Hot Die Forming - Flat (HDF-F^{Al}): An innovative hot forming technology for extreme lightweight in aluminum sheet alloys

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Hot Die Forming - Flat (HDF-F^{Al}): An innovative hot forming technology for extreme lightweight in aluminum sheet alloys

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Abstract. Aluminum is an ideal material for light transport applications. Despite the obvious advantages in weight ratio and corrosion resistance, high strength aluminum alloys have limited formability compared to traditional steels at room temperature conditions. A solution is to combine mechanical loading with thermal component i.e. deformation at elevated temperature. Currently super plastic forming and Quick Plastic Forming (QPF) is used to enhance the formability of Aluminum alloys. However, the cycle time for super plastic forming as well as for QPF is too high for mass production. An innovative and novel forming method called Hot Die Forming (HDF) has been developed to achieve high strains in high strength aluminum alloys (maximum 700 [MPa]) by heating them to Solution Heat Temperature (SHT), while keeping the cycle time suitable for large scale production. To study the feasibility and optimize the process parameters, a digital platform has been developed for simulations of HDF process. The simulation process has been automated, the user can provide tool geometries and input parameters to check the feasibility of HDF process or to optimize the parameters and die shape.

1. Introduction

The CO_2 level in atmosphere has reached to 410ppm in 2018 compared to 315ppm in 1960. The average rise in 2019 is expected to be 2.75ppm [1]. It is of vital importance to maintain the CO_2 level in atmosphere. One big source of human made CO_2 is combustion of fossil fuels for the purpose of transportation. In Europe, 12% of the total CO_2 comes from cars [2]. The new cars sold in 2017 had an average CO_2 emission of 118.5 g/km. The target, set by EU, is to bring the average CO_2 emission from new cars in 2021 down to 95 g/km [2]. This corresponds to a petrol consumption of 4.1 litres/100km and diesel consumption of 3.6 litres/100km per car. Further on the EU decided to reduce the CO_2 emission for cars by 37.5 % by 2030. One way to achieve this target is by making the cars electrically driven which will shift the CO_2 burden from cars to the power generation industry. This solution is viable if the power used to charge the automobile batteries come from green energy and the EU countries develop the infrastructure for charging cars. The driving distance of the eCars has to be minimum doubled to be attractive to the buyers. These conditions are difficult to meet until 2021. Another solution is to make all cars lighter and as fuel efficient as possible. However when making the cars lighter, the safety standards must not be compromised.

In any case car light weighting is a must and can be achieved by replacing the traditional materials with high strength lightweight materials. Components which do not have a significant structural and safety function - mostly the interior of a car - can be made by composites and plastics. However, the body in white (BIW) and most car exteriors are generally made with steel due to high strength and safety requirement. The car weight can significantly be reduced if these steel components can be replaced with high strength (>700 [MPa]) aluminum alloys. The automotive industry has already replaced many parts with moderate strength aluminum alloys, most of which are produced by castings and extrusions [3]. However, the biggest challenge to introduce high strength aluminum alloys is their limited formability (less than 10% strain), due to their enhanced aging response at room temperature. Forming these alloys at high temperature increase their formability significantly [4]. Superplastic forming is an established method of the very high formability of aluminum alloys, but thinning is not controllable [5] and the cycle time is not suitable for large scale production. To overcome these issue, an innovative high temperature forming method using hot dies has been developed, called Hot Die Forming (HDF) and has been proven already in hollow parts [6].

2. Hot Die Forming (HDF)

The basic concept of HDF is to deform the work piece at elevated temperatures (e.g. above SHT) with gas. The work piece is pressed against mold (dies) which are also in the elevated (SHT) temperature range, thus minimizing the temperature drop when the work piece contacts the die. A schematic of the process is shown in figure 1. The blank and the tools i.e. the die, punch, seal and blank holder are all at high temperature. In this specific HDF process friction between blank and the tool surfaces has been minimized to obtain almost frictionless forming conditions. Due to the high temperature, the required pressure for forming the blank is quite low. Only forming the very last bit, such as the die radii shown in figure 1, may require additional high pressure at the end of the HDF process, requiring a relative small volume of highly compressed air. If sufficient pressure is not available (limited by the directive of 2014/68/EU on pressure equipment) this final step can also be formed with the punch.

