variability to the process - the production of large tool shells will inevitably have an adverse effect on the operator in terms of fatigue. Although variability is mostly acceptable for smaller tools, the production of large tools requires a wholly different approach. When it is considered that a single tool half for a tool 3m x 2m at a thickness of 3mm, may comprise up to 80kg of sprayed material, it is clear that operator fatigue will reduce the effectiveness of manual spraying. For this reason, it was decided that the only realistic route forward for the production of large tools was through automation - specifically, the use of a robot for the automated thermal spraying of tool shells.

The first important aspect of the system automation is development of an *off-line programming* capability. There are a number of different robotic simulation packages available, which allow the user to define a computer model of the robotic cell, and simulate the movement and other actions of the robot. This simulation is then post-processed into the robot language, allowing a programme for the robot to be defined. This principal advantage in this situation is simple; the vast majority of aerospace components are now defined as CAD models. If the tooling is also defined as a CAD model, the geometry may be incorporated directly into the simulation package (these are specifically designed to accept data from CAD formats). Thus the robot path may be defined by the simulation package, at the same time that the tool master pattern is being generated (from the same CAD information). This means that the robot programming time may be reduced, and also eliminates the manual programming of the robot. The off-line programming capability will improve the overall flexibility of the system, and allow total integration from the tooling design stage - simple data transfer will place the tooling geometry directly into the robot cell simulation, which may be used to directly produce a robot programme.

The next major consideration for the automation of the system was the physical layout of the spraying cell itself. The current spray booth is capable of accommodating patterns up to approximately 2.5m x 2m. However, this is under manual spraying conditions, where the movement of the spray gun is virtually unlimited. The spraying of larger patterns would require extension of the spray booth, even for manual spraying. For automation purposes, the spraying 'reach' of a robot is likely to be more restricted. In order to spray a large pattern, it is likely that the shell will have to be sprayed in sections. The alternative to this is to install a large robot, capable of spraying the whole 3m x 2m tool surface. However, one of the objectives of this programme is to demonstrate the scaleability of the process up to much larger tools (up to 14m for a whole wing skin tool).

Another important aspect of the automation of the spraying facility will be the control of thermal input into the pattern during the spraying operation. This is currently accomplished manually, and is thus dependent on operator experience. Overheating of the thermal sprayed surface can lead to damage to the pattern, and in some cases distortion of the shell due to thermal stresses. To try and eliminate overheating, the system will make use of thermal imaging equipment to monitor the thermal input at the sprayed surface. This will be linked in to the robot control, and will enable a speeding up of the robot arm, in a situation where the thermal input becomes potentially damaging. This should minimise distortion and pattern damage, improving the dimensional accuracy and surface finish of sprayed tool shells.

In order to provide accurate and repeatable spraying of the pattern, it will be necessary to locate the pattern in the booth. As mentioned previously, handling patterns of this size proved problematic during the compression moulding project. For future use, it is anticipated that a custom-built trolley will be required for pattern manipulation. The system described in previous paragraphs will provide an ability to spray master patterns in a repeatable manner, and allow the accommodation of a variety of patterns sizes. However, another important consideration is the actual route used for the production of patterns, and the way in which the sprayed shell is used. This will become particularly important when using HVOF spraying for tool shells. The use of this system will require a total revision of pattern materials, pattern production route, and backing systems.

5.3 Personal Contribution

This programme is designed to provide industrially-focused research and development, specifically aimed at improving the performance of large tooling produced by thermal spraying. I was responsible for defining the technical package for the project, as well as establishing the requirements of the partner companies, determining the level of financial and technical contribution from each partner, and defining the overall value of the three year program. The innovation within the project centres around the design of a system specifically aimed at the production of large tooling. The compression moulding project described previously, highlighted a number of problems specific to the production of such tooling. Whilst this was applicable to automotive applications, I was also able to foresee the requirements of the aerospace industry for such tooling. I therefore approached the aerospace companies with an outline proposal, describing the potential benefits. The interest generated by the proposal led to a full submission under the aerospace sector of the IMI. The proposal was successful, and the programme is currently under way. Although I was responsible for the generation of the proposal, my personal contact with the project is over - hence the project forming the 'further work' section of the portfolio.

6.0 Conclusions

The portfolio as a whole has concentrated on the development of thermal spraying as a viable route for the production of low cost tooling for prototype or limited production. The work has demonstrated many of the limitations of thermal spraying as a tooling technique, but has also demonstrated the considerable benefits which can be gained, in terms of cost and lead time savings. This section will summarise what has been learned from the work, and also highlight the achievements within the portfolio.

A large section of the work was devoted to quantifying the limitations of thermal spray surfaces, and to overcoming these limitations in order to improve overall performance. This was achieved through an experimental programme looking at a variety of properties of thermal spray surfaces. A number of novel techniques were developed, which showed clear benefits in the performance of thermal spray surfaces. These are summarised below:

- The development of a route for the production of tool shells using HVOF spraying. HVOF has the capability to produce extremely high quality coatings, but has never previously been used as a method for tooling production, as there has been no viable route for pattern production. An extensive investigation into pattern materials resulted in a method for pattern production using castable ceramics, allowing HVOF sprayed surfaces to be produced accurately without damage to the pattern material. Stainless steel samples sprayed using HVOF were shown to provide significant performance benefits when compared to arc sprayed samples, albeit at a higher cost.
- The work demonstrated that arc-sprayed coatings such as zinc and kirksite showed significant degradation under thermal cycling, but that HVOF coatings were affected to a far lesser extent. This is significant, as most moulding operations involve thermal cycling - it was concluded that in order to improve tooling life, it would be necessary to move away from low-cost coatings such as zinc, and further develop HVOF as a tooling production technique.

