Proposed Roadmap for Product and Process Redesign in the Migration from Joining Processes to Monolithic parts Production for Sheet-metal Components

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Abstract

Continuous improvement is the cornerstone of business survival as the chase to satisfy the ever-changing market demand intensifies in the midst of the reality of global competition. The improvements may be in the product, the process or both and can be minor or major changes. This paper presents a proposed roadmap and guideline for the product and process re-design when migrating from joining processes to monolithic parts in the production of sheet-metal components. The research focuses on replacing TIG welding as a joining process with deep drawing to produce monolithic components. A hypothetical cylindrical cup of height 56 mm and diameter 100 mm is used as a case study and superimposed in the two manufacturing methods and the end product evaluated using simulations. The starting sheet material is aluminium 6061 of 2 mm thickness. The results show a minimum weight reduction of 5% for the deep drawn component. The weight reduction also results in corresponding cost reduction. A five-step roadmap with specific work packages is proposed for smooth migration. The proposed steps are product redesign, process design, tool design, tool manufacture and product manufacture.

Keywords
TIG Welding, Deep Drawing, Monolithic Components, Sheet-Metal Forming

1. Introduction

A clear strategic roadmap is required before any major product or process changes are adopted for continuous improvement. This enables companies to plan the sequence of steps and all the activities that will lead to complete changeover to the new product and process. In this way the potential risks are dealt with at the planning stage and the possible gains of the changeover will be realised. In this research a strategic roadmap for replacing a Tungsten Inert Gas (TIG) Welding process with the deep drawing process in order to produce monolithic (one-piece) components. Monolithic parts completely eliminate or reduce the need for joining processes as well as the associated resources and costs leading to resource efficient production methods (Allwood, Ashby, Gutowski, & Worrell, 2013). The use of monolithic parts has become an option for many manufacturers as they try to reduce the number of parts. In the automobile industry processing time has reduced by over 50 % in some cases (Boothroyd, Dewhurst, & Knight, 2011). Replacing TIG welding with deep drawing results in reduction in raw materials input into the manufacturing process and in turn reduces the weight of the product as well, weight reduction brings enormous advantages to the automotive industry like savings on fuel (Mazahery, Habibnejad-korayem, & Takrouri, 2019). Other notable benefits of producing deep drawing include the increased strength of the components due to strain hardening during drawing (J. Liu, Tan, Jarfors, Aue-u-lan, & Castagne, 2010). Parts made from deep drawing thus have a higher strength to weight ratio. However, in order to realise the benefits of switching over to deep drawing from TIG welding a clear roadmap is required and the potential benefits need to be quantified to give an objective insight of the envisaged new process.

2. Tungsten Inert Gas (TIG) Welding

Tungsten Inert Gas (TIG) Welding is a metal arc welding process that is used in joining similar or dissimilar metals of varying thickness using a non-consumable tungsten electrode and a passive gas for arc shielding. Figure 1 shows an illustration of the TIG welding process. The process can be done using a filler metal or not. It is most commonly used for aluminium and stainless steel and produces a high-quality weld. However, the process is usually slow especially when performed manually (Groover, 2010). According to Haynes (2020) the recommended speed for manual TIG welding is between 100 and 150 mm/min. In manual welding the quality of the weld may be affected by the inconsistencies in the weld seam (Cevik & Ozer, 2016). In most cases manual TIG welding would then require post processing of the welded assemblies like grinding and polishing. Another short-coming of the TIG process is that it produces relatively weaker welds compared to other process like Friction Stir Welding (FSW) and Metal Inert Gas (MIG) welding (Ren et al., 2018). These challenges compounded make the manual TIG welding process a candidate for replacement using more efficient production methods like the deep drawing if the product permits. However careful planning is required before switching.

