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Experimental investigation of sheet metal forming using a recyclable low melting point alloy tool

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ABSTRACT

Due to intense competition in automotive industry, new car models must be brought to the market as quickly as possible. A re-evaluation of the design and development phases has created a drive for streamlined processes in prototype development. Although it is possible to produce parts using rapid prototyping (RP) and Rapid Tooling (RT), the materials used in these technologies are dissimilar to those used in mass manufacturing. As a result, RP parts are often used as a guide for visual and packaging analysis. However, there is a requirement to use these parts for functional testing as well. Therefore, the sheet metal parts must also be representative of the actual part performance. Creating a part that embraces all these aspects has historically limited the materials used for tooling; hence the process can be time consuming and costly element of the project schedule. Developing alternative RT methods which shortens the physical prototype production phase while adequately supporting visual, packaging and functional aspects of sheet metal forming can lead to considerable savings in vehicle prototype development.

This study examines a new approach to produce sheet metal parts using low melting alloys, rapid prototyped 3D prints for rapid tooling. A number of sheet metal prototype parts were manufactured, inspected and analysed for application in automotive industry prototype testing.

Key Words: Prototype, sheet, metal, forming, bismuth, alloy

1. Introduction and Background

In this paper the use of a low melting alloy to create a deep drawing tool for low volume sheet metal production is investigated. The performance of the tooling is evaluated by practical experimentation and 3D analysis. Sheet metal forming is a high volume manufacturing process commonly used in a wide variety of industries to produce parts for white goods, computers, jewellery, building construction and vehicles. Typical forming processes can include bending, drawing and stamping operations. Sheet metal drawing processes were investigated using low melting bismuth alloy to produce the tools, which were then used to stamp 100 prototype parts. The tools and parts were then assessed for dimensional accuracy and tool wear to test the efficacy of Bismuth alloy tooling in the context of the low volume manufacture of vehicle prototype components. Traditionally dies are usually manufactured from aluminium or steel at considerable cost to the manufacturer, which can only be offset by high volume production. A number of studies have been carried out to test high volume sheet metal forming methods, associated tool wear and production parameters. (Pereira, 2012, Jeswiet, 2008)

Rapid Tooling is mostly used for prototyping and rapid manufacturing whereas Rapid Prototyping (RP) is typically used for visual design evaluation or physical and functional verification. RP also provides an effective communication between design, management and marketing teams. RT uses similar technology to create tooling using 3D digital technologies (Kus et al., 2013). Tools can be manufactured directly in sintered metals or indirectly by using the 3D RP pattern as a transfer mould for the final tool. Additive manufacturing, using laser sintering technology, has been adopted in industries such as aviation and aerospace, where low volume, light weight metal parts with high tolerances are required. These include assembled components that would have been impossible to manufacture using traditional methods. However, the costs of these technologies are currently very high, which prevents their use in most commercial applications as either a direct method of manufacture or for rapid tooling in sheet metal forming. Nakagawa (2000) presents a variety of rapid tooling methods and emerging rapid production methods for sheet metal forming processes including die-less forming, hydraulic counter pressure deep drawing incremental NC forming and laminated tooling technologies. Mueller, Mueller, (2000) and Altan et al. (2001) examined the use of RP in the manufacture of sheet metal forming tools and prototype tooling for the automotive industry. A structured evaluation was given into the effectiveness of various methods of direct and indirect manufacture to produce low volume parts, including laminated tooling and low melting point alloys.