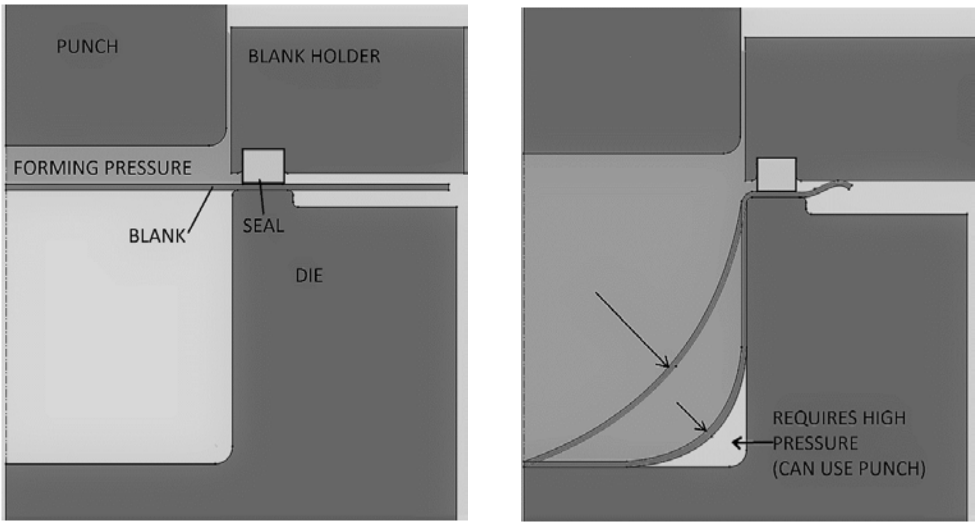

Figure 1. Schematic of hot die forming steps.

Generally, at high temperatures Aluminium alloys are very soft (~ 25 MPa) so less forces are required to deform it. On the other hand, the strain hardening behavior of the material at elevated temperatures is also weak, causing it to localize much earlier, see figure 2 [6]. However, when a material starts to localize, the strain rate increases locally and stabilizes the process. If the material does not have sufficient strain rate hardening at elevated temperature then the material will fail much earlier than that at room temperature. In most of Aluminum alloys due to the enhanced diffusivity of alloy elements in solution and their interaction with moving dislocations the strain rate hardening behavior increases at

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elevated temperatures [4] which suppresses the strain localization and necking. The higher the strain rate sensitivity increases, the higher the strain without failure. So for most Aluminum alloys, forming at elevated temperature has two advantages: lower forces and higher strains (For Al-Mg alloys this has been discussed in [6] and is demonstrated in figure 2).

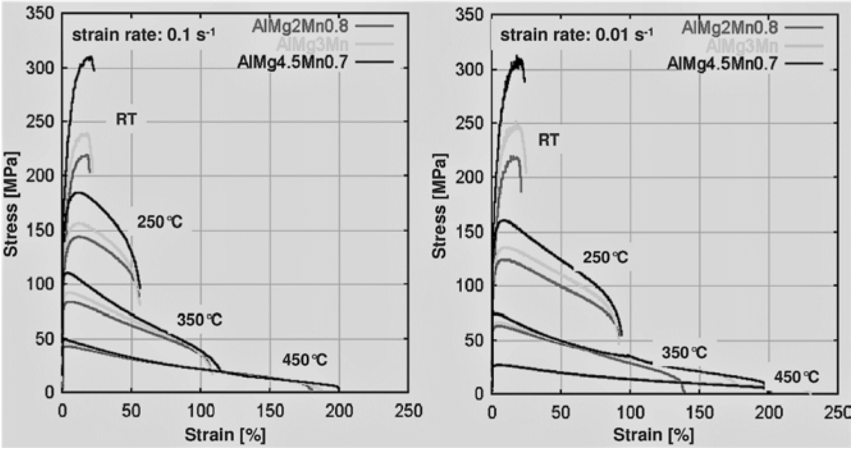

Figure 2. Stress-strain curves of some industrial Al-Mg-Mn alloys in tensile tests at various temperature and two level of strain rates [7].

