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An overview and evaluation of alternative forming processes for complex aluminium products

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Abstract

Many industries are facing new forces that cause upheaval in the way products are designed, engineered, produced and used. Consumer preferences in terms of personalization and customization, sustainability criteria and the availability of digital technology together create a new paradigm for integrated product and process development. This paper unfolds from this macro perspective and makes a trajectory towards how this view influence existing and emerging metal forming processes. Knowing that design spaces in many applications are compressed, we hypothesize that characteristics such as die cost, formability, dimensional accuracy, production volume, cycle time, change-over-time, and value stream synergies become ever more important in the future. This paper outlines opportunities and limitations of several alternative forming processes due to these characteristics, and provides advice on how to select an appropriate process in relation to problem at hand, and shortfalls on industrial maturity and applicability of the following processes, viz., single point incremental forming, hydroforming, stretch-bending, and press form hardening.

Keywords: quality; aluminium forming; dimensional tolerances; product properties

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1. Introduction

We hypothesize that part complexity increases in the transport sector due to more dense systems, where a number of factors contribute towards added mass simultaneously as volume demand for passengers and freight increases. A number of studies document the trend of increase in vehicle weight and size, where an EU report [1] tells that the average mass of the best-selling passenger car models in selected EU Member States increased by 18% over the period 1995-2010, whilst the average EU-27 new fleet mass increased by 3.2% between 2004 and 2013. In addition, this study tries to calculate the trend in car density by looking at the car's footprint (vehicle wheelbase multiplied by its track width) and pan-area (vehicle length multiplied by vehicle width). By using these proxies for the surface area of a vehicle the density in terms of kg/m2 has increased by 4% between 1995-2010. Reasons for mass and density increase are safety applications, electronics, a shift from petrol to diesel cars, and the popularity of crossover vehicles.

A study by EPA [2] shows that average mass for US cars increased steadily from 1980 to 2004 by in total 20%, and from 2004 to 2017 a mass drop was noticed according to the financial crisis but 2017 is the highest registered mass since 1975. Vehicle mass-reduction technology offers the potential to reduce the mass of vehicles without compromise in other vehicle attributes, like acceleration, size, cargo capacity, or structural integrity [3]. These technologies involve the commercialization of more advanced mass-optimization technologies, involving more comprehensive vehicle optimization designs that incorporate component-level mass reduction, a diverse mix of materials, secondary mass-reduction effects, new manufacturing techniques, and component integration to systematically make the whole vehicle more mass-efficient.

A recent report by European Aluminium states that the average aluminium content in European passenger cars is

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179Kg, distributed on sheets (34Kg), extrusions (19Kg), forgings (10Kg) and castings (116Kg) [4]. The same report forecasts an increase in sheet demand by 26% and extrusions by 21% within 2025. Although an increase in the number of EVs and hybrids in the European market, parts like battery casings, battery cooling systems and electric motor housings in aluminium currently sum up to 1.5% of the total aluminium usage in cars. A number expected to grow, giving opportunities for forming and assembly of sheet and extrusion parts in the future.

Due to its low density, high strength to weight ratio, good formability, and corrosion resistance, aluminum is a preferred material of choice for many automotive applications such as chassis, autobody and many structural components. Some of the advantages of aluminium are its availability in a large variety of semi-finished forms, such as part castings, extrusions and sheets, all suitable for mass production and relatively innovative solutions [5]. Previous usage of high strength aluminium alloys has been limited by restricted ductility at room temperature, but recent developments in metallurgy and forming techniques have contributed towards the manufacture of complex-shaped high strength aluminium components [6]. For instance, applications such as body-in-white aluminium alloy structures have been significantly extended in vehicles made by Jaguar, Land Rover, Tesla, Ford, and Audi. The growing demand for lightweight materials in the transport sector causes pressure to develop new and advanced forming technologies, as conventional forming methods lack the ability to meet [7]. Part of this trend is the many innovative sheet- and tube-forming methods that have been proposed by researchers and R&D facilities, that greatly can improve the formability of materials with low plasticity and can produce complex-shaped parts with good surface qualities [8].

This paper aims to answer the following research questions:

RQ1: What are the recent status and developments of the selected forming processes with regards to aluminium and shape complexity?

