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Research Paper

DEVELOPMENT OF KNOWLEDGE-BASED SYSTEM FOR PROCESS SEQUENCE DESIGN FOR PRODUCTION OF PULLEY USED IN AUTOMOBILE COOLING APPLICATIONS

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Because of global competition, manufacturers are compelled to produce the products with high quality and short delivery times. In manufacturing, sheet metal industries has major role to play for cost effective solution. Pulley used for power transmission in automobile cooling application is a sheet metal product. An attempt has been made here to shorten the delivery time by developing a Knowledge-Based System (KBS) for sheet metal product. Different customers have different dimensional specification for the said pulley. Also frequent design changes make it difficult for the manufacturer to develop process plan, production schedules and in turn reduce delivery time. Some decision support system requires helping in development of process plan as well as for production scheduling. KBS is developed here keeping these requirements in mind. Data related to process sequence to produce the part has been gathered and stored in required format. An inference engine is developed to get the process sequence for the production of the pulley. It also gives parametric CAD models for each process sequence stage, which can be used for the development of production drawings. The CAD data generated can also be used for FEA analysis.

Keywords: Knowledge-based system, Decision support system, Process sequence design, Deep drawing

INTRODUCTION

Sheet metal forming is a very important manufacturing method. The complex parts can be produced cheaply and quickly. Also, it is easy to manufacture parts which are sufficiently strong against dynamic loads and have sufficient accuracy for general manufacturing. Therefore, this manufacturing method is preferably used in almost every mass-produced product. However, nowadays, sheet

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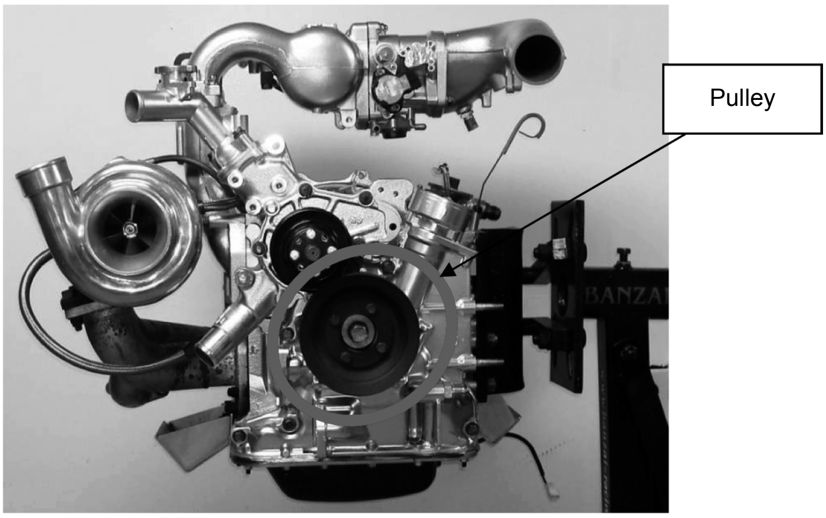
metal sectors have been forced to present products with high quality and short delivery times as a result of the globalization of markets. Researchers develop new systems so that production time and cost can be reduced and production quality can be improved. Knowledge-based System is one such tool to help the industries to cope up with the fast track solutions (Yu Dequan *et al.*, 2006).

Knowledge-based System is an Artificial Intelligence application, which uses a knowledge base of human expertise for problem solving. Its success is based on the quality of the data and rules obtained from the human expert (Kendal *et al.*, 2007). It derives its answers by running the knowledge base through an inference engine, which is software that interacts with the user and processes the results from the rules and data in the knowledgebase. It is obvious that for development of a Knowledge-based System, it requires knowledge as well as experience of the domain for which it is to be developed.

The problem taken here is from a sheet metal forming industry, which manufactures pulleys used in automobiles for power transmission from engine crank shaft to cooling fan, as shown in Figure 1.

