3D sand printing for automotive mass production applications

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Abstract: Additive manufacturing (AM) of metallic products is seen by many to be commercially viable for only small and highly complex components, manufactured with difficult to machine materials using heat sintering process. In the automotive manufacturing sector, metal hard tooling is often required to produce mass produced components, and the tools are typically bespoke, large in size, inflexible and complex. Conventionally these tools have either been machined from solid billets or near-net-shape cast and then machined to get final size. Rapid casting technologies (RCT) use AM 3D sand printing process to manufacture sand mould tools used to create the production tooling. Adopters of this technology can achieve an increasingly agile and robust production process, RCT can also rewrite the design hand book for casting design. The research findings demonstrate that RCT can be successfully applied within the automotive industry, achieving considerable cost and time savings whilst improving quality and product flexibility.

Author: Please check the edit(s) made in the sentence "In the automotive manufacturing sector … cast and then machined to get final size" and correct if necessary.

Keywords: rapid casting technology; rapid tooling; 3D sand printing; sand casting.

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Biographical notes: Philip M. Hackney is a senior member of the Department of Mechanical and Construction Engineering management team, managing several programmes both at Northumbria and Validated programmes at other HEI institutions worldwide. Hackney first started researching rapid prototyping in 1996, with the development of casting tools from the LOM process and later using the ZCast process awarded him a PhD in 2007, with over 30 published papers and a research group of 6 PhD students under his supervision. His current research interests include shop floor scheduling using genetic algorithms, additive manufacturing of polyurethane foams and sand printing of AM.

Richard Wooldridge is currently a PT PhD Student at Northumbria University, following completing an MSc in Advanced Manufacturing Engineering at Loughborough University. He has developed and managed a major automotive Rapid Product Development Centre, at the forefront of commercialisation of industrial applications of AM, for over a decade.

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1 Introduction

1.1 Traditional foundry moulds compared to printed moulds

In the aerospace industries where weight and high temperature resistance are critical, then thermal sintering processes can be justified for metallic parts; however, in the automotive production sector, mass production is the key driver rather than part weight. To date, additive manufacturing applied to metal rapid casting tooling applications has received little research focus or made significant industrial impact, other than in the early product development stages for prototypes and small-size polymer mould tooling (Matta, Ranga Raju and Suman, 2015).

The traditional method of sand casting uses conventional patterns and core boxes to produce the sand mould tools, where molten metal is poured and solidified. These mould pattern tools can be expensive and take approximately 8–12 weeks to produce; however, once produced, the productivity of traditional sand mould tooling can be very high, producing each component at relatively low tooling cost per part (http://thelibraryofmanufacturing.com/metalcasting_basics.html).

3D sand printed mould tools however are high in cost, in terms of cost of production of each sand mould tool, in comparison with traditional methods, and are relatively low in output with regards of speed of production (Hart and Taylor, 1996).

This causes three issues:

1 There is a break-even point of traditional vs. printed moulds on a cost/time basis.

2 The foundry must adopt a different mindset when using printed moulds rather than traditional moulds.

3 Very few foundries have access directly to their own 3D sand moulding production equipment, they source their sand tools from bureaus or machine manufacturers, resulting in a time delay between sand mould production and pouring. The sand moulds also have different characteristics to normal mould production techniques, such as high binder content and poor permeability for gas venting (Almaghariz et al., 2016).

Experienced foundries that use 3D printed moulds generally consider the break-even point financially at approximately 30–50 castings (Levy, Schindel and Kruth, 2003) based on a typical for general automotive castings such as cylinder heads, manifolds and engine blocks. This however can vary wildly depending upon the complexity of the part and does not take into consideration the time to market benefits that printed moulds can bring.

Three approaches can be considered for time vs. financial constraints of individual casting projects, in preferred order:

1 Project completely sand printed.

2 Hybrid version - large simple parts of mould produced conventionally complex parts using sand printing.

3 First off completely sand printed until conventional tooling comes on line.

When a foundry uses conventional tooling, the first off parts will often be considered scrap, these castings are often used to trial out the running system, looking for improvements, etc. The foundry will want to minimise the running system and other efficiencies to reduce costs. The moulds and metal parts will be recycled back into the foundry reclamation system, and after modifications are made, further parts will be produced, and the cycle repeated until the optimum settings have been found. This approach has been adopted due to the low cost of mould tool production, Figure 1 shows the production of sand casting.

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Figure 1 High volume of traditional mould making line and large mould assembly

When using a sand printed mould, a completely different attitude needs to be considered, each sand mould is 'precious' in as much as it has a higher value and takes time to produce and ship to the foundry. Therefore, mould and running system design is prepared to a much higher standard. Mould flow analysis often being used to ensure that the running system is optimised, and the design and checking of the mould are carried out at every stage of its production and assembly in the foundry plant, similar for traditionally produced complex high value castings.

The moulds are designed to be 'right first time' to justify the higher cost of the design and simulation of the mould and runner system and extra time to assemble the mould. This is much more expedient than running the risk of failure, and the mould having to be rebuilt and shipped again. Mould assembly as shown in Figure 1 shows the size and complexity of the mould and assembly.

1.2 Foundry issues with printed cores compared to traditional mould packs

Author: Please check the edit(s) made in the sentence "When additive manufactured … or for low-grade applications" and correct fi necessary.