RQ2: What are the practical implications of RQ1 as support for product and process decisions due to critical properties?

2. Method

We will map the current state of the following metal forming processes for sheet and extrusions – in particular by focusing on the aluminium material regime. The following metal forming processes are included: single point incremental forming, hydroforming, 3D stretch-bending, and press form hardening. These processes are selected due to the reason that they can contribute towards achieving increased formability and the demand for more complex-shaped products. Thus, these four processes are at the top hierarchy search words and combinations when searching for literature through Sage, ScienceDirect, Scopus, Springer and Norwegian University of Science and Technology (NTNU)-Open. At the next level keywords such as formability, complex shapes, aluminium is applied, before the third level of strings are added when trying to find publications which give an overview with regards to trends, outlooks, developments, etc. No limitations about the time period was set since initial searches revealed that the amount of literature covering at least 2 search word levels is somewhat scarce. The next step was to systematically examine the scholarly literature about the selected processes, and to analyzes, evaluates, and synthesizes the research findings according to product and process properties as state-of-the-art for research and practice.

3. Results

The result part will summarize the literature search for the four typical metal forming processes, viz., single point incremental forming, hydroforming, 3D stretch-bending, and press form hardening.

3.1. Single point incremental forming

Single point incremental forming (SPIF), as shown in Fig. 1, is a sheet metal forming process that is regarded as a flexible and low-cost process for rapid prototyping and for small quantity production volumes [9]. The idea is not new, where the patent by Leszak for dieless forming goes back to 1967 [10]. The basic components of the process are; the sheet metal blank, the blank-holder, the backing plate, and the rotating single point forming tool. The blank is fixed in position by the blank-holder and the backing plate supports the sheet and its opening defines the working area of the forming tool. The tool progressively shapes the sheet into the final design, most commonly directed by a CNC machine. The single point incremental forming is inspired by the conventional spinning process, where the part is formed by a series of sweeping strokes with a rotational tool. This spinning process can again be broken down into the sub-groups; conventional spinning, shear forming, and flow forming [11]. Research of the SPIF process has so far been concerned about limits of formability, and Martins et al. [9] state that the process can be defined in terms of the following four major parameters; thickness of the sheet, size of the vertical step down per revolution, speed of sheet and tool, and radius of the forming tool.

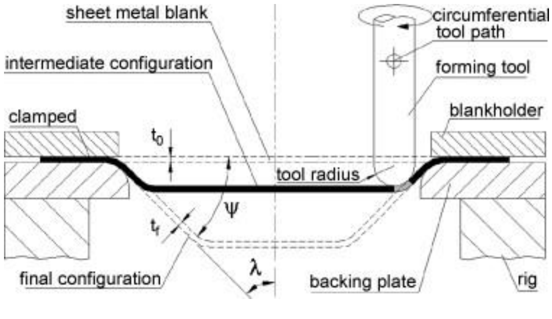

Fig. 1 Schematic representation of SPIF [9].

SPIF offers a relatively fast and cheap production of small series of sheet metal parts, but the process has some drawbacks related to achievable accuracy [12] and process limits [13]. The latter points to the case of defining reliable process parameters according to maximum forming angle. Fratini et al. [14] assert that characterization of the forming limits and the mechanics of deformation remains little understood in order to make the industrial application more widespread. The literature discusses the effects of step size and rotational tool speed on formability. Jeswiet [11] claims that step size itself does not play a significant role in the formability. The forming tool speed is known to influence formability due to friction conditions, where smaller tool radius is claimed to provide better formability due to concentration of strains at the zone of deformation and larger ones to distribute the strains over a more extended area making the process more similar to conventional stamping [9]. In recent years, in order to improve the formability of SPIF, some modified processes have been proposed, such as electrically-assisted SPIF[15], heat-assisted SIPF [16], etc. In addition, by replacing the single point tool with a local electromagnetic field, the electromagnetic incremental forming (EMIF) method was developed, in which the small coil and discharge energy is used to create a local deformation of the workpiece at a very high rate [17]. Micari [18] summarizes characteristics of the SPIF process, and the pros include the following aspects:

- Set-up costs are practically zero;
- Tool movement is supported by standardized CNC machines;
- Process flexibility is very high, and the minimum lot size is "one";
- Suitable for rapid prototyping and small series - as well as repair;
- Formability is larger than the typical of conventional stamping processes.