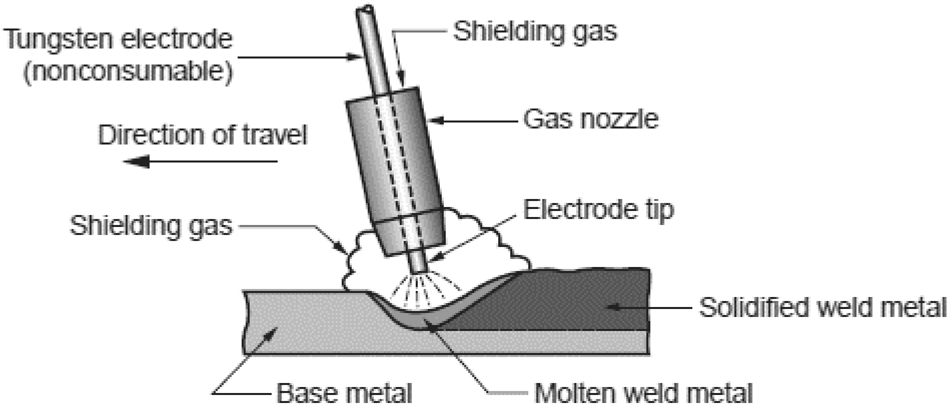


Figure 1: TIG Process overview (Groover, 2010)

3. The Deep Drawing Process

Deep drawing can be defined as a forming operation in which a punch draws a sheet metal called a blank into a die to form a recessed component (Poli, 2001). In other words, components are made by plastic deformation of sheet metal using a combination of punches and dies. The manufacturing technology is used in the production of sheet metal components with cavities. Figure 2 shows an illustration of the deep drawing process. In most cases the products of deep drawing are cup-shaped or box-shaped, with varying degrees of complexity. The process has been in use for several years and is mainly applied to materials that have high ductility and low yield strength, although these properties can be altered by the temperature (Groover, 2010). The temperature at which the process is conducted defines whether the process is cold working, warm working or hot working. The material recrystallisation temperature is used as a reference point for classifying cold, warm and hot working. Cold forming is done at room temperature, while warm forming is done at temperatures slightly below the recrystallisation temperature and hot forming is done at temperatures above the recrystallisation temperature (Callister, 2007).

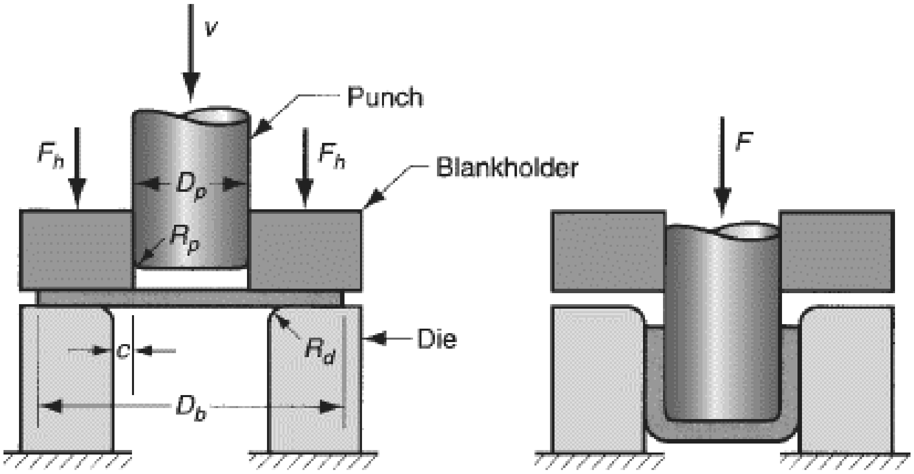


Figure 2: Illustration of the deep drawing process (Groover, 2010)

Some of the common parts that are made using deep drawing include beverage cans, sinks, cooking pots, metallic tubs, wheelbarrow shells, aviation and automobile body panels (Poli, 2001). In the automotive industry sheet metal forming accounts for about 65 % of the components (Hu, Ning, Li-zhong, & Yi-guo, 2013). In general, deep drawing is used in the manufacture of relatively light weight parts with high surface area to volume ratio (Groover, 2010). It is applicable for high production volumes because of the high tooling costs (Boothroyd et al., 2011). The deep drawing has cycle times of less than 20 seconds for the actual drawing operation (Chiorescu, Chiorescu, & Olaru, 2018).