When additive manufactured moulds and cores were first produced, they were considered for 'experimental' or for low-grade applications. This was mainly due to the production method - i.e. selective laser sintered (SLS) sintered cores (Wang et al., 2003). They had very high resin content and this would cause high production rates of gases within the moulds resulting in poor quality castings - especially for aluminium, where the metal is susceptible to gas porosity (Snelling et al., 2013; Druschitz, Seals and Snelling, 2013). Volume output from the thermal processes was also slow, and build envelopes small, limiting the suitability of this technology for casting industry. The process also required post-processing and curing of the moulds, leading to potential inaccuracies due to

Author: Please check sentence "Volume output from the thermal … for casting industry" for clarity.

warping and higher scrap rates due to cores breaking in the process (Budding and Vaneker, 2013).

With the introduction of sand printed moulds using Furan resin bonding agents, and its use on larger machines, many of the negatives of SLS sand bonding have been eliminated. The 3D sand printing process now has a large build volume envelope, parts are very accurate; however, one area for improvement remains that of resin content (Casting Media Alternatives) of the sand tools produced.

With the Furan process, the base sand grains are coated with activator and then selectively printed onto the binder. These chemicals are not 100% utilised in the bonding process, leaving 'uncured' resins within the parts. This is also aggravated by the higher resin content of the cores due to the printing process, as opposed to conventional processes (Hussein, Ayof and Mohamed Sokri, 2013).

The machine manufacturers are all developing alternative sand and binder combinations to overcome some of the COSHH issues with Furan binder and the additional gas generation produced by the extra binder. Whilst none of these are in mainstream use, they may well improve many of the issues found with Furan bonded sand and could form an important area of research for the future (Andrew Busby).

1.3 The need for process improvement for printed mould tools

Foundries have found that when pouring printed moulds, excessive fumes are expelled from the mould pack. This can only come from two sources, resin content or moisture in the mould (Hussein, Ayof and Mohamed Sokri, 2013).

When parts are produced, they are built in a clean, dry environment, once cleaned, they are placed in the purpose of shipping boxes, covered over polythene and shipped to the foundry by courier; however, foundries are notorious for poor conditions in terms of air conditioning or control of air temperature and humidity; also it is not known under what conditions the moulds are stored prior to use. There is the possibility that moisture is absorbed into the moulds in transport or storage at the foundry.

Whatever the cause, the most experienced foundries will bake the moulds for 3–4 h at 70°C to 'dry them out to remove moisture'. This appears to greatly reduce the gassing of the mould; however, it has not been fully analysed by the foundries to substantiate this technique.

Another technique used by the foundries is to produce 'gas ports' in the mould - holes running down the middle of cores and vented out to the outside of the mould. This allows the gas to easily flow away and out of the mould.

A further technique is to apply a core wash to the critical surfaces of the mould - for example, an inlet port in a cylinder head. The metal would flow all around the 'finger' of sand. If covered with core wash, sealing the surface, gas will find its way out through the sand, if aided also by gas ports (Bulan et al., 2008).

However great consideration must be made regarding the use of core wash, as if applied to too many surfaces, then it can have the opposite effect by trapping gas within the mould, which will often find its way back into the mould, causing faults.

1.4 Why the process needs to be improved?

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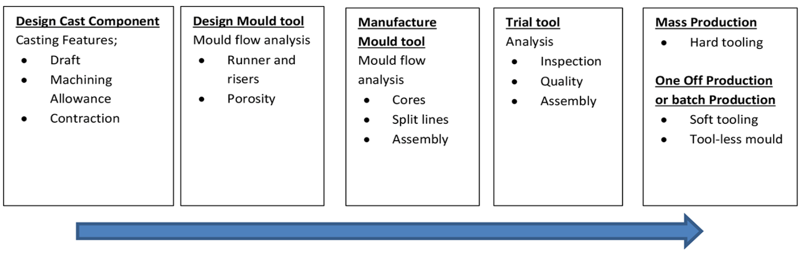
Sand casting is the most common (90%) production method for metal castings (Shi and Wang, 2010), it is used extensively in the automotive industry to produce structurally strong net shape parts, and requiring minimal machining post-cast machining. Aluminium alloys are used extensively for weight and cost reasons, with the purpose to manufacture lightweight and fuel-efficient vehicles. One automotive manufacture alone currently produces 1,215,000 sand castings per year for powertrain use to support the production of 81,000 vehicle sales per annum.

Traditionally this process requires expensive inflexible tooling with large lead times, costing £10k to £100k and taking many months to manufacture and test before release for production.

Additive manufacturing (AM) is a relative new manufacturing process in the global industrial market, the process has several unique characteristics. The principle of manufacturing using AM is very simple, it begins with the digital design created by 3D computer-aided design which is translated into a simple polygon files, sliced along a flat 2D plane, with each slice fabricated on top of the previous 2D manufactured physical slice or layer. These two combinations give the designer new product design opportunities, rather than limiting designs to traditional production constraints.

The ability to produce rapid bespoke moulds that can be used with traditional production metal casting techniques can provide the user with key commercial and strategic advantages (Krouth, 2002). It supports the capacity to build products without tools, generating new design freedoms, production and market growth opportunities, otherwise not permitted with traditional sand casting manufacturing systems (Figure

Figure 2 Conventional casting process flow chart (see online version for colours)



1.5 Properties of sand pattern materials

The types of sand can vary considerably and are dependent upon the location of source. Sand is defined as rock particles that range in size diameter from 0.0625 to 2 mm. The sand is mixed with a binder such as clay or in production a Furan binder and activator. Furan binder systems account for approximately 38% of the UK chemical binder market. Furan is a popular binder system since it is easy to control, having generally the lowest material costs, excellent strength with low addition levels and a high mechanically reclaimed sand reuse level (Andrew Busby).