However, there are some cons of the SPIF, such as follows:

- Incremental forming is a slow process, which normally takes time to achieve the complexity properties of the process;
- Simple clamping configuration may cause extensive springback effects, resulting in great difficulty to ensure the dimension accuracy.

3.2. Hydroforming

Hydroforming is a well-known process that was first employed to form sheets by the use of the fluid medium as a soft punch before World War II [8]. Basically, the hydroforming process is classified into two categories, sheet hydroforming and tube hydroforming. The Sheet hydroforming process utilizes oil or other pressurizing liquids as a medium to press the sheet metal tightly onto the punch when it is drawn into the die by the rigid punch. At this stage, the friction between the sheet metal and die is reduced as a result of the liquid medium in the die cavity which results in a lubrication effect [19]. In the 1980–1990s sheet hydroforming technology achieved extensive development [20]. For instance, to increase the ability to manufacture complex-shaped components, the radial pressure-assisted hydraulic counter pressure deep drawing is proposed to increase the draw ratio [21]. Also, integral hydro-bulge forming technology (IHBF) of shell products, the hydroforming of sheet metal pairs and viscous pressure forming (VPF) appeared successively [20].

In the tube hydroforming process, the initial workpiece is placed into a die cavity which corresponds to the final shape of the component. As shown in Fig. 19, when the die closes fluid pressure is applied internally in the workpiece for expansion towards die walls simultaneously as axial compression seal the punch and force material into the die cavity [22]. Water and oil emulsions are typically used media to apply pressure in the range of 250-600 MPa. Fuchs [23] found that the forming limit of tubes can be improved remarkably by applying liquid pressure to the inside and outside simultaneously. For double-sided tube hydroforming, the increase of external pressure can positively affect the fraction of grain boundaries and the number and size of the micro-voids in the transition zone [8].

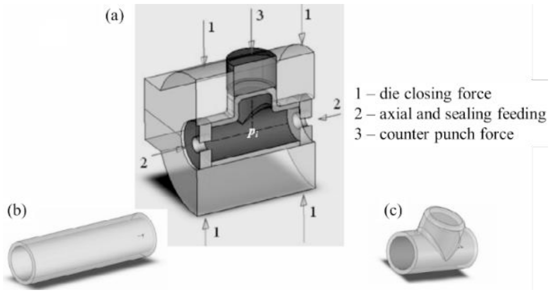

Fig. 2 The hydroforming principles [19]: (a) tool setup; (b) initial tube; (c) final product (T-joint).

A more recent trend is to combine warm forming and tube hydroforming, which can improve formability significantly. Bolt et al. [24] experienced a significant increase in product height for 1050, 5754 and 6016 series aluminum by elevated temperatures in the range of 100-250° C applied to the die, blank holder and workpiece. Xin et al. [25] found that the traditional limiting drawing ratio of 2.4 at room temperature can be increased to 2.8 at 100°C for 1 mm thick 5A06 aluminum alloy sheet. In general, it is widely accepted that hydroforming improves formability by impacting the material with through-thickness normal stress which causes superimposed hydrostatic pressure. Thus, lowers the true stress level at yielding by the amount of the superimposed hydrostatic pressure without affecting work-hardening [26].

The requirements for the pressure of the tool in tube hydroforming are small, where the internal pressure for the tube is closed and self-restrained and the closing forces are relatively small. One big difference between hydroforming tubes and sheets is that the latter requires far more closing forces than the former, and thus limits the applicability of sheet hydroforming. Predominantly, tubular material is considered for mass production within the domain of hydroforming due to comparatively lower cycle times, controllable context, press investments, lower clamping forces, etc. than sheet hydroforming [22]. However, advances in process technology enable a wider industrial application of sheet hydroforming for small batch sizes and flexible production set-ups.

In many cases, independent of tube or sheet forming, hydroforming can reduce weight and/or extra joining processes, as welding, due to flexible ways of making complex shapes in one operation [27]. For closed sections, the tube is also more mass efficient than the equivalent stamped assembly. It is convenient to combine forming and piercing in the same operation, making good repeatability of hole punching on advanced geometries. If designed smart dimensional accuracy is an asset of utilizing hydroforming for net-shape production in one step or as a post-process calibration step. By part consolidation and integrated functionality fewer parts and process steps are needed to make the final product, reducing total cycle time and capital investment. Comparing with the conventional deep drawing process sheet hydroforming benefits from high forming limits, high precision, low springback effects, good surface quality where wrinkling can be reduced or eliminated, fewer passes and lower cost [25].