3.1 Planning the Deep Drawing Process

There is a lot of ongoing research around the deep drawing process, this can arguably be attributed to the process being used predominantly in the automotive industry which has stiff competition. Most of the research is showcased through the Numerical Simulation of 3D Sheet Metal Forming Processes (NUMISHEET) conferences and workshops. NUMISHEET aims to promote research of sheet metal forming simulations and assess the reliability of numerical analysis algorithms (Hu et al., 2013). The research focuses on the product design and the deep drawing process design. The product design stage provides input into the process design stage. For a new product and new process, the design stages can be approached sequentially or concurrently, although concurrent engineering approaches are recommended because they have capacity to reduce total costs by more than 80 % as problems are easily detected at an early stage in design (Boothroyd et al., 2011). The research found five thematic areas that need to be addressed in order to make products using the deep drawing process. These are namely (i) the product design, (ii) the process design, (iii) tooling design, (iv) tool manufacture and (v) product manufacture. The thematic areas form the foundation of the strategic planning roadmap for a successful switch to the deep drawing process. A complementary work package of related activities must then be incorporated into the roadmap in order not to miss important tasks.

3.2 Product Design Phase

When switching a production process from TIG welding to deep drawing it is essential that the product be redesigned to make it easier for it to be manufactured using the deep drawing process. Boothroyd, Dewhurst, and Knight (2011) have recommended a number of Design for Manufacture (DFM) guidelines for deep drawn components. The component should be designed having parallel straight edges that define the part width and the other end profiles ought to meet the edges at angles not less than 15° to allow for parting off operations. The product design also has a bearing on the tooling required thus narrow projections and notches must be avoided as they compromise the strength of the tools. Hence, it is recommended that any features be at least twice the material thickness. Poli (2001) also weighs in with additional DFM guidelines for all the sheet metal forming operations including the deep drawing process. He recommends that the number of distinct features in a part should be kept minimum and that side action features should be eliminated when designing a component. This is done to minimise the cost of the tooling. Sharp corners are also not easily achievable using the deep drawing process. It is therefore necessary to redesign the product to suit the product to the envisaged process of deep drawing. Computer Aided Numerical Software programs that do Finite Element Analysis may be used during the product design process.

3.3 Process Design Phase

In the process design phase, it is necessary to determine the process parameters that affect product quality so as to be able to control the process parameters that affect product quality. Some of the identified process parameters for the deep drawing process include the blank holding forces, friction coefficients, strain-rate, blank thickness, blank shapes, temperatures, drawing force and punch velocity (Sahu & Pradham, 2020). The quality of the product is dependent on these parameters for example, insufficient blank holding force leads to formation of wrinkles, while excessive blank holding force may lead to tearing (N. Liu & Fang, 2011). Due to strain hardening more research is being done towards the provision of a variable blank holder force in order to produce a component without any defects (Solfronk & Sobotka, 2011). Drawing ratios are also important process parameters that affect spring-back in deep drawn components (Lal, Choubey, Dwivedi, & Kumar, 2018). The quality of product changes using different parameter settings as was shown from research conducted by (Yang, Wang, Zhou, Dang, & Xiao, 2020) to investigate the effect of temperature, tool velocity and friction on the product quality in hot forming. These parameters have different levels of criticality. The forming temperature is one of the most critical forming parameter in the drawability of Al/Mg/Al laminates, followed by other parameters like tool dimensions and drawing speed in addition to clearances and gap support at flanges (Nie, Chi, Chen, Li, & Liang, 2019), (Kusumi, Nomura, Yamamoto, & Nakata, 2014). In a study to investigate the spring-back behaviour of high-strength aluminium alloys based on cross profile deep drawing tests, the geometry of punch and die as well as the blank holder force were identified as variable process parameters that affect spring-back (Hetz, Suttner, & Merklein, 2020). In the production of monolithic parts by deep drawing it is therefore necessary to investigate the effect of the following process parameters in the quality of the products; (i) Forming temperature (ii) Blank holding force (iii) Drawing force (iv) Friction and lubrication (v) Strain rate (vi) Dimensions and shape (blank and tool) (vii) Tool velocity and others. This should be done with the view of prudently seeking to prevent, minimise, or predict the following defects plus other customer perceived quality parameters in deep drawn monolithic parts; (i) Wrinkling (ii) Tearing (iii) Earing (iv) Excessive Thinning (v) Spring back and (vi) scratches (Groover, 2010).