Pham and Dimov, S.S., (2003) explored direct rapid prototyping (RP) and rapid tooling (RP) from CAD data in the fabrication of physical models, functional prototypes and small batch parts. A range of technologies were discussed and classified in twenty-five categories, which were evaluated in terms of their potential as aids to rapid manufacture. Stucker, and Qu (2003), explored the use of Rapid Tooling directly in conjunction with other processes such as casting, plasma spraying etc. to create metallic or ceramic tooling for limited production and an STL-based finish machining technique for tools and parts made using RP. Balc and Campbell (2004) provides an overview of the connections between CAD, RP, RT and Innovative manufacture. The paper acknowledges that additive technologies have not replaced subtractive tool manufacturing methods, such as milling or EDM, but speculates on the future of manufacture where small batches can be directly and economically produced using RP and RT systems. Pinto et al. (2007) studied the use of non-conventional tooling in the manufacture of a complex sheet metal part. Wear, surface roughness and geometric deformation were measured in the punch and die tooling and in the manufactured parts over a 500 unit production cycle. A comparative cost evaluation was also presented to assess the feasibility of these materials for low volume production. Early use of Low melting alloys for sheet metal forming goes back 1952, by Ford Motor Co, US Patent (Klemach, 1952). The patent covers a method of forming sheet metal with low-melting dies, using materials of bismuth, tin and lead. Later Kolt (1959) by Gen Motors Corps and Miura (1987) also patented tooling methods for low volume production in sheet metal forming.

Small volume sheet metal forming can be carried out using a tool made of bismuth, cadmium, lead and zamak, which is an alloy of zinc with aluminium, magnesium and copper. This method reduces the health hazards normally associated with melting metals with toxic oxides to produce machine tools. Bismuth tin alloys used in press tool manufacturing are not only easy to melt but also the volume changes that occur in solidification are minimal. This material property is crucial in the simplification of the tool creation process as it enables an actual size model to be used as master model. The low coefficient of expansion and shrinkage of the alloy is therefore a key criterion in its selection as an effective tooling material. Another significant property of bismuth is its ability to alloy with other elements in eutectic proportions. The optimum eutectic point is achieved when the alloy displays its lowest temperature for consistent solidification and melting of all the constituent metals. The eutectic point changes in accord with the materials combined with the bismuth base component, giving rise to alloys with melting points much lower than that of the original elements. For example, Field's Metal, a combination of bismuth, tin and indium melts at 62°C, in comparison with pure Bismuth which melts at 271.3°C. In this study MCP 137, Bismuth (58%) Tin alloy was selected with a melting point of 138°C, density of 9.8 g/cm^3, a low coefficient of expansion and shrinkage. Compressive properties of MCP137 are between 42-58 MPa and mechanical properties are given in Table 1. The alloy is recyclable and retains its properties after many usages, which offsets the higher costs of the initial investment for sheet metal prototype part production.

Bismuth MCP 137 alloy is denser than steel (7.8g/cm^3) or aluminium (2.7g/cm^3). Although bismuth alloy is approximately 20 times more expensive than steel the initial high cost can be recovered by recycling the material. It is also important to note that a considerable quantity of the steel material is wasted in the production of the die. This is particularly relevant in deep drawn dies where a high volume of the original material must be machined away to produce the tool. CNC machining also has associated costs in the form of trained technicians, workshop equipment. Additionally the energy consumed in recycling steel is much greater than that of bismuth MCP 137.

Alloy		Bi58Sn42%
Melting Point	°C	138
Density	g/cm^3	8.56
Thermal Conductivity	W/m^{2}K	19
Tensile Strength at Break	kgf/cm^2	565
Tensile Elongation at Break	%	55
Brinell Hardness	HB	23

Table 1 Mechanical properties of Bismuth MCP 137

The material and method used in this research should be compared with other rapid tooling technologies rather than traditional CNC hard tooling methods. Low volume manufacturing differs from mass production, where high tool costs are offset against high numbers of units. Low volume or short batch production tooling is better suited to specialist industries such as aviation manufacture or automotive prototyping.

Alternative low volume sheet metal forming techniques include multi-point forming, Chunguo (2010). This research shows the potential for pressing and stretching aluminium sheets using a digitally controlled multi-point tool to produce “qualified parts” that are suited to the needs of the aviation industry. The DATAFORM (2009) project is funded by the European Commission under the 6th Framework Programme in the area of Aeronautics studied the application of multi-point forming for aircraft production. The study investigated multi-point positioning, forming and integration of CAD/CAM/CAE software into dieless sheet metal forming, pressing and testing. This method requires relatively high initial investment, manual setting would be time consuming and therefore greater investment is needed for computerised control. In addition it is less suited to manufacturing deep drawn parts.

2. Experimental Method

The purpose of this research was to investigate the changes in the tool and parts at intervals over the production cycle. 3D scanning technologies were utilised to measure surface and dimensional changes in the tool and the component parts produced.