Sand quality greatly affects casting quality and required to have the following characteristics:

- **Strength:** The ability of the sand to maintain its shape once formed.
- **Permeability:** The ability of gas to pass through the sand. Gas porosity found in castings is reduced by having higher permeability; also better finishing of surface is

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gained by having lower permeability. It is determined by the sand grain's shape, size and bond area.

- **Thermal stability:** The ability of resisting damage by heat such as cracking and distortion.
- **Collapsibility:** The sand's ability to collapse or compress during casting solidification. In the mould, castings that cannot shrink freely may result in casting cracks or distortion (Parkes, 1971).
- **Reusability:** The sand's ability to be recycled for future use.

1.5.1 ExOne 3D sand printing process

Two commercially available 3D sand printing systems are supplied by VoxelJet and ExOne, both use the MIT print technology and based in Germany. The ExOne 3D sand printing process (3DSP) can be used to create a core or mould through the rapid casting technology (RCT) method and will be used in this project.

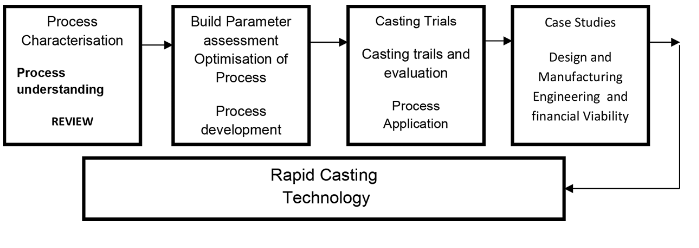
The 3D sand print (3DSP) process is a cold process, a deposition head uses a 100–150-mm-wide multi-jet print head travelling at 60–80 mm/s to deposit microdroplets of binder to sand (mixed with activator) in 0.28–0.5-mm-thick layers, each layer taking 40–60 s to produce each layer of the sand mould tool. The process utilises traditional sand casting materials of sand activator and furan binder to bond the silica sand grains.

The build deposition rate of 60–85,000 cm^3/h or 96 kg/h is achieved (http://www.exone.com/en/materialization/what-is-digital-part-materialization/sand) in a near skip size (1.8 × 1.0 × 0.7 m) build chamber; the industrial scale sand build chamber has been developed on rails to enable quick change over and transportation to the offline depowdering station. Post-processing comprises manually vacuuming and recycling of the unbonded sand, the patterns are then ready for dispatch to casting by traditional techniques in the foundry. The lower gas content allows the system to be readily used for high-end use automotive components such as cylinder heads.

1.6 Experimentation

The investigation focused upon the requirements of the casting company when manufacturing a sand mould, these parameters were then used to create rating tables to enable the selection of 3DSP process parameters. These parameters where then applied to manufacture a complex cast turbo charger casing. The process of the investigation is shown in Figure 3

Figure 3 Research experimental stages



Stage 1 - established from casting company's desired sand pattern properties, using a set of trials establish operating parameters to achieve the casting company's requirements. This was achieved by holding face-to-face meetings with the production team within two casting companies.

Stage 2 - Run a series of tests, under combinations of resolution, binder and actuator levels and repeated three times for consistency and robustness of data generated chosen set points shown in Table 1 based on process operational experience. Tests were carried out to investigate:

- Dimensional accuracy of the tensile test dumb bells, cylinders and geometric features.
- Material properties.
- Tensile tests of the tensile test dumb bars.
- Compression tests of cylinders.
- Burn out test to establish rigidity at elevated temperatures.
- Impact strength.
- Permeability.

Table 1 Fourteen trail sample settings

Sample no	*Print resolution mm*	*Binder %*	*Z-Step mm*
1	0.090	10%	0.30
2	0.140	–40%	0.30
3	0.080	20%	0.30
4	0.120	–20%	0.30
5	0.080	20%	0.30
6	0.100	Standard%	0.30
7	0.130	–30%	0.30
8	0.110	–10%	0.30
9	0.090	10%	0.28
10	0.110	–10%	0.28
11	0.140	–40%	0.28
12	0.120	–20%	0.28
13	0.100	Standard%	0.28
14	0.130	–30%	0.28

Stage 3 - generate a parameter selection matrix based on input from Stage 1 and the results of Stage 2 experiments.

Stage 4 - Casting trail of aluminium turbo charger casing, using the developed operating parameter data from Stage 3, these where analysed for geometric accuracy and metallurgical evaluated for casting defects.

The Stage 2 build comprised three test pieces, the ISO standard ISO/CD 6892-1. Tensile test bars shown in Figure 3, positioned in X and Y directions, a compression and permeability test cylinder Φ40-mm by 50-mm deep and a detailed test piece and built over a period of 20 days.

The ratio of binder, resolution and Z-step were controlled as per Table 1 with the activator constant at 0.32%, standard refers to manufacture recommended setting and current operational setting.

Stage 5 - Turbocharger test component

Three turbocharger body castings were manufactured in aluminium for all four box settings three times on the ExOne machine totalling 12 parts for experimentation. This requires moulds and cores being printed for each box setting subsequently followed by casting and heat treatment of the turbo parts. Views of the turbocharger part as shown in Figure 3.

Two castings from each box settings were sent to Exova (UK) ltd for destructive and non-destructive testing (NDT). The inspection was conducted to ASTM E155 standard:

- Tensile test ISO 6892-1:2009 A.133.
- Micro examination - ASTM E122:2010.
- Micro examination - 200× and 800× magnification.
- Hardness testing - BSEN.ISO 6506-1:2005 - Brinell hardness 1000 kgf.

