ADVANCED SHEET METAL MANUFACTURING USING RAPID TOOLING

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ABSTRACT

A closed loop process is proposed for making sheet metal prototyping parts by using advanced computer aided techniques and computer controlled machines. The key aspect of this process is the method used to fabricate and modify the sheet metal forming tools, which are not necessarily for mass production but should be suitable for short run production or design evaluation of sheet metal products where the prototyping cost and lead-time are greatly reduced.

Various approaches are investigated in the preparation of the tooling for onward embossing on a sheet metal. The three indirect approaches use Selective Laser Sintering (SLS), Stereolithography(SLA), and high speed Computer Numerical Controlled (CNC) milling to build the masters from computer data models. And the masters are then served in the vacuum casting process to generate the non-ferrous tooling. The direct approach uses DTM’s RapidSteel to produce the metal tooling without going through any secondary process. Comparisons on quality, leading time and cost are presented.

Keywords: Sheet metal manufacturing; Rapid prototyping; Rapid tooling; RapidSteel

1. INTRODUCTION

Parts from rapid prototyping (RP) / rapid tooling (RT) [1,2,3] could be produced not only for engineering prototyping, but also for marketing purposes by distributors and dealers. With RP and RT, plastic injection molds have been created to produce prototyping parts by many academic institutes and industrial organizations in a bid to reduce leading time and cost. However, only a few developmental results have been reported so far on sheet metal products by using RP and RT [4,5]. Berger, et al. [6] discussed that the process of sheet metal forming can be improved with the integration of concurrent engineering methods and RP technology, and one case study was presented using easily castable amorphous material and integrating Stereolithography in the fabrication of the casting shell. However, the more result and information desired are still unavailable.

It is well known that the tooling preparation is the most crucial stage for a successful sheet metal manufacturing. Conventional methods for manufacturing a forming tool usually adopt a trial and error-prone approach, therefore hardly to obtain the correct tooling shape and forming conditions probably because of spring back in the deformed sheet metal, material non-linearities etc. Often few calculation or simulation of forming operations can be done because of complex mathematical constraints and unpredictable material behaviours. If a part shape variation or a specific manufacturing requirement occurs, the whole process must be reiterated and the forming dies be rebuilt. The die building process often requires Numerical Controlled (NC) programming which is time consuming, especially when the design has a large number of complex surfaces. Therefore, the forming dies for small-batch series and prototypes cause disproportionally high costs or risks [7].

There exists a strong demand in industries for rapid tooling of sheet metal forming with a shorter time and lower cost. Eventually, the high risk of unsuccessful design and tooling becomes avoidable. The tooling might not be strictly desired to produce a large quantity of products like the existing one does, but it must be of good service for a short-run production. The prototyping parts produced by this means serve as a functional tool in formability study, design iteration, process optimization, or even as final products for customized demands. Therefore, the concept of Rapid Sheet Metal Prototyping (RSMP) emerges.

2. RAPID SHEET METAL PROTOTYPING (RSMP)

Present RP techniques are not intended for forming of sheet metal products directly but they are useful in transforming the CAD model into the final sheet metal product with additional steps. The RSMP includes certain additional methodology to complete the transformation to sheet metal parts with the aids of advanced computer aided techniques and computer controlled machines. There are three major steps involved in the closed loop system (shown as in Figure 1).