The physical verification stage for sheet metal automotive components requires testing using the durable high tensile materials, which will be used in final production. The part chosen for this experiment was designed to reflect the deep drawn forms commonly found in a range of automotive components such as suspension and body reinforcements or fuel tank assemblies. The shape of the experimental part was selected to create stresses during the forming process that were expected to accelerate any detectable evidence of wear on the surfaces of the tool.

The team considered RP and CNC methods to produce the bismuth alloy tools, An RP model was 3D printed using a Stratasys Printer and the resulting ABS model was cleaned and prepared (Fig 3b) for use as a pattern to create a bismuth cavity tool by pouring alloy directly onto the RP pattern. The RP pattern was mounted on a horizontal surface and surrounded by a frame to create a bismuth mould cavity. Steel tubes were inserted above the pattern to facilitate lifting after pouring the bismuth alloy (Fig 3c). The team's intention was to minimize the processes required to achieve the alloy tool. However the 3D printing materials employed in the experiment were not sufficiently strong to resist the loading produced by the high density bismuth alloy and the resulting tool cavity was deformed and unusable in the experiment. The team also used a CNC miller to create a second pattern in yellow pine, reduced to the inside surface dimensions to compensate for the steel thickness of the finished part.

The iron-oxide and gypsum plaster is also used for ceramics industry due to its low shrinkage and accurate retention of dimensions. The poured plaster was taken after a partial cure and placed in an oven for 3 hours at 150°C. The iron oxide in the plaster mix helps to visually monitor how the part has dried as the colour changes to pink in the dry areas while wet areas retain a red hue.

Once the drying process has been completed, the plaster part was placed into a frame which was levelled to ensure the base of the plaster cast was horizontal and would therefore align with the surface plane of the bismuth casting. The recycled Bismuth alloy retrieved from the earlier RP pattern was reheated to 142° C, which is 5° C above the melting temperature of 137° C to allow for heat loss during the casting process thereby ensure the metal stayed liquid until the casting was completed. The block of Bismuth was lifted from the frame using a small crane and to minimise cooling stresses within the casting, and was left for approximately 5 hours to cool to room temperature. After cooling the male bismuth tool was coated with a 1.0 mm layer of wax sheet to accommodate the thickness of the sheet metal. A female bismuth tool was manufactured and the resulting parts were post processed before mounting in a hydraulic press machine (Figure 1).

Figure 1. Mould Pattern, Bismuth Tool, Hydraulic press

3. Prototype Part Production and Analysis

The aim of the project was to identify changes in tool manufacture and production using the original CAD model as the datum for all further measurements. This method enabled to identify inaccuracies in the tool manufacture as well as deformations in the production cycle. The surface deformations of the male & female tools were recorded by scanning before and after the production cycle of one hundred and one components. In addition, the first, fifty-first and final components were retained for surface analysis.

	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
EN10130 DC04	190	300	36	50

Cold rolled low carbon DC04 sheet steel was used in the experiment. This steel is also classified as EN10130 and is a commonly specified in the automotive industry because of its mechanical properties.

3.1 Scanning and Analysis

Using an ATOS GOM 3D optical scanner, a numbered selection of the components taken at intervals during the production run for analysis,.

The experimental process of data capture employed the following steps:

- Male and Female Bismuth tools are both scanned before the press forming operation
- From the 101 components, only the 1st, 51st and 101st are scanned for surface analysis
- After 101st component is pressed, the male and female bismuth moulds are again scanned and analysed for surface changes.

3.2 Tool Analysis

In Figure 2 shows a comparison of the scan data for the female tool before and after the production cycle. The 3D CAD model of female die was used for reference data at a series of numbered point locations. These point locations (1-13) were selected where deviation was expected to be at its greatest due to material flow as a result of compression forces in the pressing process. Maximum deviations are in the lip at points 5 and 6 of 0.56 and 0.54 mm. This is where the curvature on the sheet metal part is at its greatest with forming forces carried along the edge of the tool throughout the stamping process. The image shown of the tool after the production cycle illustrates that the wear has been greater on the right hand side of the tool due to balancing issues in the tool setup.