1.7 Results

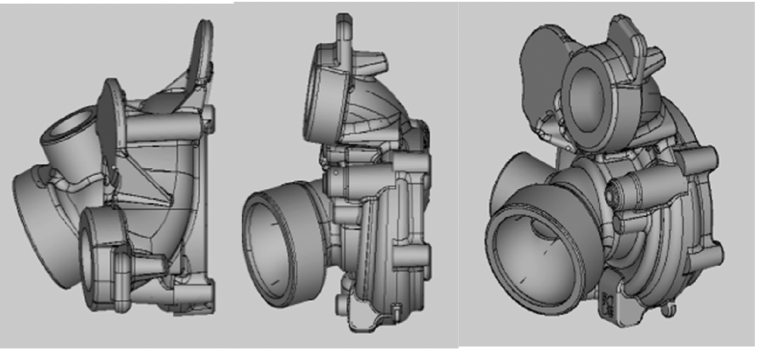
Stage 1 - the output from the discussion with the casting companies regarding the mould feature ranking is seen in Table 2, with one least important and five most important features. When they was a difference in opinion, an average value was used (rounded up). Compression strength and dimensional accuracy are the most important parameters followed by rigidity (strain), impact and permeability to degas the moulds.

Table 2 Mould feature ranking

Compression	5
Tensile	2
Strain	3
Impact	3
Permeability	3
Mass	1
Dimensions	4
Surface roughness	2

Stage 2 - the samples from the 14 tests were evaluated, cylinder compression test results shown in Figure 4.

Figure 4 Turbocharger casing



Stage 3 - The results were collated from five results from every sample test. A Table 3 was developed to show which box had the best settings, using a scoring system, where 5 was the best result and the 1 was the lowest.

Table 3 Top 5 results of each experiment

Box	Compression	Tensile Stress X	Tensile Stress Y	Strain X	Strain Y	Impact	Permeability	Mass	Dimension X	Dimension Y	Dimension Z	Surface Roughness
1	1	5	3				4				5	
2				4	5							
3	5	4	5			4		5	4	5	4	
4							3					
5	3	3	2			5	5					
6			1			1						
7				1	1							
8						2	2					5
9		2	4			3		3	1	2	1	2
10	4											
11				5	3			2	3	3	2	1
12				3	4					1		4
13	2	1						4	5	4	3	
14				2	2		1	1	2			3

Once the ratings for developed for each experiment, another table was constructed using the figures from the previous table and multiplying by the ratings as shown in Table 3 to form the overall scoring matrix shown in Table 4. From Table 4, it is clearly seen that box setting three has highest total sum which suggests that this box has the optimum settings for the sand patterns. Sample 3 has a resolution of 0.08, binder quantity of 20% more than standard, Z-step 0.30 mm and an activator of 0.32%. The box with the least number is box 6 which was the standard machine setting with a resolution of 0.10, binder quantity is standard, Z-step 0.30 mm and an activator of 0.32%.

Table 4 Ranked results'

Box	Compression	Tensile Stress X	Tensile Stress Y	Strain X	Strain Y	Impact	Permeability	Mass	Dimension X	Dimension Y	Dimension Z	Surface Roughness		Total Sum
1	5	10	6				12				20			53
2				12	15									27
3	25	8	10			12		5	16	20	16			112
4							9							9
5	15	6	4			15	15							55
6			2			3								5
7				3	3									6
8						6	6					10		22
9		4	8			9		3	4	8	4	4		44
10	20													20
11				15	9			2	12	12	8	2		60
12				9	12					4		8		33
13	10	2						4	20	16	12			64
14				6	6		3	1	8			6		30

Table 5 Selection matrix for S-print settings for all experimentati[illegible]

Selection Matrix										
Criteria		Weighting (%)	Box Setting One		Box Setting Three		Box Setting Six		Box Setting Eleven	
			Rating (1-5)	Weighted score	Rating (1-5)	Weighted score	Rating (1-5)	Weighted score	Rating (1-5)	Weighted score
Sand part accuracy		16%	3	0.48	4	0.64	3	0.48	2	0.32
Tesnile strength		8%	4	0.32	5	0.40	3	0.24	2	0.16
Compressive strength		12%	4	0.48	5	0.60	3	0.36	3	0.36
Visual inspection	Casting Integrity	20%	2	0.40	1	0.20	3	0.60	4	0.80
	Surface Finish	12%	2	0.24	2	0.24	4	0.48	5	0.60
Casting CMM	Outlet Size	16%	2	0.32	2	0.32	3	0.48	4	0.64
	Plane Angle	16%	3	0.48	3	0.48	4	0.64	3	0.48
TOTAL		100%	2.72		2.88		3.28		3.36	

These scores were then used to select the operating criteria for the turbo charger castings. Four settings were then selected to be used to generate the turbo charger castings, box setting one, three, six (machine default setting) and eleven.

Stage 4 - Casting

The turbocharger parts were delivered to the University after being cast and heat treated at XXX LTD, the heat treatment does not affect the cast defects investigated in this study. Tw[illegible] parts arrived compromising of three manufactured from each box setting (one, three, six and eleven) Each turbo had a number cast onto the body to identify which box setting mould and core was used to manufacture the part. The parts were then given a code, so that they could be recognised individually in each category for experimentation purposes. An initial visual inspection of each part was undertaken to validate that the parts were of suitable casting quality. The inspection takes into account all aspects of the casting, including integrity surface finish and waste material.