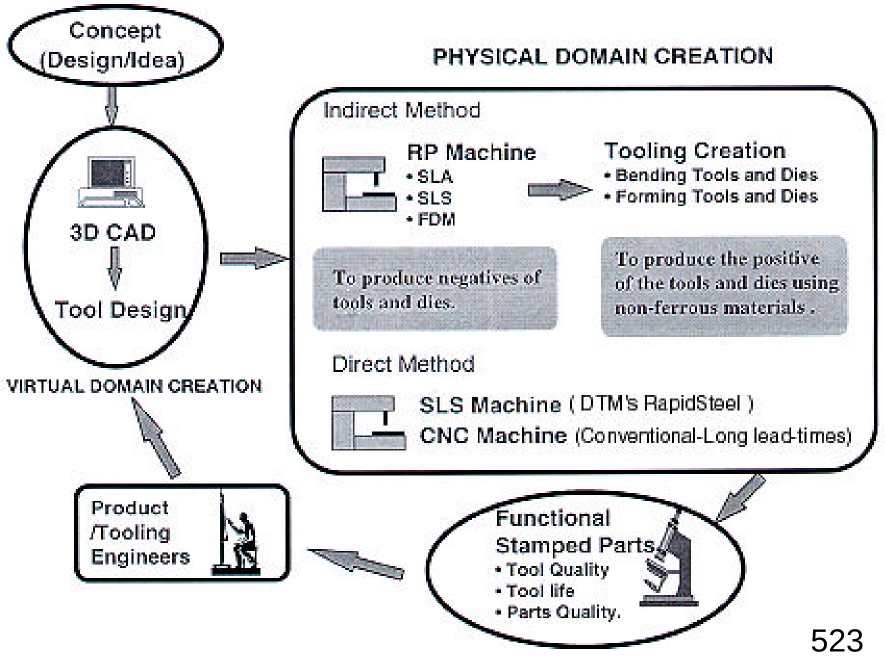

Figure 1. The closed loop of the RSMP system

- Virtual Domain Creation

For a start, a conceptual product or tool is modelled by using computation and analysis function in one three-dimensional (3D) CAD software. This is an essential step that is carried out at the outset to ensure the viability of the project.

- Physical Domain Creation

Once the 3D model is developed, techniques such as RP and RT, high speed milling machine etc., serve for creating the soft tooling, which will in turn be functioned in a short run of sheet metal forming. However, the tooling is not hard enough to be employed in a mass production.

- Functional Stamped Parts

After functional parts, or prototyping parts, are produced, they may be fitted into an assembly or analysed for quality and appearance. At this stage, tool design and embossed parts can be evaluated. The geometry of the functional parts can be reconstructed with the measurement data by either contact or non-contact 3D scanners. By importing the reconstructed model into the virtual domain, a comparison can then be made between the design model and actual product. Features such as the spring-back for bending and least die radius curvature or other errors will be figured out in CAD systems. By using this feedback loop and computer-aided verification (CAV), modifications can be made to compensate and eliminate errors in the next design iteration of tooling and functional parts.

Currently, much attention is concentrated on finding alternative ways to create the special tooling. Consequently, two major approaches are undertaken to explore the methodology with the aids of RP. The indirect methods involve several conversion steps before the required tools are prepared. The masters have to be made before going through casting to produce the aluminum/epoxy tooling. Here, masters refer to models that posses the physical outlook of the desired parts but lack of the material properties such as tensile strength, hardness, durability, etc. In this case, three processes selected to make the masters are Stereolithography (SLA), Selective Laser Sintering (SLS), and high speed CNC milling. The direct approach for rapid tooling is implemented by using the DTM's metal sintering in order to avoid any intermediate step.

The various approaches undertaken can be seen as the four paths A, B, C and D in Figure 2.