3.4 Tooling Design and Manufacture Phase

The other important phase in planning for the deep drawing process is the tooling design followed by tool manufacture phase. Tool design encompasses the design of the punch and the die set to be used for deep drawing. This also includes the selection of an appropriate press machine (Boothroyd et al., 2011). Like the product design phase Computer Aided Finite Element Methods (FEM) can be used in designing the tools (Panicker & Panda, 2019). Besides the product geometry, the process parameters that are determined by the formability of the materials to be used also have an influence in the design and manufacture of the deep drawing tools. Tool life is an important consideration during tool design (Hazrati, Stein, Kramer, & Van den Boogaard, 2018). Therefore, friction modelling becomes a vital process in the design of deep drawing tools. Hillman and Kubli (2009) invented a product parametrised geometry and process model to determine the tooling geometry. When the tooling is designed the next process is the manufacture of the punch and die. These can be produced using conventional manufacturing methods depending on part complexity. Non-conventional machining methods and additive manufacturing methods can also be used to produce the moulds.

3.5 Product Manufacture Phase

The final stage in switching to deep drawing process from TIG welding is the actual use of the deep drawing process after installation and commissioning of the manufacturing setup. Full throttle production is usually preceded by trial runs that often involve a lot of adjustments and training of the manpower. It is important to pay attention to the product quality during the early stages of manufacture. The process parameters will need to be controlled to ensure higher product quality. When everything is in order the process of changing from TIG welding to Deep drawing would be complete.

4. Methodology

After the review of the two processes under study that are the TIG welding and the deep drawing process, a simple framework of a 5-step roadmap for adopting the new process was developed based on the reviewed literature with suggested work packages. A hypothetical cylindrical cup of height 56 mm and diameter 100 mm was used as a case study and superimposed in the two manufacturing methods and the end products evaluated using simulations. The selected material was an aluminium alloy 6061 sheet metal of 2 mm thickness. Product dimensions and the forming tool were designed to satisfy all the technical feasible deep drawing conditions according to Poli (2001), Groover (2010) and Boothroyd, Dewhurst, and Knight (2011). These were a drawing ratio of 1.8, reduction of 0.44 and thickness to blank diameter ratio of 1.11 %. The two products were constructed using SOLIDWORKS software and were evaluated by comparing their properties. Table 1 shows the properties of aluminium 6061 used in the study.

Table 1: Properties of Aluminium 6061

Property	**Value**	**Units**
Elastic Modulus	6.90×10^{10}	N/m^2
Poisson's Ratio	0.33	
Shear Modulus	2.60×10^{10}	N/m^2
Mass Density	2.70×10^{3}	kg/m^3
Tensile Strength	1.24×10^{8}	N/m^2
Yield Strength	5.51×10^{7}	N/m^2
Thermal Expansion Coefficient	2.40×10^{-05}	/K
Thermal Conductivity	170	W/(m·K)
Specific Heat	1300	J/(kg·K)

A forming tool was developed in SOLIDWORKS in order to simulate the deep drawing process and produce a virtual monolithic component. The forming tool developed is shown in Figure 3.