Table 1. Comparison of different hot forming processes.

Parameter	Super Plastic Forming (SPF)	Hot forming Quench (HFQ)	Quick Plastic Forming (QPF)	Hot Die Forming (HDF)
Material feeding	no	yes, not active	no	active controlled
Sheet thinning	not controlled	not controlled	not controlled	controlled
Minimum sheet thickness	all	>1mm	>1mm	>0.5mm
Complexity of the product	nearby all	simple	simple	nearby all
Forming time	minutes, days	<1min	1-2 min	<1min
Forming gas pressure	1-5 bar	NA	10-50 bar	1-250 bar
A-surface possibility	yes	no	no	yes
Maximum strain	Up to 1000%	Up to 50%	Up to 50%	Up to 300%
Spring back effect	no	conditional	no	no
Production volume	small	high	small-medium	small-high

The increase in strain rate sensitivity not only depends on the temperature but also on the strain rate at which we deform the material [5], see also figure 2. For a given high temperature, the highest value of strain rate sensitivity is obtained at a slow strain rate i.e. ~10^{-3} [5]. Figure 2 shows that higher strains can be obtained by reducing the strain rate while maintaining the same temperature level. This means that if the material has to be deformed to a very large strain it must be deformed very slow. This is the concept of super plastic forming. When the hot blank touches the cold tools, the blank temperature drops which results in lower strain rate sensitivity. The drop in strain rate sensitivity can be compensated by reducing the strain rate. Therefore, the biggest disadvantage of super plastic forming is the large cycle time for forming. In HDF, the tools are also at the very high temperature, therefore the blank temperature does not drop significantly. This allows to deform the material at a higher strain rate. With HDF it may not be able to go to very high strains as in superplastic forming but still a quite high strain of >200% can be obtained, which is sufficient to form most of the automotive parts with reasonable cycle time. Table 1 shows the comparison between different hot forming processes and HDF.

A general concern with hot forming is the final properties of the product. However, hot forming in the SHT condition will not affect the final properties of the products of heat-treatable Al alloys. As long

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as forming takes place above the SHT, the final strength is determined by the aging process, which can be performed in the same way, as achieved after normal (standard) heat treatment. The only issue to be considered is the quenching conditions, which might lead to residual stresses and distortion, if not properly performed. In contrast to other processes like press-hardening, quenching is performed in a different (subsequent) step in HDF, which can be designed to meet all requirements of (complex) alloys and/or parts. Another critical issue might be the issue of recrystallization, which in the combined effect of high temperature treatment and forming might lead to some grain coarsening, which can affect final properties and surface appearance. Grain coarsening also occurs in conventional hot forming processes (like hot rolling or extrusion) where it is controlled by specific alloy design and pre-annealing/homogenization treatment. The same methodologies can be applied for HDF as well.

3. Simulation Model

A cross die shape has been used to show the feasibility of HDF process. The cross-die forming process covers a wide range of triaxialities, thus it is very useful for determining the formability. Apart from the wide range of triaxialities, some regions of the blank undergo severe strain path changes as well.

The tool dimensions were determined in accordance to the available machine press. The die is closed at the bottom since the blank is pressed against it under pressure. The vertical surfaces of the die are tapered to 1.5^{o} to ensure easy retraction of the part. The punch does not have a taper face. The minimum clearance between the die and punch is one sheet thickness. Note that use of punch is optional in the simulation program (only if the shape cannot be formed by pressure).