Tube hydroforming has the advantages of part consolidation, weight reduction, improved part strength, and tolerance accuracy [8]. Despite challenges with cycle time comparison with more traditional forming processes, tube hydroforming is widespread in the high-volume automotive industry. First used for nonstructural components such as exhaust and intake systems or cooling pipes, but today a common process for structural components such as suspension frames, A-pillars and engine cradles. The typically change-over-time is generally low for hydroforming, and often two sets of tools are used alternately, and a movable double-position worktable is adopted.

In recent years, with the reduction of cycle time and improvement of process controls, the fields of application of hydroforming have become broader. Hydroforming technology has gained increased interest in the world because of its many advantages.

3.3. 3D stretch-bending

Traditional stretch bending is an important bending method, where extruded aluminium profiles are curved around a die simultaneously as a tensile force corresponding to the yield force or somewhat higher is applied to the profile specimen [28]. Consequently, local buckling is avoided, and the applied tension contributes to a rather homogenous stress state over the cross-section height before unloading. When applying a heavy axial loading, the neutral layer is located somewhere between the curvature center and the interior face of the bend, and the bending moment required to bend the profile into a specified radius is low, indicating that the elastic curvature released upon unloading is small compared to that in the case of rotary draw bending. This means that the overall tolerances of profiles bent in stretch bending are quite insensitive to elastic springback [29]. This process is common for high volume parts, for instance, automotive parts such as bumper beams, wheel suspension systems, and cross members, where cycle times and repeatability are favorable features. For some hard-to-deform aluminium profiles, some modifications of the stretch bending are developed to improve the formability, by the assistance of forming at elevated temperature [30] and the pulse electrical current [31]. Additionally, for the more complex part shapes, the traditional stretch bending technology can be extended to three-dimensional (3D) stretch bending, where additional degrees of freedom in combination with proportional straining hypothetically enables geometrical accuracy at a new level. A three-dimensional bending process typically consists of two opposing sets of gripping towers, where a translational movement in the base gives the bending operation a combination of force-controlled and strain-controlled stretch bending [32] and where the rotational movement of the towers gives the second degree of freedom and the third degree of freedom is given by the vertical movement of the tower dies where the extruded profile is bent over a set of forming dies. Each die is provided a turning moment around the pivot points, continuously stretching the extrusion to a fixed final configuration. The position of the pivot points is critical. If the pivot points are positioned such that the length of the workpiece is not continuously increasing during the bending stroke, the workpiece will experience strain relaxation locally, resulting in large springback and hence large sensitivity to process variations. The translational movement thus provides several advantages. Firstly, the machine can accommodate extrusions of different lengths, supporting the flexibility of various products needed in mass customization [33]. Secondly, it enhances the machine's repeatability, supporting the effectiveness for mass customization. Lastly, it can adjust the stretching during bending process to secure a proportional stretching path.

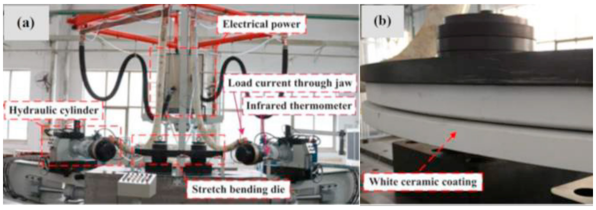

Fig. 3 Electrically assisted stretch bending of profile [31]: (a) set-up; (b) workpiece and die.