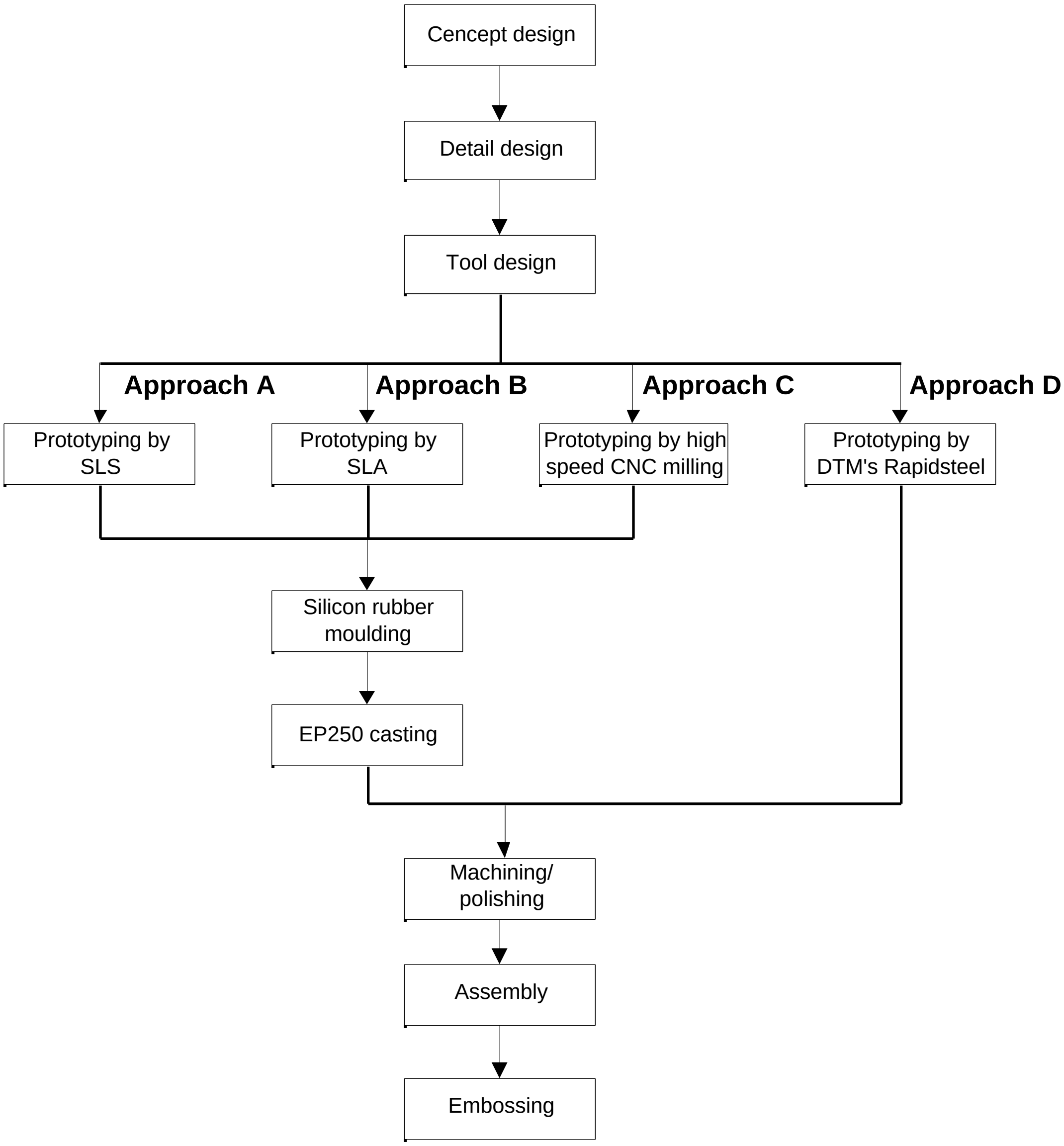

Figure 2. The flow diagram of the four approaches

3. DESIGN CONSIDERATIONS

3.1 Embossed Design

A Merlion logo (a lion head with a fish body/tail) is selected as the embossed design for all the approaches. The 2D design is first generated using Pro-Engineer Sketch module. The text is next incorporated into the design such that it carries the meaning of NTU (***N***anyang ***T***echnological ***U***niversity) and TP (***T***emasek ***P***olytechnic) where both of them share the same lettering 'T'. This is shown in Figure 3. A good design should avoid the possibility of crumpling the sheet metal and disfiguring the shape of the merlion head and the lettering.

Figure 3. The embossed design

3.2 Tooling Design

The Turret Punch Press driven by servo-motors will be used for the embossing process. By modification of the standard forming tool to incorporate the concept of die insert, various embossed designs could later be changed easily. Once this concept is established, the die insert and punch are modeled using Pro-Engineer. After the modeling, the top surface of the die insert and punch is then ready for placement of the embossed design. Each forming surface on the die insert is then subsequently offset by half the material thickness followed by a mirror function to get an opposite effect of the embossed design. The radius curvature of corners is initially set to be 0.6mm which can be reiterated later in the process to obtain a good value for the embossing operation.