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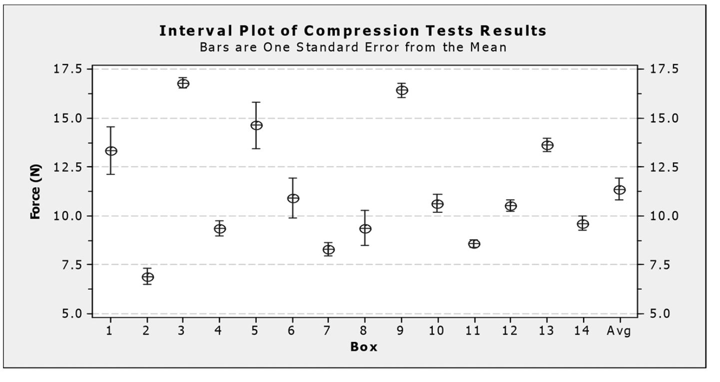
1.8 Evaluation of cast turbochargers

A careful radiograph inspection was undertaken for each of the four settings, examples of casting defects are shown in Figure 5.

Figure 5 Interval plots of the compression tests



Turbo 3-C had some casting failure defects on an outlet of the part. The part also had a poor surface finish in some areas that looked to be caused by gas bubbles.

1.9 Casting material and radiograph inspection

Two casting from each box settings were sent to Exova (UK) ltd for destructive and non-destructive testing (NDT). The inspection was conducted to ASTM E155 standard.

The reports showed the material properties varied from 284 to 294 N/mm^2 for UTS which is within specification for the material showing the box settings had no detectable effect on material properties of the final castings. The micrograph reports under the two magnifications showed small areas of porosity of between 0.4 and 0.7% (Figure 6b) and dendrite arm spacing of 0.04–0.045 mm for all box settings, with no box better or worse than each other.

Figure 6 Outlet casting failure near boss, poor surface finish on part 3-C

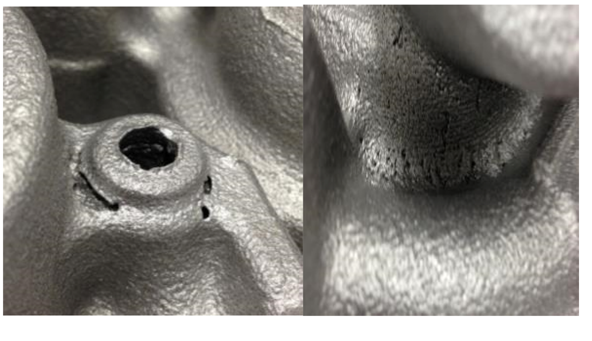


Figure 6c shows X-ray of casting, A summary of all the radiographs: the shrinkage sponge severity rating was derived in accordance to ATM E155 reference radiographs. The range was from a rating of 4 to 8 for all box settings with no discernible difference between box settings, as in practice, shrinkage sponge is an internal casting defect dependent upon geometry, casting tool design and cooling factors not a function of the mould material itself.

All the castings passed the material and metrological inspection, but box eleven clearly performed better for the dimensional and casting defects.

1.10 Discussion of casting experiments

Reviewing the selection matrix, it can be seen that box settings six and eleven are more favourable with scores of 3.28 and 3.36, respectively. This is due to the fact that these box settings performed well in experimentation on the cast parts which have a higher weighting in the grand scheme of the project. Box setting six performed well through all lines of experimentation, so it can be argued that this is a good setting to use as a standard. Box setting eleven gained the highest overall total as the sand parts met casting standards and produced an exceptional casting. Box settings one and three are less favourable with respective scores of 2.72 and 2.88. Although these parts performed well in the strength tests, this factor was actually detrimental to the casting quality achieved from the use of these box settings. The scanning electron microscope (SEM) analysis showed that the less binder used in the printing process the higher the permeability of the built material.

Gases are produced in a mould from the heat of the molten metal. The water in the mould produces steam and the carbonaceous materials in the sand produce other gases. There must be a provision to vent these gases from the mould as they are produced or else gas defects will result. Permeability provides an important relative measure of the sand's venting characteristics (American Foundry Society, 1994). The scanning electron microscope (SEM) analysis showed that the less binder used in the printing process the higher the permeability of the built material.

When considering the practical use of the parts as moulds, it is important that these parts have the ability to de-gas. When more binder is used, the bonds between the particles are much larger, therefore the spaces between the particles are smaller and less frequent. This is also affected by the resolution used in the printing process, box setting one used a resolution of 0.09 mm, box setting three of 0.08 mm, box setting six of 0.10 mm, and box setting eleven of 0.14 mm. For the build material to bond the binder must react with the activator contained within it. For the purpose of fair experimentation, this was constant at 0.32% for all box settings. Finer resolutions print to a smaller area, and as a result, the mixture of binder and activator is more concentrated producing in theory a stronger yet less permeable part. This theory also applies to the Z-step or layer thickness selected. This is confirmed by the results from the SEM microscope analysis which show that finer resolutions and Z-steps produce less permeable parts.

This can be seen first-hand looking at the quality difference in parts between box setting three and box setting eleven. Box settings six and eleven produced high-quality parts which had little or no defects. Box settings one and three had parts with defects that occurred in the casting process potentially from the moulds inability to de-gas due to low permeability.

Box setting three had the most severe defects and also the lowest permeability reading of 36.3%. This clearly shows that there is a clear relationship between permeability and resolution, binder content and Z-step.

1.11 Conclusions of casting trials

In conclusion a selection matrix was used to calculate which box setting is the most appropriate for rapid casting based on industrial input, the 3DSP process was then used to generate test samples which were evaluated against the casting criteria. Four settings were chosen to cast turbo charger casings which were then evaluated dimensionally, visually and using NDT.