To design a three-dimensional bending machine, it is important to classify parameters that influence bending of aluminium alloy extrusions. Deformation of the workpiece will be classified into intended and unintended deformations. The intended deformation will be defined as the nominal, final geometry of the product obtained by the bending operation under nominal, and the actual deformation will be defined as the deformation of the workpiece at its current state. The deviation between actual and desired deformation will be defined as unintended deformation. The unintended deformations can be classified as local cross-sectional distortions and overall dimension variations of the extrusions [34]. Necking, thinning and cracking are all typical failure modes regarding formability. The driving factor of these deformations is the localized stress state imposed by the bending kinematics and forces applied. The bending method used can influence the tendency of necking or fracture since it influences the local stress state; for example, stretch bending increases the strain levels at the extremities of the section and hence the possibility of these modes to occur [35]. The material properties most important to the part's formability are strain hardening, strain rate sensitivity, and anisotropy. Also, the cross-sectional geometry affects the distribution of stress which may cause localized strains close to the formability limits. Sagging, local buckling and volume conservation are all typical unintended deformations regarding cross-sectional distortions. The driving factor of local buckling, or wrinkling, is compressive stresses in combination with a lack of instantaneous structural integrity of the stressed cross-sectional member. Cross-sectional distortions degrade the aesthetics, service capabilities and dimensional accuracy in regions to be joined to other parts [35]. Local buckling is one of the major bottlenecks for improving bending limit and dimensional accuracy of thin-walled tubes bent at tight radii. Also, the product's structural integrity and durability (fatigue life) could be reduced, along with the forming limit and the overall bending quality. These deformations can also cause complications on a larger process scale in terms of process interrupts [34].

Mandrels supporting the inside of the cross-section reduce cross-sectional distortions, but the possibility of local buckling increases with the nominal clearance gap between the mandrel and the extrusion. [36]. The contact conditions between the mandrel and the profile will affect the onset of buckling as these affect the stress state. Applying external tensile stress can reduce local buckling, but can increase other types of cross-sectional distortions, such as sagging. Applying internal pressure in hollows can reduce all the forms of cross-sectional distortions, at the expense of other challenges such as cycle time and investment levels. Combining tensile stress and internal pressure provides further benefits in terms of dimensional cross-sectional accuracy [37]. Springback is known as the elastic response after unloading of the workpiece. It affects the curvature and angle of the final bent extrusion, and its variation is one of the major bottlenecks with regard to bending quality and dimensional correctness. Controlling springback through stretching increases the die and product costs. Springback is dependent on many parameters throughout the whole forming process and their complex interrelationships [32]. Over-bending is typically used to compensate for springback. The guiding principle for controlling springback is that the higher level the nominal springback, the more sensitive the part shape is to springback variations — and vice-versa. Applying tensile actions is used to reduce springback, but the stretching increases allowable bending radius and increases the complexity of the tool — especially the gripping/mandrel arrangement. Friction, especially in the case of sliding friction, can also affect springback.

3.4. *Press-form-hardening*

Hot Form and Quench (HFQ) is a novel and interesting hot stamping technique to manufacture complex-shaped panel components of high-strength aluminium alloys [38]. Traditional cold forming of aluminium sheets limits formability and dimensional accuracy, an output mode of forming that can partly be overcome when forming at elevated temperatures. However, cooling rates for the hot forming process may be too low to preserve the solid solution required for subsequent age hardening. Thus, solution heat treatment and quenching are needed, where the latter may cause thermal distortions and reduced geometric accuracy [39]. As shown in Fig, 3, press form hardening is a process with integrated hot forming and quenching, where the sheet is held at solution heat treatment temperature when water cooled dies are applied to the workpiece for simultaneously forming and quenching [40, 41]. This process is somehow derived from general hot forming processes and the shortcomings of the quick plastic forming processes [42], investigated the strengthening behavior and microstructure evolutions using a hot gas forming process integrated with heat treatment [19]. The objective of this process was to avoid subsequent heat treatment and resultant thermal distortion. The sheet is formed into the required shape by high gas-pressure within several seconds after being solution heat treated, then cooled quickly with appropriate cooling methods.

Mendiguren et al. [43] analyzed the press hardening process of AA7075 high strength aluminium alloys for body in white structure with regards to springback control taking into account the strength change associated with the microstructural modification carried out during the press hardening process. Their result shows a significant reduction of the final springback, altering some mechanical properties. Lucacs also emphasized [44] the reduced need for springback compensation in tool and part design in relation to HFQ processes, and also the general applicability of the process across the different aluminium alloys. The quench cooling rate is important to control the thermo-mechanical properties of the final product, and the in-die cooling rate is partly determined by the interfacial heat transfer coefficient between the stamping dies and formed alloys [45].