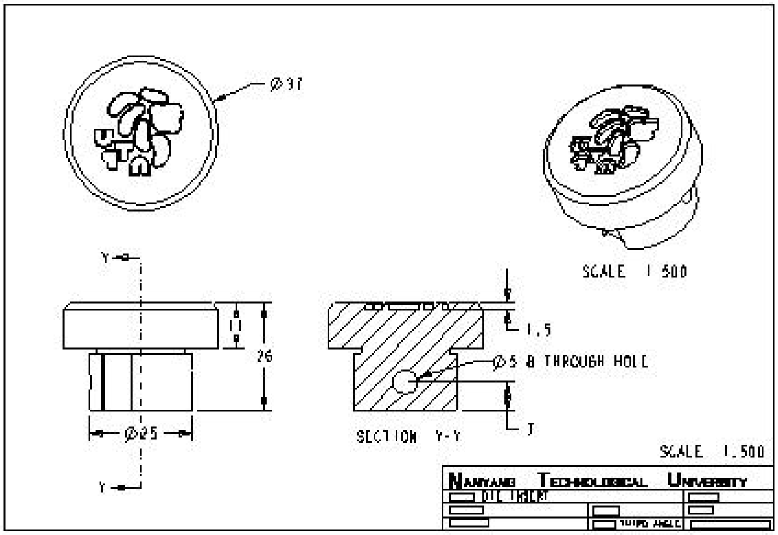

Figure 4. The design of the die insert

One important point for the tooling design is the alignment between the die insert and the punch. Slight misalignment will affect the quality of the embossed design and tool fracture will result in serious misalignment. Alignment problem in this case is solved by incorporating pin holes on the punch and die insert. A die holder for holding the die insert and a stripper are next designed in Pro-Engineer to fit that of the new concept. Since both the die holder and stripper, the exchangeable parts in the whole die, only need to be produced once, they were produced using conventional machine instead of RT technology by an external contractor.

In order to ensure viability of the design, the forming tools with the holder and stripper are assembled in Pro-Engineer to verify that they fit nicely with each other and virtually simulate the embossing process. The design of the die insert is presented in Figure 4.

3.3 Design of Masters

The masters of the tooling are next developed by modifying the design of the actual tooling. It is known that the dimensional and surface accuracy produced by RP techniques can not meet the requirement for precise assembly in many cases. Therefore, an allowance of 4mm is applied to the surfaces that fit into the die holders for machining and polishing purposes. Other modifications are optional like removing the step that is present in the actual tooling in order for easy releasing of the masters during the casting stage. Once this is proven, the 3D CAD models are converted into STL-formatted files ready to be input to the building stages. The die insert master is shown in Figure 5.

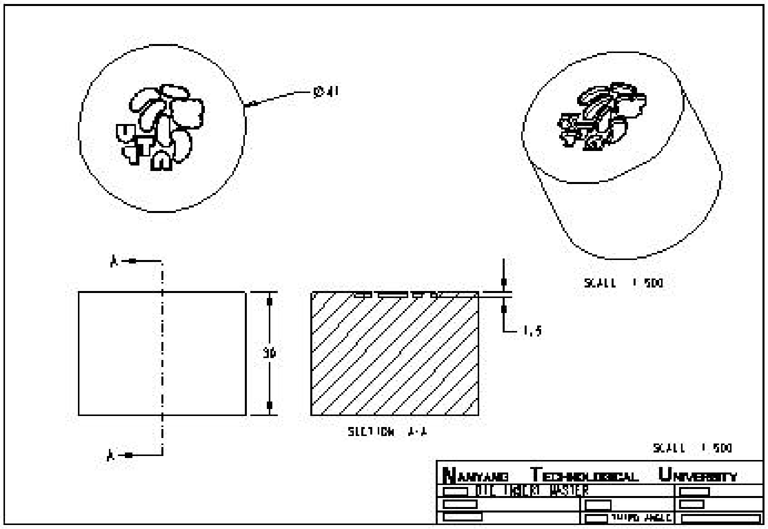

Figure 5. The design of the master

4. TOOLING PREPARATION

4.1 Use of SLS

The steps involved in this approach (Flow A in Figure 2) are:

4.1.1 Building of masters by SLS

In the SLS process [8], a thin layer of powdered material is deposited from feed cartridges over the working area by a roller. Within an inert nitrogen atmosphere, the powder is maintained at a temperature just below its melting point. A focussed CO_2 laser beam is directed onto the powder, tracing out the pattern of the cross-section of the model to be built, and causing fusion of the powder. The process is then repeated with the next layer of powder until all layers are complete.

The quasi-solid part is finally produced within a powder cake, which provides natural support for isolated parts. After slowly cooling down, the cake is gently removed. Finally, the parts are broken out and cleaned using a bead blaster machine. The required masters built on a Sinterstation 2500 (DTM Corp.) are shown along with the produced by other two routes in Figure 6.

Figure 6. Masters made by SLS, CNC, and SLA

4.1.2 Silicone rubber molding

Once the masters are built, they are then used in a secondary process, or vacuum casting, to generate the non-ferrous forming tool. Vacuum casting[9] uses silicone rubber that can be moulded around a master pattern to produce a cavity. Transparent silicon rubber (Product name: VTV 750 from MCP, Germany) is first mixed with the determined amount of catalyst (recommended ratio is 10:1) and de-gassed in a vacuum chamber. The de-gassed mixture is then poured around the master which is initially mounted to a sprue (typically with super-glue) and suspended within a casting frame. The casting frame with the master and uncured mixture is then further de-gassed at room temperature. This is done to avoid trapped air bubbles which could cause mould surface defects if they happened to occur at the interface between the master and the silicon rubber. After the mixture has been properly de-gassed and poured into the casting frame, the whole frame with the master and mixture is then placed in a temperature-controlled oven and cured at 40°C for about 5 hours.

After curing, the mould is cut with a scalpel at the pre-determined parting line. Release of the master leaves a mould in two segments or more, which depends on the complexity of the master. It is easy to bend the segments together into a mould with tapes (as shown in Figure 7). The cavity constructed with the silicone rubber can be used to mould a variety of materials at relatively low temperature. The biggest advantage of the silicone rubber molding is the material flexibility that facilitates taking out both the master and casting products from the mold no matter how complex the geometry may be.

Figure 7. Silicon rubber mold assembled

4.1.3 Aluminum epoxy casting

The casting material used in the study is the aluminum epoxy EP250 from MCP, which comes along with resin and hardener in two separate packages. This EP250 mixture is then poured into the silicon rubber cavity in a vacuum to avoid air bubbles. It is cured at a temperature of 50°C for a duration of 6 hours after which the mould is separated to release the aluminium epoxy parts. The parts then go through a secondary curing at a temperature of 150°C for 6 hours to strengthen its mechanical properties. The finished parts are tested to have mechanical properties that are similar to those of aluminum. The EP250 parts have to be machined on a lathe machine to the nominated dimension and with the pin holes drilled before assembled into the die and punch holders. Three sets of the EP250 tooling by various approaches are presented in Figure 8.