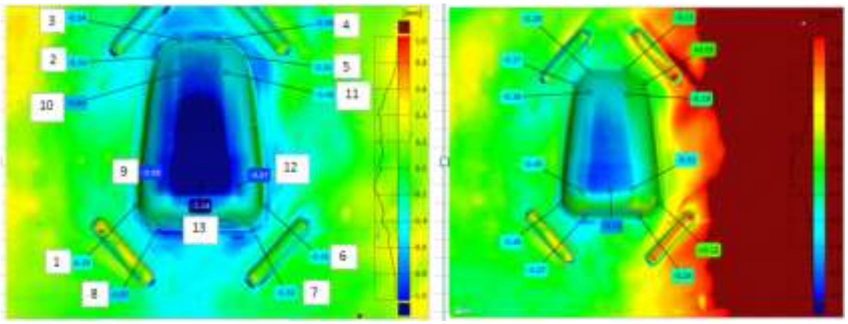

Figure 2. **Female Die** - before and after stamping

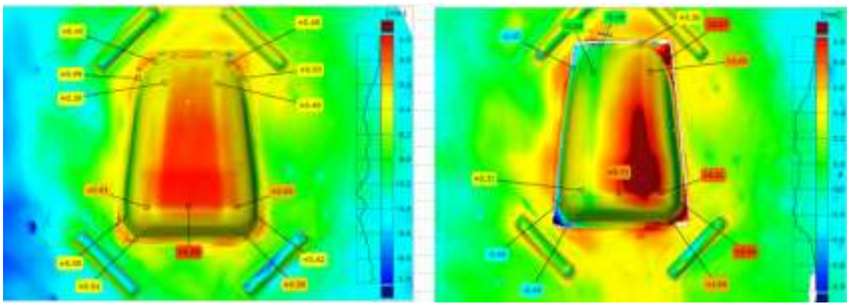

Figure 3. **Male Die** - before and after stamping

Figure 3 shows the comparison of the original CAD data to the Bismuth male die before and after stamping. Deviation on the male tool is at its greatest at points 2 and 8 where the material is forced into the female die. After 101 pressings the deviations in the tool dimensions due to wear are in the region of 0.5 mm. Although this may seem excessive for some vehicle parts the process is viable for prototyping. It is also worth noting that the tool manufacture produces around 50% of the total deviation. Figure 3 also shows that contrary to the female tool, there is more deviation in the male die where the first interaction between tool and sheet metal occurs.

3.3 Component Analysis

Figure 4 show the dimensional changes of 1st, 51st and 101st stamped parts using the original 3D CAD reference data. Figure 4 shows the data for the first component in the production cycle. Maximum deviations of -0.62 and +0.67 were inspected in the locations indicated. This may be seen as unexpected, but could be as a result of inaccuracy in the tool manufacture process for Bismuth.

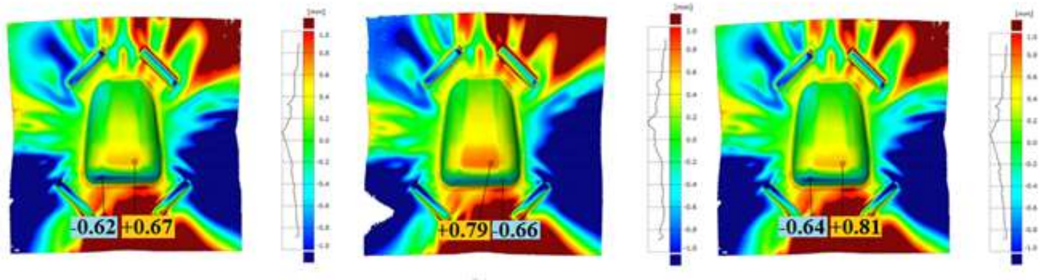

Figure 4. Dimensional conformance of the components a) 1st , b) 51st , c)101st

Figure 4 shows in the selected points deviation of -0.54 and +0.81 using CAD data as the reference. If the first part is used as the datum points the dimensional changes in the tool due to wear is in the region of 0.25 mm as shown in red. Experiments also show that the minimum deviations on selected points remain almost constant during the whole cycle but maximum deviation increases by every stamping part. For all three sample pressings the maximum and minimum deviations remain within acceptable tolerance parameters. All the parts produced meet the requirements for low volume production.