- The work clearly showed the potential of using 'hybrid' coatings, i.e. a combination of electric arc spraying and HVOF. This was the first time that a combination of spray technologies had been combined to produce a hybrid coating for a tooling application. Hybrid coatings allow a low cost coating to be produced (arc spray), but with a thin, higher quality coating (HVOF) to provide improved performance in terms of wear and vacuum integrity. Even a thin coating of HVOF-sprayed stainless steel was shown to provide significant performance improvements when applied to low-cost zinc shells.
- The work demonstrated the potential of thermal spraying to be used as a route for the production of autoclave tooling, for the production of composite components. Thermal spraying could have significant benefits in this area, as the mechanical stresses on the tooling are low when compared to other moulding processes such as compression moulding. However, the porous nature of thermal spray tooling would limit the ability of the tooling to hold a vacuum. The work developed a route which would allow the tooling to hold vacuum, using a combination of backing materials and post-treatment, to a point where thermal sprayed samples had comparable performance to current, established tooling surfaces. This was significant, as thermal spraying has considerable potential for increasing tool life, when compared to current composite tools, which even in low volume aerospace applications, can require replacement tooling sets to be produced in the duration of a production run.

The next phase of the portfolio built on the experimental programme described previously, via a demonstration of the potential of thermal spraying as a route for tooling production. This was accomplished by the manufacture of a suite of 5 tools for Rover Group, using thermal spraying. This was an important project, as the moulding application was new for Rover Group, and required validation through the use of low cost tooling. The project generated a number of achievements, which are summarised below:

- The work generated the largest tool ever produced using thermal spraying, for the compression moulding of Glass Mat Thermoplastic (GMT). The tool was approximately 4m^2, and weighed in excess of 3 tonnes. This was the first time that thermal spraying had been used for such an application, and the project provided a unique opportunity to demonstrate the overall potential of thermal spraying. The project produced considerable cost and lead time savings over conventional prototype tooling (£145K and 19 weeks saved), and successfully produced the required number of component assemblies.

- The forces involved in the moulding operation necessitated the use of a backing material with extremely high compressive strength. Densit was selected for this reason. However, this material reacts with zinc due to its alkaline nature, and also does not adhere well to thermal spray surfaces. It was therefore necessary during the course of the project to develop a novel fixing method between thermal spray surface and backing material, which provided both a strong mechanical key, but also formed a barrier between the two materials. The solution was a large number of mechanical fixings, which were actually incorporated into the sprayed layer. A layer of epoxy was then applied to the thermal spray surface, which was capable of curing in a moist environment. This epoxy provided both a barrier and a bond between the Densit and the thermal spray surface. This fixing method allowed two otherwise incompatible materials to be used, both of which were ideal for the particular tooling application.
- This project was the first time that compression moulding tooling had been manufactured using thermal spraying. The component moulding phase of the project was important in showing how such tooling performed in a compression moulding situation. The mould trials generated a wealth of information concerning the performance of the tooling. This included changes in design unique to thermal spray tooling, changes in material processing to reduce the risk of damage to the tooling, and changes in the actual moulding parameters to suit the tooling. The project was unique in this respect, as many of the problems generated were inherently due to the tooling size. Tests under laboratory conditions would not necessarily have highlighted many of the issues which arose, and the application of the tooling in an 'industrial' environment was therefore extremely valuable.

The project described above provided clear proof of the potential of thermal spraying as a tooling production technique. It also demonstrated a number of shortcomings with the technology, particularly relevant to the production of large tooling. It was therefore decided that the most appropriate course of action would be to define a further programme of work to address these shortcomings, to enable thermal spraying to become a more viable manufacturing route for tooling. The final section of the portfolio sets out a research programme to address the problems encountered during the compression moulding project, with the ultimate aim of automating the process of thermal spray tooling production. The project is building on the results from both the experimental programme, and the technology demonstrator, concentrating on producing large tooling particularly aimed at the aerospace industry. The work already carried out has formed the basis of the project, which is driven by a number of industrial partners. The Spraymould project has now been running for two years, with a robotic spraying cell now installed at Warwick University.

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Appendix A - Summary of Portfolio Documents

A Review of Rapid Tooling Technologies - This is a basic literature review, and contains an overview of Rapid Prototyping & Tooling, as well as a more detailed review of thermal spray technologies, and tooling production techniques.

Criteria for Design and Manufacture of Metal Spray Tooling - This document provides a basic guide for the design and manufacture of thermal spray tooling. The document is based on empirical research, and describes some of the constraints on tooling imposed by thermal spraying.

Introduction to Metal Spray Tooling - This was a paper providing an overview of thermal spray tooling, presented at the 28th ISATA in Stuttgart, 18-22nd September 1995.

Physical Characteristics of Thermal Spray Tooling - This was a paper based on research into thermal spray surfaces, presented at the 1st National Conference on Rapid Prototyping & Tooling Research, Buckinghamshire, 6-7th November 1995 ISBN 085298 9822, p249-256.

Physical Performance of Thermal Spray Tooling - This document provides the majority of the research content within the portfolio, and consists of a broad-based investigation into thermal spray surfaces and their physical properties. Included is a programme on the use of HVOF spraying as a medium for tooling production.

Compression Moulding of a Floor Assembly - This was a technology demonstrator programme carried out for Rover Group, in order to demonstrate the benefits of thermal spray tooling. The programme was confidential, but involved the production of large thermal spray tooling for compression moulding of Glass Mat Thermoplastic (GMT)

Strategic Requirements for Moulding Composite Structures - This document forms the 'further work' section of the portfolio. The document has as its basis a successful IMI project submission, to carry out a 3 year development programme, specifically aimed at producing large thermal spray tooling for the aerospace industry.