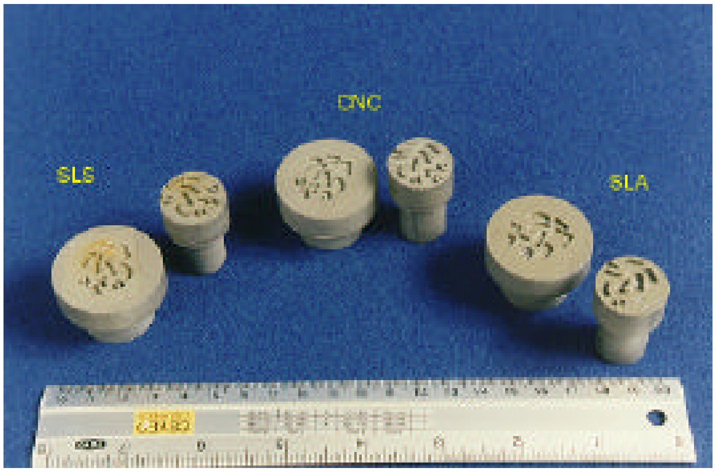

Figure 8. The three sets of aluminum/epoxy tooling

4.2 Use of SLA

Basically, the process is similar to that described in Section 4.1. The major difference is that the master is built on an SLA250 machine, from 3D System, USA.

The Stereolithography (SLA) process involves a control computer which reads in the build file in order to direct a focussed ultra-violet laser beam onto the surface layer of a vat of liquid photosensitive resin (photopolymer). The laser energy causes the layer of resin to polymerise, so that it becomes solidified. Within the vat of liquid resin is a platform which holds the solidified resin layer. Once a layer is complete, the platform is lowered under computer control so that the liquid resin flows over the polymerised layer. Excess resin is removed by a blade, so that the depth of liquid resin remaining above the solidified layer is exactly equal to one layer thickness of the model being built. The polymerisation process is then repeated layer by layer. When the object has been completely built, the platform is raised above the vat of the resin to drain off the excess liquid resin that has adhered to the object. The parts are post-cured in an UV oven before they are served as masters to create the silicone rubber molds, and eventually the EP250 tooling.

4.3 Use of High Speed CNC Milling

It is also possible to work initially with the STL files and proceed onto high speed milling machining and vacuum casting as in flow C in Figure 2. The detail processes are almost the same as the approaches described previously. The masters of the forming tool in this case are fabricated using a high speed CNC milling machine. The experimental system is well developed so that it can operate on a spindle speed in excess of 70000 rpm to easily cut machinable plastic materials instead of steel. The feedrate adopted here is 400mm/s and the diameter of the ball-end tool is 1mm. The control programme for the system has a function to automatically generate tool paths based on STL-formatted files. Indeed, the STL files used in this project are uniform for any of the approaches, which keeps the comparison independent of possible errors coming from data representations.

4.4 Direct Use of RapidSteel

This approach can build the forming tools directly without going through secondary processes. RapidSteel 2.0, commercialized by the DTM Corp., is a stainless steel-based powder mixed with binder. By using the STL file of the actual tooling that has previously been developed, the Sinterstation 2500 System processes the powder. The result is called a 'green' part. The green part is then post-processed in a furnace where the binder is burnt out and the metal powders are bonded together through the traditional sintering mechanism. This cycle is named the sintering furnace cycle and it takes place at a temperature of 1120°C. The part is then allowed to cool. At this stage, the product is referred to as a 'brown' part that exhibits durability, but is also porous in nature.

After debinding, Bronze infiltration is the final step that will be conducted in the same furnace. This metal melts with elevated temperature and infiltrates the brown part via capillary action, resulting in a fully dense part. The part is then allowed to cool at a rate of 180°C per hour. The fully dense component consists of 60% steel and 40% copper. The die inserts from RapidSteel are shown in Figure 9. And it is found that the RapidSteel part has a good machine-ability to be post-processed by milling, turning and polishing. However, due to the existing of the copper and porosity in the final part, the RapidSteel product shows the weakness in strength, hardness, durability and other mechanical performance compared to the exact steel tooling.

Figure 9. The RapidSteel die and punch insert (left)
and the partially polished insert (right)

4.5 Sheet Metal Embossing

The tooling built from different approaches are machined and polished before they are then assembled with the die holders and mounted onto the Turret Punch Press machine one after another (see picture in Figure 10). The embossing process is carried out on a 0.4mm thick aluminum sheet metal with the prepared tooling. Figure 11 shows the samples produced.