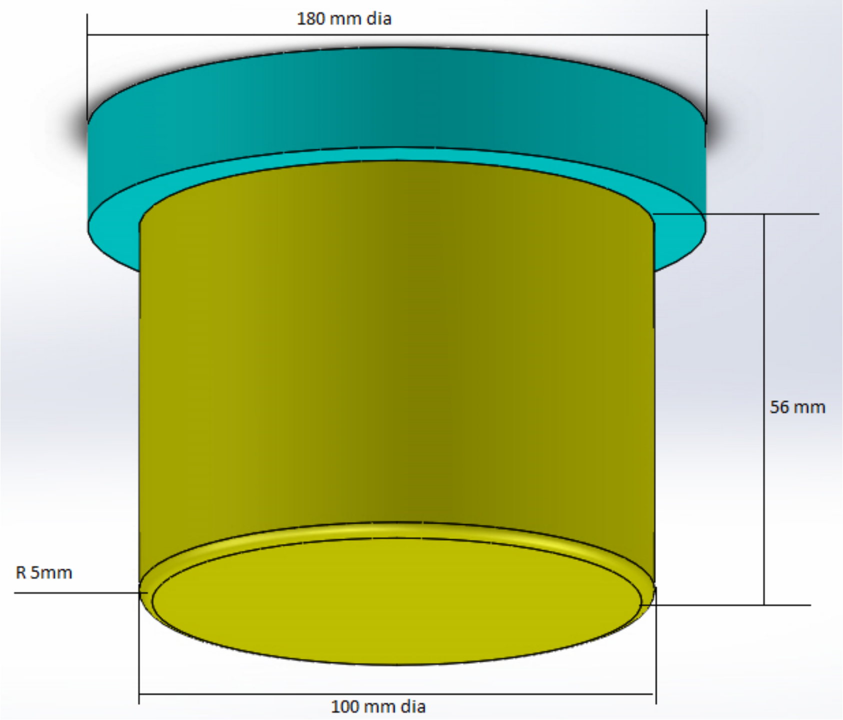


Figure3: Forming Tool developed in SOLIDWORKS

5. Results

The results from the review suggested five-step roadmap in order to successfully adopt the deep drawing process as an alternative to the TIG welding when the production volumes increase. Figure 4 shows the key milestones and suggested specific work packages for a smooth migration.

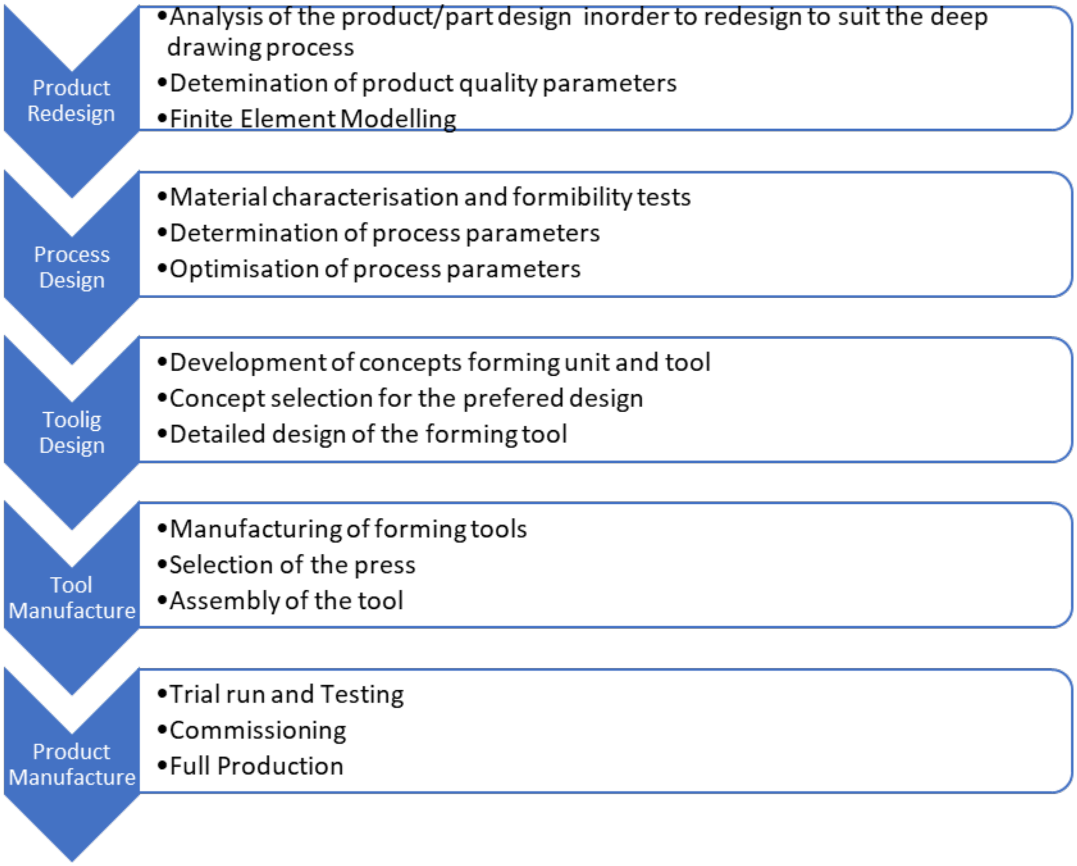
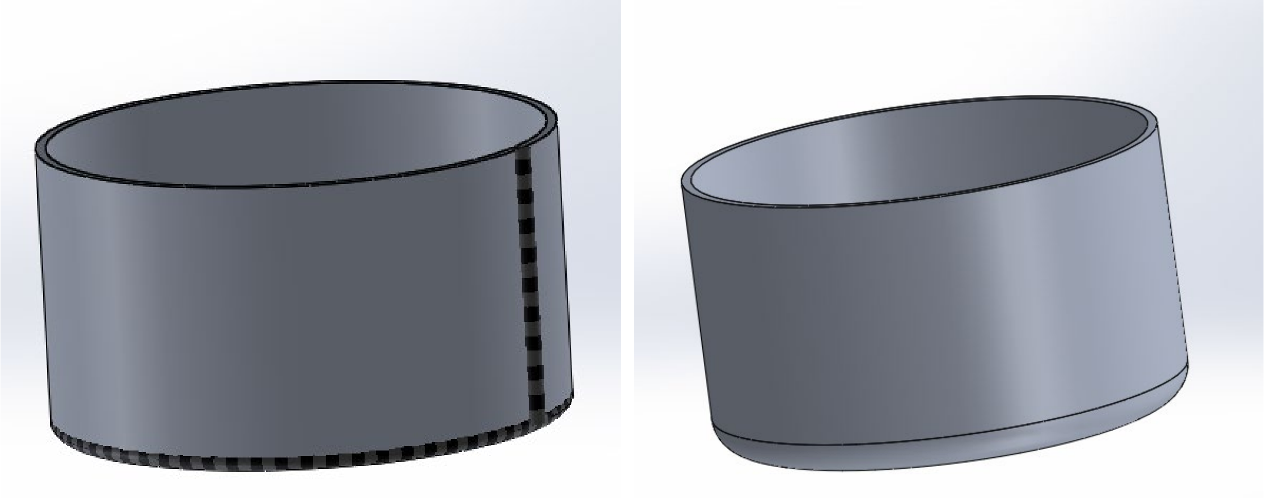