3.1. Finite element Model

To simulate the cross-die test, a parametric finite element model was developed in MSC.MARC. Due to double symmetry, one quarter of the blank is sufficient in the simulation. The tools were modelled as rigid bodies. The blank is modelled using solid shell elements and the seal is defined by hexahedral 8 node elements. The friction coefficient between blank holder and blank is taken as 0.15, between blank and die as 0.05, between blank and punch as 0.05. The FEA model for HDF is shown in figure 3.

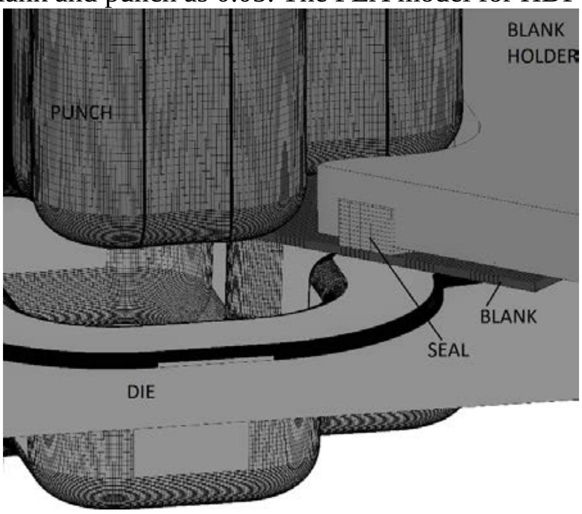


Figure 3. Finite element model for HDF.

The gas pressure used for forming is increased from 0 to maximum in 1sec. The maximum pressure was set based on the machine capacity. Symmetry boundary conditions are defined on both symmetric edges of the blank as well as the seal.

3.2. Material data

The material used for this study is Aluminium EN-AW5083. The temperature dependent stress strain data and Young’s modulus were obtained from literature [7]. The strain rate sensitivity and forming limit diagram were also obtained from literature [5]. The material was assumed to be isotropic so the Von Mises yield criterion was used. To include temperature and strain rate sensitivity in the hardening model, Johnson cook's hardening model was used in the simulations. The flow stress for Johnson Cook model is defined as

$$\sigma_f = \left[\sigma_0 + Q_R\left(1 - e^{-C_R\varepsilon_p^{eq}}\right)\right]\left[1 + \left(\frac{\dot{\varepsilon}_p^{eq}}{\dot{\varepsilon}_0}\right)^m\right]\left[1 - \left(\frac{T - T_0}{T_M - T_0}\right)^{C_v}\right] \tag{1}$$

Where σ_f is the flow stress. ε_p^{eq} is the equivalent plastic strain $\dot{\varepsilon}_p^{eq}$ is the equivalent plastic strain rate and T is the temperature. σ_0 , Q_R and C_R are the strain hardening parameters, $\dot{\varepsilon}_0$ and m are the strain rate hardening parameters and T_0 , T_M and C_v are the temperature softening parameters. The model parameters were fitted to the temperature and strain rate dependent data obtained from the literature. The forming limit diagram at elevated temperature is shown in figure 4. The diagram was given as input to calculate the forming limit parameter. The forming limit parameter defined the ratio of the current state of a material point from the forming limit. A forming limit parameter of 1 or higher means that the material will fail (according to the provided forming limit curve). A forming limit parameter of less than 1 is considered safe.