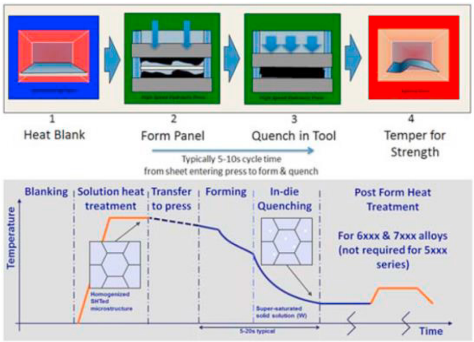

Fig. 4 Schematic illustration of the HFQ process [40].

Factors such as the contact material pair, die temperature, contact pressure, surface roughness, lubrication, oxidation, and clearance – all impacts quenching time and process efficiency. Snilsberg et al. [46] reported that one of the challenges with in-die quenching is to manage the friction stability due to rapidly changing temperatures at both the tool and the blank surfaces under complex deformation modes. In this study of AA6070, reduced adhesion of aluminium at the tool surface can be obtained by choosing the right combination of tool and lubrication parameters. AP&T claimed that cycle times of 4-8 seconds are achievable and that the process enables multi-cavity, which makes the process well competitive compared to other forming processes [47]. In many cases, about 30% of the cycle time in hot metal process is cooling time, so having properly designed cooling channels for uniform and rapid cooling is important. Additive manufacturing of dies or die inserts may offer further improvements for controlling the press hardening process towards quality and efficiency, where conformal cooling channels can give local and global optimization of the cooling process [48].

Although the research of in-die quenching of hot stamping aluminium alloys is still limited [45], the possible advantages show that this process provides the possibility to produce high-quality complex geometry components within narrow tolerances at a feasible cost.

4. Summary and conclusion

The four different forming processes, viz., single point incremental forming, hydroforming, 3D stretch-bending, and press form hardening are hypothesized to offer advantages for shaping complex aluminium parts. These processes have a long history, at least when looking back at patents and first applications. From the overall view, the industrial maturity of bending and hydroforming is relatively higher, while the single point increment forming and press form hardening are lower. However, when it comes to the forming of complex-shaped aluminium structures with higher accuracy and performance, maturity and readiness are relatively emergent. All processes are somehow applicable to both aluminium profiles and sheets, but SPIF and press form hardening are mostly referred to as a sheet metal process whereas hydroforming and 3D stretch bending are processes related to profiles and hollows when talking about manufacturing efficiency. This study is not presenting material selection as a variable for the different processes, but the searched literature in general points to a great variety of alloys, heat treatable and non-heat treatable, as examples across process typology.

Table 1 summarizes some important product and process-related quality with respect to the alternative forming processes in this study, serving as a guideline and decision support for the practice field but also pointing to knowledge gaps to be addressed by academia. The main aspects of product and process quality are concluded as formability, die cost, springback, production volume, cycle time, change-over-time, and synergy.

As shown in Table 1, the first is the formability, which is generally related to mechanical properties of the material, geometry of the structure as well as forming method. For example, necking or ductile fracture may occur for bending at tight radii, particularly when using stretch forming or press forming. However, formability is different from that in uniaxial tension as specific material parameters, such as anisotropy, along with strain distribution and history may influence failure mode. The important formability parameters are strain hardening, yield stress, anisotropy and strain rate sensitivity. Local geometrical defects are essential to aesthetics, functional and performance characteristics as well as dimensional accuracy of the product, particularly in regions where surfaces have to meet up with surfaces of other components, e.g., for welding purposes. Drawing ratio and bending radii, in combination with strength properties, are ever-increasing industrial requirements, and important inputs to problem statements for researchers. This also prominent in the researched literature. Process efficiency and implicit sustainability, in terms of the number of process steps, applied energy to operate presses or heat the material, and cycle time performance are highlighted factors for further development and maturity of these processes.