Figure 4: Thematic areas in deep drawing processes

Results from the simulations done in SOLIDWORKS are as shown in Figure 5 and Table 2. The mass of the welded component was 139 g while that of the monolithic component produced by deep drawing was 131.78 g neglecting the mass of the weld bead which also varied according to weld thickness. The monolithic part used less material by at least 5 % neglecting weld thickness. If weld thickness was to be considered savings of up to 75 % would be realised. However, for fair comparison the weld thickness would be neglected since at times TIG may use or not use a filler metal and that would mean a varying weld mass and an unfair comparison. The weld length is 370.15 mm and this would take between 2.5 to 3.7 minutes in manual welding. This cycle time is far too long compared to that of deep drawing which has less than 20 seconds in some of the reviewed operations. There is therefore a potential of improving the cycle time by up to more than 80 %.



TIG welded component Deep drawn monolithic component

Figure 5: Welded and deep drawn components

Table 2: A comparison of the welded component and a deep drawn component

TIG Welded Component	**Deep Drawn Monolithic Component**
Mass = 139.00 grams	Mass = 131.78 grams
Total weld length = 370.15 mm	Total weld length =0 mm
Total weld mass = 370.15 grams (variable)	Total weld mass = 0 grams

6. Conclusion

In conclusion, there is a lot of potential for the replacement of TIG welding with monolithic components produced by sheet metal forming through deep drawing. As the production volumes increase at times the TIG welding becomes slower especially when done manually. The research achieved a reduction in weight of at least 5 % for the deep drawn component used in the simulation. The weight reduction is desirable in saving resources hence also reduces the cost of producing the product. The deep drawing process also has 80% shorter cycle times compared to TIG welding and there is potential to benefit from economies of scale. A five-step roadmap is proposed for the migration from TIG to deep drawing. The steps involved are product redesign, process design, tool design, tool manufacture and product manufacture. It is recommended that the steps be carried out concurrently in order to minimise the migration time. Incorporating life cycle thinking through out the stages will ensure sustainability.

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