As box setting six is the standard setting of the S-max machine, it has been used as a reference to rate the experimental box settings. Box setting one performed 17.1% worse than six rendering, this setting is inappropriate for rapid casting. Box setting three performed 12.2% worse than six. Box setting eleven performed 2.4% better than six overall, therefore making this setting the most suitable for rapid casting. Although this box setting provides the weakest mould due to its low binder content, the castings produced are accurate and highly repeatable. Further work will be undertaken to establish if the mould can be built strong (high binder content) after transportation a secondary drying/evaporation of binder content to provide the permeability as per box setting eleven of resolution of 0.14, binder 40% less than standard with a Z-step height of 0.28 mm and 0.32% activator.

A strong argument has been constructed for the continued use of rapid manufacturing technology in manufacturing processes. In particular, the ExOne S-print system and its ability to augment traditional sand casting methods for low volume and trial production. When the right settings are selected, this machine can produce a mould which will produce an accurate and high-quality part at a reduced cost and shorter lead time, mainly due to the digital nature of the process. This technology also allows for the introduction of a new approach to engineering design for sand casting as it removes the need for a draft angle on the part.

2 Applying the results of the project

The results of the research have been implemented within the production process and demonstrated by the following case study.

In the production process, the sand systems have been changed to mirror the findings of this research. The foundries have also been informed of best practices, and in turn we have seen a reduction in scrap and enhancement in quality as a direct result. This has given new confidence to the design team, and RPD has seen a dramatic increase in the use of the systems for conventional casting applications. This has been built on the confidence that has been developed through the use of case studies that have demonstrated that they improve all three cornerstones of the engineering quality triangle - quality vs. cost vs. time. This has been confirmed by the manufacturing stamping group at xxx production plant, xxx Germany, which have raised initial orders of 3,500 moulds per year.

2.1 Rapid automotive seat foam tool production

Automotive car seats are built around a strong metal frame that is securely bolted into the bodywork of the car which provides operational and collision support. The metalwork is clad in a polyurethane (PU) foam cushion that provides the seat its shape, the customer comfort support and protection from the steel frame. This whole structure is then covered in a sewn material cover, which provides the seat its final appearance and texture.

The combination of the material cover, rigidity of the foam and the shape of the metal under structure all combine to give the user the feeling of support and comfort. This complex combination of material properties can give rise to many difficulties in the design optimisation stage of a new product. The number of prototypes manufactured and speed of iterations to accomplish a final prototype for customer sign off is a major concern in the automotive industry. It is essential to ensure that the prototypes perform in the same manner as the production version otherwise all the prototype time and expense is fruitless.

2.2 Problem statement

Prototype seat foams are produced using a different method to production seat foams. This variation is mainly due to the prototype foam not having a 'skin' as created in production by heated tools. This often means that the prototype foam seat product, when assembled, behaves significantly differently to the production version. This causes a large number of design iterations to take place, causing delays and expensive tooling changes.

2.3 Traditional solution

Figures 7–9 show a typical production seat pad tool ready for PU foam injection, final prototypes are produced using early production tooling to ensure that 'make like production' prototypes give true production representative parts. Prototype seats are initially created using hand carved or CNC milled foam as shown in Figure 10, produced using resin tooling from 2 pack PU foam resin.

Author: Please check the paragraph "Figures 7–9 show a typical … tooling from 2 pack PU foam resin" this has been done to maintains sequential order of the figures.

Figure 7 (a) Example of casting radiograph (6c) with shrinkage sponge areas indicated (b) micro structure (200 magnification)

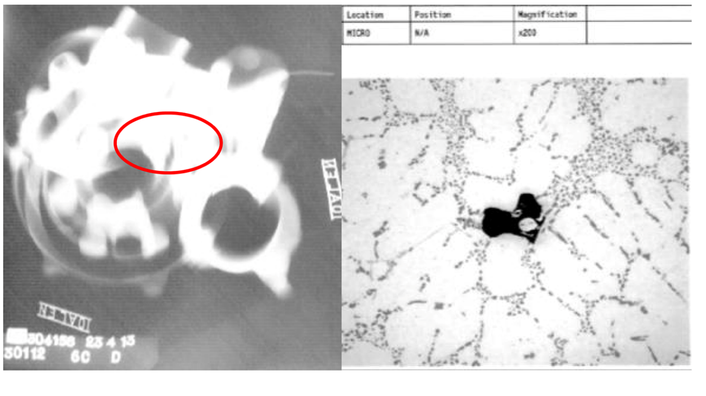


Figure 8 A prototype seat pad CNC milled from solid foam

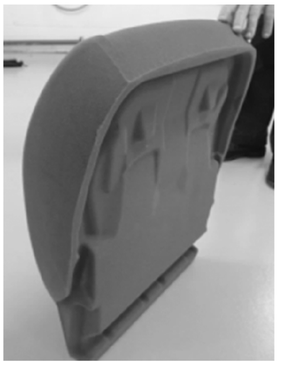
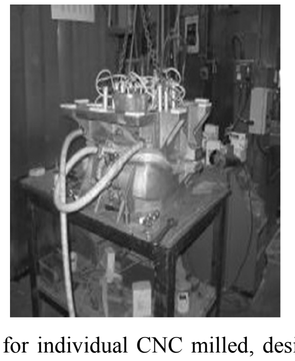


Figure 9 Resin tooling for prototype use

Figure 10 Traditional production seat tooling



The current prototype costs for individual CNC milled, design aid foams are front seat cushion €2,900, front seat back €4,100.