As one of the most significant factors determines the global dimension accuracy of bent and formed components, elastic springback is generally unavoidable in metal forming. Dealing with springback is a great challenge in manufacturing, particularly for aluminum due to the lower Young’s modulus and the processing sensitivity of the material. The key is to establish tight control throughout the process route, providing consistent mechanical properties and forming conditions. The fact that aluminium alloy is an engineered material makes its yield characteristic extremely sensitive to processing conditions. Since the amount of springback in one way or another, depending on bending process, is related to the yield characteristics, the dimensional accuracy is directly affected by variability in the processing route. In summary, the manufacturer’s concerns related to the part quality of formed products are primarily repeatability, i.e. controlling and minimizing the effect of noise parameters and secondarily formability, i.e., choosing the optimal design parameters that maximize formability of the component. Here, press form hardening, hydroforming and 3D stretch-bending, typically in that order, give promising springback control and, thus, high quality parts for further processing and assembly.

Die cost is an important factor, indicating process flexibility and durability, where cost to a large extent increases by part complexity and size, integrated medium for forming and/or heating/cooling of die and part, surface quality and functionality. Thus, hydroforming and press form hardening rate relatively high on this parameter.

Production volume potential is somewhat a function of cycle time, where, again, the processes press form hardening, hydroforming, and 3D stretch bending can compete against more traditional stamping and bending processes. Today, hydroforming is the most widespread process of the selection studied – especially for tube hydroforming of high-volume automotive parts. Still, cycle time is a challenge – a parameter that is an advantage for 3D stretch bending and press form hardening for comparable part complexity. Value chain synergies are important factors for evaluating total cost, throughput time, final part quality and sustainability across a set of process steps or production line. Comparing only single process steps may be misleading and give wrong conclusions. For instance, can the press form hardening process, due to its simultaneously hot forming and quenching, give good material properties as well as the reduced number of process steps, investment cost, and total throughput time. Both 3D stretch forming, and hydroforming has the potential for near net shape part geometry and dimensional accuracy that enables improved control in further joining and assembly steps.

To summarize, there are many ways to handle the increased demand for part complexity – and the processes studied here are only four out of many distinct process technologies and derivatives of these. Light weighting in the transport sector is predicted to continue, and aluminium plays an increasing role in this material shift. Thus, product and process properties have to be developed and evaluated in combination to optimize the value chain for complex-shaped products.

Table 1. Product and process properties across different forming processes.

	Single point incremental forming	***Hydroforming***	***3D stretch-bending***	***Press form hardening***
Formability	Flexible and higher formability ratio than traditional stamping processes. But, may be lowest among the ones examined in this study.	Well suited for deep drawing of asymmetric shapes, and applying heat and/or double-sided liquid pressure give maybe the highest formability potential in this study.	Form 3D shapes, but has bending degree limitations due to machine and tool constraints.	Potential to combine formability, strength and dimensional accuracy in a good manner.
Product accuracy (with focus on springback)	This process gives low dimensional accuracy due to the nature of local forming.	Well controllability for tube forming, and comparable to stretch-bending processes.	Controlled stretch throughout forming reduces spring-back	Controlled and integrated forming and heat treatment gives very accurate dimensional accuracy
Die cost	Relatively low tooling and set-up costs. The forming is primarily done by a movable tool instead of fixed dies.	For tubes comparable to 3D stretch-bending, but for sheets extensive die costs are to be expected due to applied pressure, size and draw height.	For hollow profiles clamping is part specific, and can exceed 50k USD. Part curvature can be made relatively cost efficient by flexible inserts. Clamping of sheets are cheaper than for profiles.	Extensive tooling cost if high level accuracy and strength is required, since channels for conformant cooling may be needed. Equally applicable for tubes and sheets.
Production volume	Suitable for low volumes and rapid prototyping, but improvements may direct this process towards higher volumes.	Extensively used for profile based automotive parts	Applied to high volume production. For instance, automotive and aluminium wind shield frames	Aluminium is an emergent material for this process, and is expected to be used for automotive applications based on sheets and profiles in near future.
Cycle time	Slow process	Tubular forming is relatively competitive on cycle time, but slower than stretch-bending and press hardening.	Low when compared to traditional forming processes, where less than 8 seconds is achievable.	Suppliers of presses and dies claim cycle times in the range of 4-8 seconds.
Change-over-time	Low	Comparable to typical die change for presses.	Change of clamps and inserts – but relatively low.	Comparable to typical die change for presses.
Synergy	Low entrance process for low volume flexible manufacturing.	Potential for large and complex shapes which eliminate downstream processes.	Potential for accurate and efficient processing of hollows.	Potential to reduce process steps and to supply quality parts for downstream operations.

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