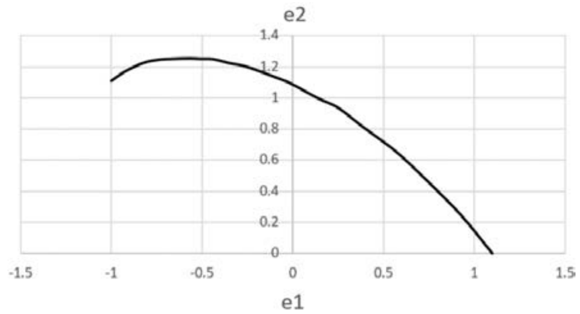


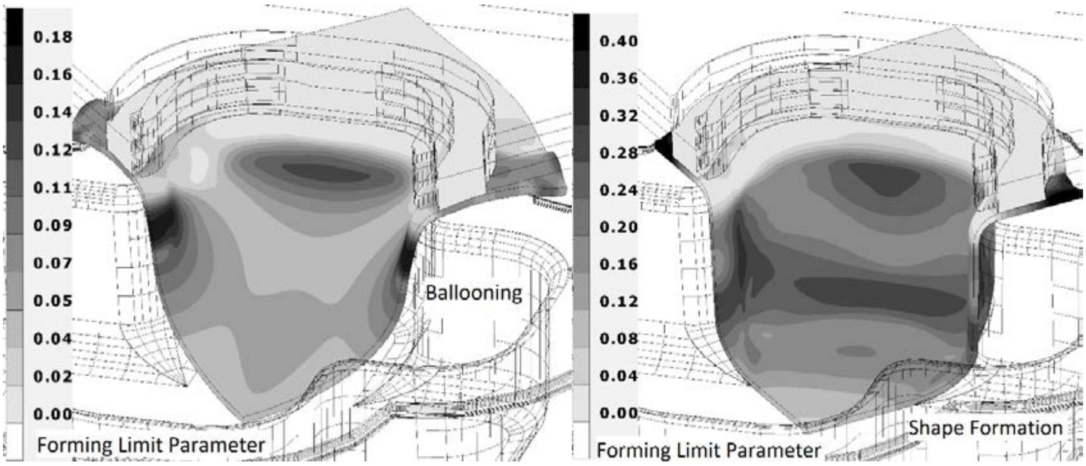
Figure 4. Forming limit diagram for Al EN-AW5083 at 500°C [5].

4. Results

In HDF-F the blank is loaded with gas pressure. The blank starts to deform in such a way that it keeps the surface area under pressure loading the minimum. So, the blank starts deforming in a shape somewhat similar to a spherical shape. This process regime can be called 'ballooning', illustrated in figure 5(a). The ballooning continues until the center point of the blank (center of the balloon) touches the bottom die surface. Then the pressure load starts to press the material against the die surface called 'shape formation', see figure 5(b). Ballooning can be done with low pressures (2.3MPa for this specific case) but shape formation requires high pressure. Especially forming the lower corners of the cross die requires the highest pressure of 10MPa. The lower corners are the last feature that are shaped during the cross die HDF process. An alternative is to form the lower corners of the cross die with the punch after the shape formation to 8MPa as mentioned in figure 1. Note that in a conventional deep drawing process, these corners are the first feature to form in a cross die.

A Super Plastic Forming (SPF) simulation was performed using the same material properties to compare the outcome of HDF with SPF. For SPF, the shape was formed at a pressure of 2.1MPa in 150sec. The blank was used as a round blank and the outer edges were fixed. Figure 6 shows the sheet thickness distribution for SPF and HDF. The starting sheet thickness is 2mm. The SPF product is significantly thinner than the HDF product. The thickness in the lower corner is 0.72mm and the forming limit parameters is 1.1 for SPF. In HDF, the thickness in the lower corners of the cross die is 1.3mm and the forming limit parameter is less than 0.4. This shows that HDF is a more suitable process compared to SPF when it comes to mass production and when extremely high strains are not required.

Another advantage of the HDF process is the control over the thinning of the sheet. By changing the settings the strain distribution in the product can be changed. Different elements which can be used for controlling the strain are the combined use of pressure and punch and changing the spring stiffness on seal segments. The variation in the forming limit parameter (indirectly in strain) can be observed in figure 7. It can be observed that how the critical regions change with different methods. The best distribution was obtained when most of the part was made by the pressure load and only the lower cross die corners are made by the punch.



(a) (b)

Figure 5. Process regime during HDF (a) Ballooning (b) Shape formation.