3.4 Thickness Analysis of the Stamped Sheet Metal components:

As well as the surface changes and deformation due to wear on Bismuth tool, thickness of the sheet metal on the formed components are also recorded and analysed. Six components (1st, 25th, 51st, 75th and 101st) are selected for analysis of the material thicknesses variation as seen the Figure 5. A manual digital spherical face micrometre is used to measure of the thickness of inspection points on the stamped parts.

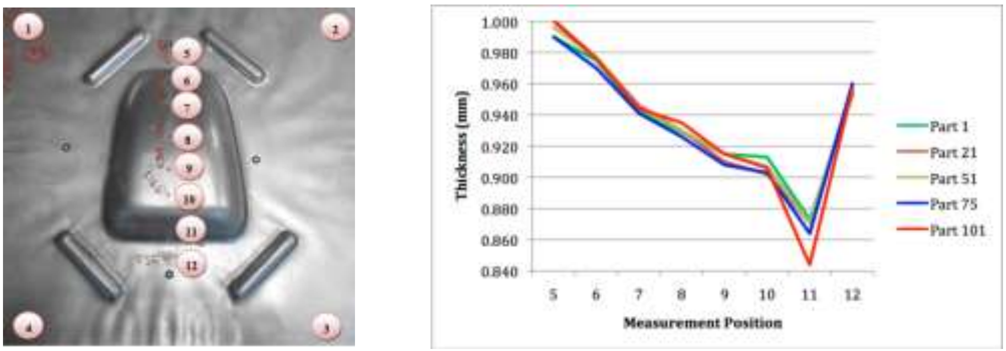

Figure 5. Part thickness deviation

4. Results

The overall production cycle for tool manufacture, including the first sheet metal forming, was 15 hours. If the curing and drying period of gypsum plaster transfer moulds is added the total tool production time was 72 hours. By the selection of a 3D print material with a higher melting point than Bismuth alloy an RP pattern could be produced, which would be capable of resisting the high density loading and consequent surface deformation during the Bismuth casting process. This would also considerably reduce the tool production time. The experiments demonstrate that there are benefits in using Bismuth alloy for sheet metal forming for deep drawn components. However, as the hardness of the Bismuth tool is not comparable to steel, as had been predicted, only a limited number of parts can be stamped before major dimensional changes occur in the parts.

Findings could be summarised as:

- Although the initial cost of the alloy is high, the material is 100% reusable, which keeps the long-term material costs low.
- The alloy is easy to use because of its low melting point (138°C).
- Except in the production of the master model (pattern) there is no need for milling processes.
- The alloy has a high compressive strength.
- Bismuth production tools can be used directly without further machining.
- Tool creation is relatively uncomplicated process from 3D model to the production of finished parts.
- Initial testing showed there were no cavities and porosity in the casting.
- A maximum of 3 mm sheet metals can be pressed (depending on hardness). This method of sheet forming is not recommended for harder or thicker sheet metal forming processes.
- Tool life strongly depends on the material, for stamping parts from harder material; tooling life will be less so new tooling must be prepared for remaining lots.
- The experiment showed the potential to produce approximately 100 parts which met the production specifications set by the engineering team for prototype part testing.
- Prototype production costs are reduced because alloy tooling has a short production cycle, which does not require finishing processes to the surfaces of the tool.

5. Conclusion

Although the methods of using low melting alloys for sheet metal forming were studied previously, integration of RP technology to this method is new and has potential. This study also utilised advanced 3D scanning technology to identify the surface changes during the pressing of required parts. The experiment demonstrated that this method can be practically used for relatively low volume production of a variety of typical small automotive parts. The digitally scanned parts sampled throughout the experiment show dimensional changes occur where excessive forces are applied or where material flow is required to form the component. However, for vehicle prototyping, all 100 parts produced were suitable for component testing.