Figure 10. The assembled tooling

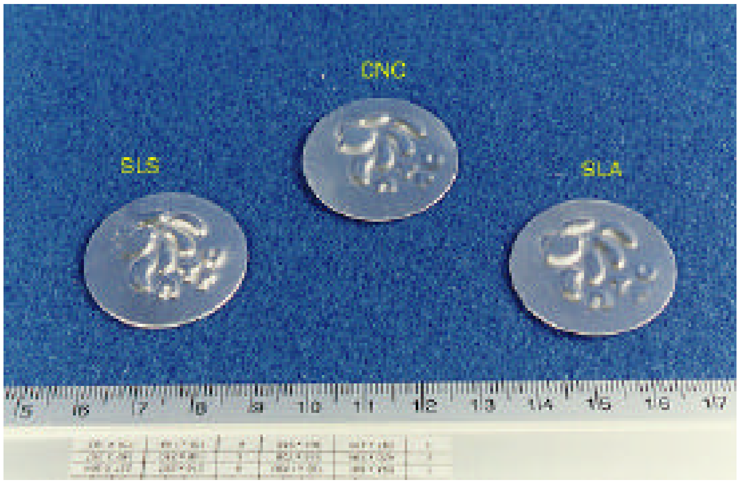

Figure 11. Embossed sheet metal samples

Results show that the spring back effect for all embossed design on different tooling sets does not vary much and is of a small magnitude. Tearing of the aluminium sheet metal is experimented when the tools are fully closed or sits on each other. This may be due to the fact that the limiting depth is exceeded. It can be calculated that the theoretical maximum drawing depth allowed for a 0.4mm thick sheet metal is 1.2mm, or three times of the sheet thickness. As the actual depth reached in this case is measured to be 1.4mm, this exceeds that of the maximum allowed. Results like these are helpful to improve the design for the next iteration until no error occurs.

In each case, no significant tool wear is visually observed after 10 stamping operation. In order to keep the tools for the further study, the lifetime is not investigated by destroy testing.

It is observed that the high speed CNC milling/vacuum casting approach produces the best surface finishing of the embossed sheet metal. The worst of all the approaches is the SLS/vacuum casting approach. The result is obvious since the SLS tends to produce a master that is rougher than other processes. The quality of masters directly affects the final outcome of the tooling, and then that of sheet metal products.

5. COMPARISON AND DISCUSSION

A total of three design iterations and several sets of prototypes are made in this case study. However, with more user experience and refinement to the tool, a higher success rate should be achievable. In addition, a set of hard tooling is also subcontracted to Liau Ying Industries Engineering so that comparison between RT and conventional technique can be accomplished. By eliminating the unexpected iteration or interfering, a comparative study is being conducted on the designed tooling by different building techniques.

The surface finish of each master and cast part is visually inspected and measured with a profilometer (Mitutoyo Surftest.301) before machining. The surface measured is the top face of the parts. Three measurements are performed on the target face of the masters and the cast parts, and the average of the measurements is then taken.

Dimensions are also measured on the feature produced to determine the processes' accuracy. As any parts of the features can be taken to be the reference dimension, the outer diameter is chosen as it is deemed to be the easiest to measure. The measured results are compared with the CAD design values and the differences yield the deviation. Both of the results on the surface roughness and dimensional deviation are summarised in Table 1.

As one of the primary objectives of RT is to produce tools with the least cost and time spent, the time and cost comparison between various approaches are given in Tables 2 and 3 respectively. The leading time for each approach is summed up with all steps covered, assumed that the steps happen continuously without any delay. In other words, the machine occupying time is the major concern in the comparison. The cost calculation includes the material consumable only.