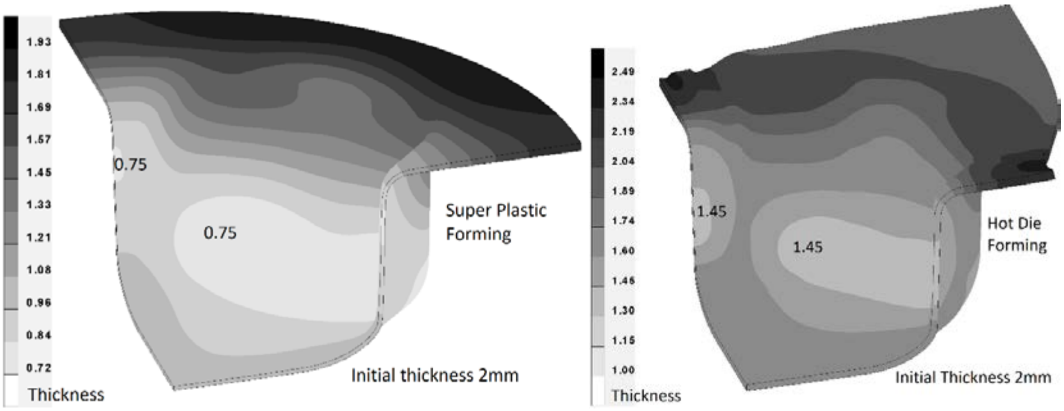


Figure 6. Thickness comparison of SPF (left) and HDF (right).

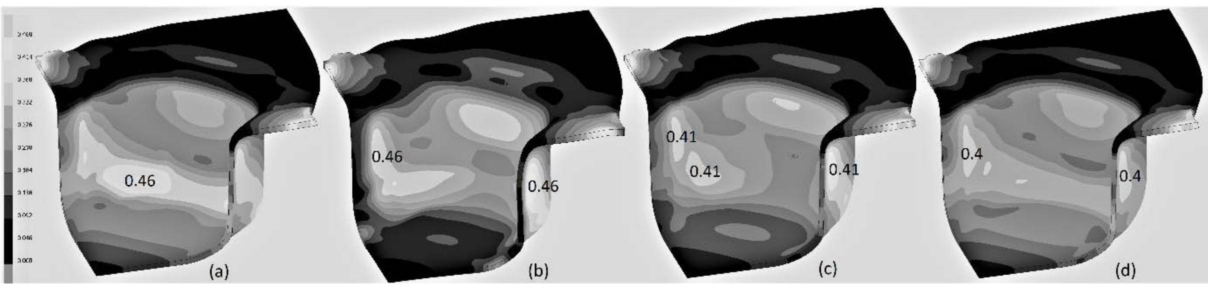


Figure 7. Process variations that give different forming limit distributions (a) Only pressure used (b) Only punch used (c) First half by pressure and last half by punch (d) only the lower corners by punch

5. Digital Platform for HDF feasibility study

Commercializing an innovative idea is one of the biggest challenge many creative minds are facing today. There are several questions which need to be answered; What are the best technologies to be used? What scaling up approach shall be adopted? How to build confidence on the product functionality and sustainability (including life cycle assessment LCA etc.). Most of these questions can be answered by a suitable prototype development. Rapid prototype development is required to reduce the time to market. The objective in this project is to provide the manufacturer and developer a digital platform for simulating their product shape to assess the feasibility of HDF technology for the production of their part. This will significantly reduce the prototype development time for a new innovative product or a new production process.