The current prototype tooling cost for confirmation prototype build phase of around 150 sets are shown in Table 6. The normal time for production of prototype tooling is 12 weeks from the release of design data to the production of the required amount of prototype products. (Data based on historical production records)

Author: Please note that the heading of 'Table 6' is repeated twice for the tables and so one of the table changed as 'Table 7'. Kindly check and approve.

Table 6 Traditional prototype and production tooling cos

Prototype tooling		
Front seat foam tool €	**€ 120,000**	
Production tooling, 000.00		
Pad Asy FRT ST, RH	Cost/Mould/Pat FSB	€ 231.0
Pad Asy FRT ST, LH	Cost/Mould/Pat FSB	€ 223.5
Pad Asy FRT ST	Climate seat	€ 85.0
Pad Asy FRT ST	Foam FSC	€ 4.8
Total		**€ 544.3**

2.4 *The aim of the case study*

The aim of the case study application was to manufacture a prototyping process capable of reproducing the production tooling process characteristics to optimise the development phase for a new seat project. It will utilise RCT techniques developed during project and access the impact on both development time and cost.

2.5 *Rapid casting technology - proposed solution*

To produce seat foams in quick, low cost 'production like' tooling that replicates the production method, to ensure that the prototype trial seats exactly emulate the final production parts. This will be carried out using sand printing technology to create cast, heated aluminium mould tools that will be identical in functionality to the production tooling.

2.6 *Application of RCT for prototype seat foam manufacture*

Stage 1 - Seat and tooling design - The seat tooling for the foam pad or seat back was designed using original CAD data of the foam as the starting point. This CAD data were used to create the mould cavities for the PU foam components applied to a 'master model' or template for a production tool. Split lines were then generated to ensure that the foam could be removed from the tooling, and over moulding of components are then designed into the tool. The PU foam injection points, runners and ejector ports are added to the tool design as shown in Figure 10

The CAD stage took 15 h and a start to finish time of 2 days. This CAD data will also be utilised in the final production tooling design with minor alteration to suit mass production techniques, saving 15 h of CAD in final tool design.

Stage 2 - Casting tooling design - The seat tool CAD is then used to generate the sand prints and core designs to make the complete casting tool as shown in Figure 11, manufactured on the ExOne 3D sand printer (Figure 12).

Figure eat design and the seat prototype tooling design (see online version for colours)

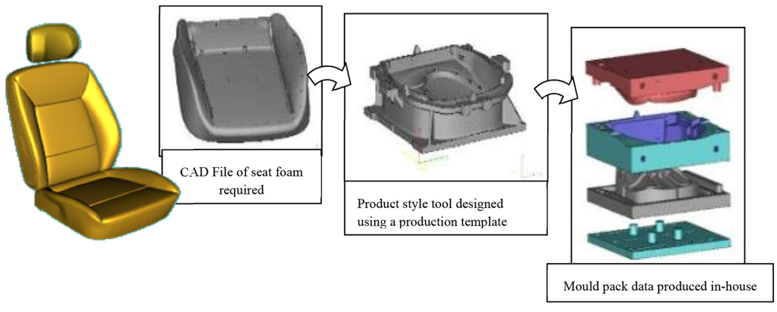


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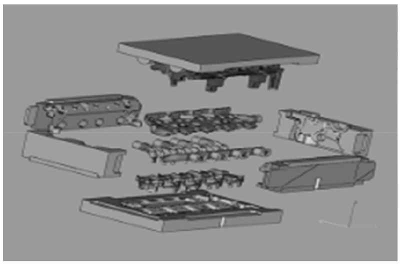
Figure 12 CAD tooling data



Stage 3 - Casting tooling manufacture by RCT - The moulds and cores are manufactured in a series of builds, stacked to increase build volume utilisation. The build time for this stage was 48 h and cost of materials was £1,200

Stage 4 - Casting of mould tool - The casting was undertaken at "xyz ltd" and they used traditional techniques with no process alteration to traditional casting manufacture. The material cast was LM25 TF and exhibited no defects from the ND testing.

Stage 5 - Production of mould tool assembly - rapid cast technology applied to seat tooling, showing the flexibility of the process to include conformal heating elements to maximise production rates and reproduction characteristics as shown in Figure 13.

Figure 13 ExOne S15 print station

The quality and accuracy of the sand printed moulds (typically within 0.2 mm) of nominal means that for foam tooling no machining is required for the foam form. The two halves of the mould are spark eroded together to ensure a perfect fit/air tight seal.

Stage 6 - Foam casting trails - The tool assembly took 8 h and was completed over a period of 3 days. (The spark eroding being automatic required no manual input). Figure 12 shows the tooling being trialled and the first off pre-production of seat pad foams.

The cycle time for each part was 60 s, at a cost of £155 per part. In total, 120 components were produced for customer evaluation; however, the tool was capable of producing production quality and quantity parts.

2.7 Summary of case study

The case study has shown how 'production like tools' can be created for use as prototype tooling. Costs are no more expensive than resin tools, yet true production foams can be produced, the 3DSP build time and cost per RCT foam are shown in Table 7.

Table 7 RCT cast tool

RCT front seat cushion tool:	*RCT front seat back tool:*
2 piece mould pack	3 piece mould pack including ejection
Time 2.5 weeks	Time 3.5 weeks
€9,000 one-off tooling cost	€14,000 one-off tooling cost
€112 per foam to full production spec (120 off)	€187 per foam to full production spec (120 off)
Total cost production 120 foam seats €22,440	Total cost production 120 foam seats €36,440
Project cost - €58,880	

The tools can also be used by the supplier as a 'lead into production' tool, eliminating production launch delays. Due to the low cost and high speed, this tooling can be used at the design level, giving true production intent foams for development work.