Table 1. Surface and dimensional quality from different approaches

	SLS		High Speed CNC milling		SLA		Rapid Steel 2	Conventional Hard Tooling
	Master	Emboss Tool	Master	Emboss Tool	Master	Emboss Tool		
Surface Roughness (Ra)	14.8μm	16μm	4.66μm	6.8μm	0.53μm	1.2μm	10.8μm	0. 12μm

Dimensional Deviation (mm)	+0.45	+ 0.5	+0.04	+0.1	+0.25	+0.3	+0.4	+0.05

Table 2. The machine occupying time of various approaches

	SLS		High Speed CNC milling		SLA		Rapid Steel 2	
	RP Master	9.5 hrs	RP Master	6 hrs	RP Master	11.5 hrs	Green Part	6 hrs
	Silicon Rubber Molding	7 hrs	Silicon Rubber Molding	7 hrs	Silicon Rubber Molding	7 hrs	Debinding	24 hrs
	EP-250 Casting	7.5 hrs	EP-250 Tooling	7.5 hrs	EP-250 Tooling	7.5 hrs	Infiltration	24 hrs
	Lathe/ polishing	3 hrs	Lathe/ polishing	3 hrs	Lathe/ polishing	3 hrs	Lathe/ Polishing	3 hrs
Total time	**27 hours**		**23.5 hours**		**29 hours**		**≈ 57 hours**	

It is obvious that presently none of the discussed techniques can produce the durable tooling for mass production due to the weak mechanical properties. However, the soft tooling, from either the non-ferrous or RapidSteel 2, manages to form functional parts using the relatively soft sheet metal like aluminium or copper material. Regarding the dimensional and surface accuracy, the result generated by CNC milling is the best because the stairstep problem is less serious in the milling process than in RP.

There are few differences in time consumed between the four RT approaches. It takes only three or four days to produce the forming tool by whatever technique used in this case. Obviously from this project, the cost on producing the short-run tooling is extremely trivial compared to that on the steel tooling.

Table 3. Comparison of the different approaches by cost of tool development

	SLS		High Speed CNC milling		SLA		RapidSteel-2		Conventional Tooling
	Master (40g)	$12	Master (250x150x 50mm)	$23	Master (56g)	$24	Green Part (500g)	$75	Die insert $1500 Punch $1500
	Silicon Rubber (1.2kg)	$89	Silicon Rubber (1.2kg)	$89	Silicon Rubber (1.2kg)	$89	Infil-trant (500g)	$34	
	EP-250 Tooling (50g)	$13	EP-250 Tooling (50g)	$13	EP-250 Tooling (50g)	$13	Nitrogen/ Hydrogen	$30	

	SubTotal	$114		$125		$126		$139	
	20% Material Wastage	$22.8		$25		$25.2			
Total Cost	**$136.8****		**$150****		**$151.2****		**$139****		**$3000**

*Cost calculation does not include labor cost and machine depreciation

The following information is used for the cost calculation:

- SLS Duraform = $2950/10kg
- SLA Epoxy Resin SL5170 = $4240/10kg
- CNC polymer (Cibatool BM5460) = $450 per 1500x500x50mm
- Silicon Rubber VTV 750 = $1485/20kg
- EP250 = $2500/10kg
- RapidSteel2 = $2750/20kg
- Brown Infiltrant = $1350/20kg

In addition, it is well known that RP techniques are able to generate freeform parts with almost no geometric constrain. However, the high speed CNC milling approach may suffer the drawback when under cut is unavoidable or special fixtures are needed. The ability of complexity independency helps the research result widely applicable.

Thanks to the time and cost compression technique, any amendment, either serious or trivial, is easy to make as the RSMP concept allows the modified design to be iterated within a few days until a satisfactory outcome is achieved.

6. CONCLUSION

The various approaches have been carried out to implement the concept of rapid sheet metal prototyping. The flexibility of CAD systems enables the optimization of the tooling needed for sheet metal manufacturing. With the further introduction of SLA, SLS, High speed CNC milling, and RapidSteel in the tool making stages, a short-run production of sheet metal product is possible with the lower cost and shorter leading time. Other work will be done in the future to optimize the tooling design based on the calculation of data errors between the CAD model and reconstructed model generated by scanning the actual part. Finally, it will bring about more benefits from the close loop concept of the RSMP system.

Acknowledgements

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