Major inaccuracies occurred during the model making and tool manufacturing phase rather than press forming. Both male and female dies demonstrated that the wear resistance of low melting point alloy is an important parameter that defines the limits to the number of stamped parts that can be produced. The tool life will be dependent on the complexity of the part to be produced and to the thickness and hardness of the sheet material used in the pressing. Harder and thicker steels will significantly shorten the usable life of the tool. The experiment demonstrates that the dimensional accuracy of the part had not significantly changed during the production cycle. All the parts produced in the experiment were within the required tolerances for prototyping tests shown in figure 3.4, as specified by the engineering team at Tofas.

The results demonstrate that, for low volume production, the initial investment costs for low melting point alloys can be recovered as a result of the simplicity and speed of the process. Additional experimentation will be required to investigate the use of RP models directly as transfer moulds, either through the selection of lower melting point alloys, the use of cooling channels in the RP mould or the selection of RP systems that use materials that are thermally stable at higher temperatures.

References:

Pereira, M.P., Yan, W., Rolfe B.F. (2012), Wear at the die radius in sheet metal stamping, 274–275 pp. 355–367

J. Jeswiet, M. Geiger, U. Engel, M. Kleiner, M. Schikorra, J. Duflou, R. Neugebauer, P. Bariani, S. Bruschi, (2008) Metal forming progress since 2000, CIRP Journal of Manufacturing Science and Technology

Altan T., Lillg B. and Yen Y.C. (2001), "Manufacturing of Dies and Molds", CIRP Annals - Manufacturing Technology, Vol. 50, No. 2, pp 404-563.

Kus, A., Unver, E., Jagger, B. and Durgun, I. (2013) 'A Study of Injection Moulding with Bismuth Alloy '.*In:* Green Design, Materials and Manufacturing Processes. : Taylor & Francis. . ISBN 978-1-138-00046-9

Klemach Fred A, (1952), Patent, US 2593571 A, Method of forming sheet metal with low-melting dies, http://www.google.com/patents/US2593571

Nakagawa T. (2000), "Advances in prototype and low volume sheet forming and tooling", Journal of Materials Processing Technology, Vol. 98, pp. 244-250.

Pinto, M., Santos, A.D., Teixeira, P. and Bolt, P.J. (2008), "Study on the usability and robustness of polymer and wood materials for tooling in sheet metal forming", Journal of Materials Processing Technology, Vol.202,No.1-3, pp 47–53.

Klemach Fred A, (1952), US Patent 2593571, Ford Motor US Patent, Method of forming sheet metal with low-melting dies http://www.google.com/patents/US2593571

Kolt Paul (1959), US Patents, 3088174 A, Method of producing a reinforced plastic die, Gen Motors Corp http://www.google.com/patents/US3088174

Hiroshi Miura (1987), US patent 5081861, A Resin die for sheet metal pressing and method for producing same, http://www.google.com/patents/US5081861

Chunguo L, Mingzhe L, Zhongyi C, Aimin Y, Shizhong S, (2010) "Digitally Adjustable Tooling Technology for Manufacturing of Aircraft Panels ", International Conference on Digital Manufacturing & Automation

DATAFORM (2009), The Sixth Framework Programme (FP6) Research Project, FP6-2005-AERO-1, Digitally Adjustable Tooling for manufacturing of Aircraft panels using multi-point Forming methodology, http://cordis.europa.eu/documents/documentlibrary/123652801EN6.pdf (accessed 3/10/2014)

Nakagawa T., 2000, Advances in prototype and low volume sheet forming and tooling, Journal of Materials Processing Technology 98, Pages 244-250.

Mueller, D. H., Mueller, H., 2000, Experiences Using Rapid Prototyping Techniques to Manufacture Sheet Metal Forming Tools, ISATA 2000, Dublin, Ireland, Sep. 25-27.

Pham, D. T., Dimov,S.S., 2003, Rapid prototyping and rapid tooling—the key enablers for rapid manufacturing, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 217:1.

Stucker, B. & Qu, X., (2003), A finish machining strategy for rapid manufactured parts and tools, Rapid Prototyping Journal, Vol.9, No. 4, pp 194-200

Balc, N., Campbell, R.I., 2004, From CAD and RP to Innovative Manufacturing, Computing and Solutions in Manufacturing Engineering – CoSME 04