The tooling trials as shown in Figure 14 produced the 120 required seat sets for the customer focus meetings worldwide, within project deadlines, and to the same quality and properties as full production seat foams. Figure 14 shows top right to left, top row, tool closing and foam injection, middle row tool opening with foam formed, bottom row foam ejected and manually removed from tool.

Figure 14 Manual cleanup with no machining required and finished tool (see online version for colours)

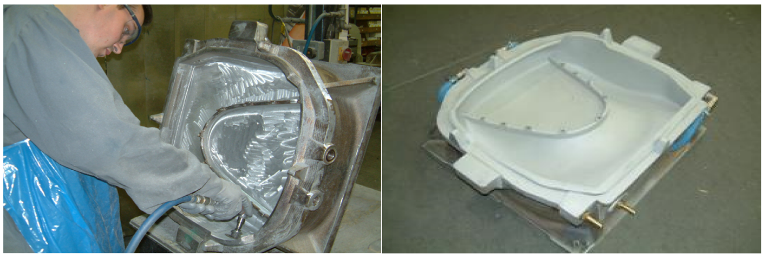
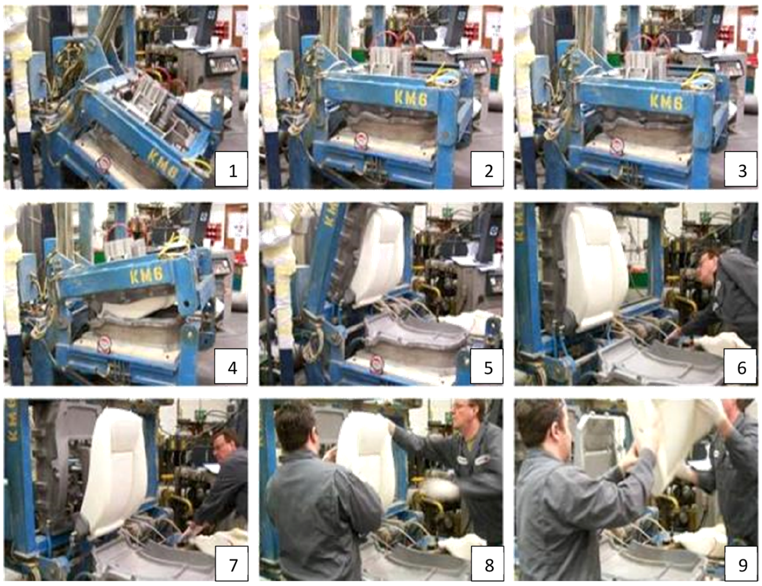


Figure 15 Trial of rapid seat foam tool (see online version for colours)



The RCT tool is of production standard and when released, will be utilised by 1st tier supplier, making substantial economic and time savings, whilst maintaining or improving quality and process steps/complexity. Having only two machine resources (sand printing machines installed) is a risk; however, with preventative maintenance procedures in place, to-date no project deadlines have experienced slippage.

Cost - Potential cost savings for prototype tooling from €107,000.00 to €49,000 - 50% cost reduction per tool. Potential saving for production - if process implemented to produce production tooling at least - €48k + €107k (pattern cost) approximately €48k per seat pair.

Time - Reduction from 12-week lead time (for a prototype mould) to 3-week lead time a reduction of 9 weeks. Final tools can be used for full production use, eliminating

Author: Please check the sentence “The RCT tool is of production standard and when released … quality and process steps/complexity” for clarity.

time delays between prototype sign off and full production. Developing design lead customer focused agile manufacturing.

Due to the low cost and high speed, this tooling can be used at the design stages giving true production intent foams for development trials.

Quality - There is no difference to production tooled foams at the prototype level - the tooling could be used for the confirmation prototype builds and then handed to the production supplier for high volume use. High-quality production tooling from confirmation prototype process.

Prototype foams can be produced on the production line, proving out the manufacturing process and tooling prior to production. This will eliminate any issues prior to full production.

Design alterations will be reduced as more in-depth analysis can be accommodated between iterations, given thanks to the shorter lead-times. Net shape castings have no machining requirement.

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3 Conclusion

The research has led to a new unique manufacturing technique for the production of viable production quality prototype automotive seat foams, previously manufactured by traditional means. The research has also shown how utilising the RCT techniques developed and industrialised by this research, applied to automotive seat foam tooling has made significant time and cost saving. The case study documented in this paper has established how lead times can be reduced to ¼ to 3 from 12 weeks and prototype production cost reduced by approximately 50%, with an increase in both quality and flexibility.

Automotive industries use significant numbers of metal castings, for example, one major automotive manufacture produces 1.2 million castings a year for both on vehicle or manufacturing tooling, with each casting tool costing £10k to £100k and taking many months to produce. Clearly, mass produced parts would still use the traditional manufacturing routes; however, niche market bespoke car models will require agile manufacturing tooling, which are unique and inherently low volume. The research and development of a continuous 3D printing process by companies, such as Voxeljet, may herald a new era for mass production using AM techniques in future.

This industrially based research has developed a process in collaboration with traditional casting technologies and knowledge, the advantages and problems have been explained by this research.

The 3D sand printing technology and rapid casting methodology have been substantiated by a real case study demonstrating its commercial viability in cost savings and lead time, enabling more agile design focused manufacturing whilst improving quality. There are still further research to be undertaken to reduce the effects of gas generation causing casting defects.

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