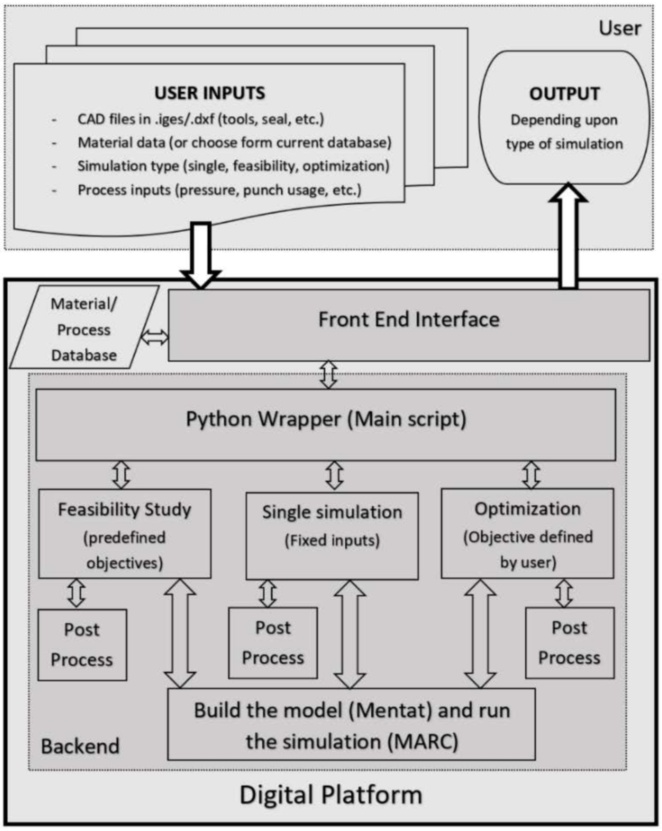


Figure 8. The HDF digital platform.

One of the key requirement in developing the back end of this digital platform is making the simulation model as robust and as generic as possible. Another requirement is high level of automation in pre- and post-processing of the FE model. The service available to the user is divided into three categories:

- Single simulation: Requires the user to provide all process inputs. Standard outputs are provided to the user.
- Feasibility check: This service can take more than one simulation. The process parameters will be varied to obtain required shape with strains within the forming limit curve.
- Optimization study: This service will take many simulations. The purpose is to optimize certain process parameters to achieve a certain objective for e.g. to reduce the cycle time.

Figure 8 shows the outline of the digital framework. The user has to provide all geometric information like tool geometries, seal geometry etc. in the form for either iges files and dxf files. However, there are a set of requirements which has to be fulfilled by the user while making the iges and dxf files. For e.g. positioning of the die, punch blank holder etc. must be defined in a standardized way. The user has a choice to select a material from the database or define the required material properties for the material such as hardening curves, forming limit diagrams etc. depending upon the type of study, the user will define process parameters. For e.g. in case of optimization, the upper and lower limits must be given while for a single simulation fixed process values must be entered for the study. All inputs are given via the front-end interface. The front-end interface has access to the pre-defined material database and the user can view the material properties for a selected material.

The back-end is completely automated using python programing. The FE model is built in Mentat which is a pre-processor for MSC.MARC solver. The python modules py_mentat and py_post are used for pre- and post-processing the FE model. The main python script calls the respective module depending upon the type of study defined by the user. Building up the FE model and running the simulation is standard for all three studies. However, the method of defining the inputs for pre-processing and post-processing differs for all three studies.

5.1. Limitations

Some limitations of the process and the digital platform are listed below

- Blanks with existing holes cannot be formed by the currently defined HDF process. This is a limitation of the process and therefore not included in the simulation model.
- Currently, only planar blanks, with initially uniform thickness, can be defined in the digital platform. In future, the platform will be extended to non-planar and tailor-made blanks as well.

6. Conclusion

Hot Die Forming (HDF) is a novel, innovative and highly flexible technology which can be used for large scale production of high strength aluminium alloys, due to its low cycle time. Note that the process is not limited to aluminium alloys. Any material which has a high strain rate sensitivity at high temperatures can be formed by HDF. This technology can also be used to form complex and re-entrant shapes. Most of the HDF-F drawing process is frictionless which is also a big advantage. High pressure requirements can be eliminated by partial use of punch i.e. for formation of small radii corners and shapes only. The variable blank holder force over the periphery of the blank gives an additional control on the product shape details and outcome.

A digital platform has been developed for simulating the HDF process. The platform has been made generic, so all kind of product shapes can be simulated. Standardized inputs and outputs are defined based on the type of study performed by the user.

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