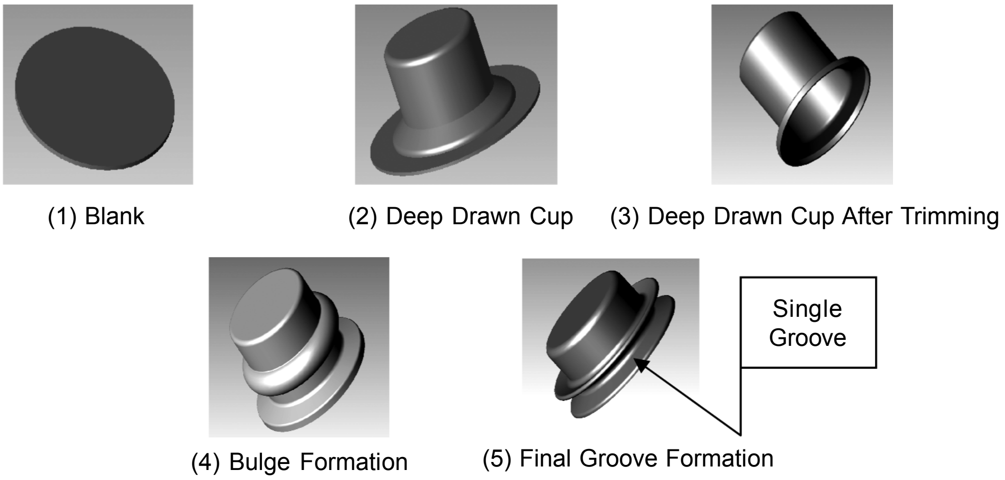
Figure 1: Pulley Connecting Cooling Fan to Crankshaft of the Automobile Engine



The pulley has single groove, as shown in Figure 2. It is made up of sheet metal by deep drawing process. The sequence of the forming is as shown in Figure 2. First the blank is cut from the sheet metal, of the required diameter. The diameter of the blank depends upon the geometrical parameters of the cylindrical cup to be drawn. Equations to calculate the blank diameter for the required size of the cup shape are available in the literature (Duncan *et al.*, 2002).

From the initial circular blank the cup shape is obtained by deep drawing operations. It can be performed in single stage or multistage deep drawing operations depending upon the Limiting Drawing Ratio (LDR) based on the product dimension and the material of the blank. LDR is an important parameter in deep

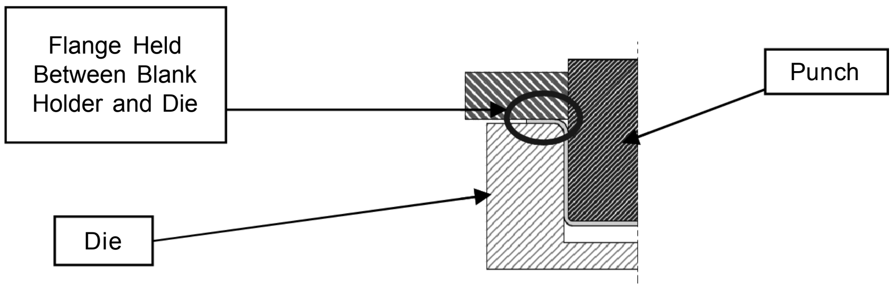
Figure 2: Operation Sequence for Single Groove Pulley Forming



drawing process. It is the ratio of blank diameter to the cup diameter. It depends upon the ratio of sheet thickness to cup diameter for particular material, along with other process parameters (Colagan *et al.*, 2003; and Padmanabhan *et al.*, 2007).

After the formation of the cup shape it requires to cut the flange, which is not required in the final part geometry. During the deep drawing operation flange is required at the upper edge of the cup to hold the sheet metal against the drawing force as shown in Figure 3. Subsequently, this flange has to be removed in the final part geometry. Trimming is done to remove the unwanted flange from the cup.

Figure 3: Flange Between Blank and Blank Holder



The cup is now ready for the bulging using elastomer. In the next stage the groove forming is done by pressing the bulged portion of the cup. This is the general process sequence for the product under consideration.

It requires a lot of experience and knowledge to determine the process sequence and other parameters, which ultimately determines the press tonnage requirements. Because of design changes and different specification requirements from different customers the product manufacturing requires frequent changes in design and development of process sequence. The process sequence will also affect time and cost involved in the production of the part.

It is also requires to prepare the drawings of the product shapes after each process. Based on the drawings, the machine settings will be done and sheet metal will be processed at the shop floor. Preparing the drawings for the component production is very cumbersome and time consuming process for the similar products with slight changes in dimensions.

So the problem considered above possesses potential for the development of the KBS, as its solutions involves domain knowledge as well as experience of the experts. For quick and effective decision making as far as process sequence is concerned, some support system is essential. To address this problem an attempt has been made to develop a decision support system for process sequence determination.

DEVELOPMENT OF KBS

KBS development cycle involves many steps like problem identification, data identification, data acquisition, arranging data in required format, development of algorithm and flowcharts, programme coding, testing and validation of the developed KBS, modifications, if required (Moores, 2001). As discussed previously, the estimation of press tonnage requirement involves a lot of experience and expertise. Process sequence, through which the product undergoes during the production, plays major role in determining the press tonnage requirement, along with the other factors. So KBS has been developed for the same. Three modules have been developed namely Process Sequence Design module, Hyperworks process manager module for FEA analysis and Economics of Production module for cost estimation of the product manufacturing. In this paper only the Process Sequence Design module is discussed.

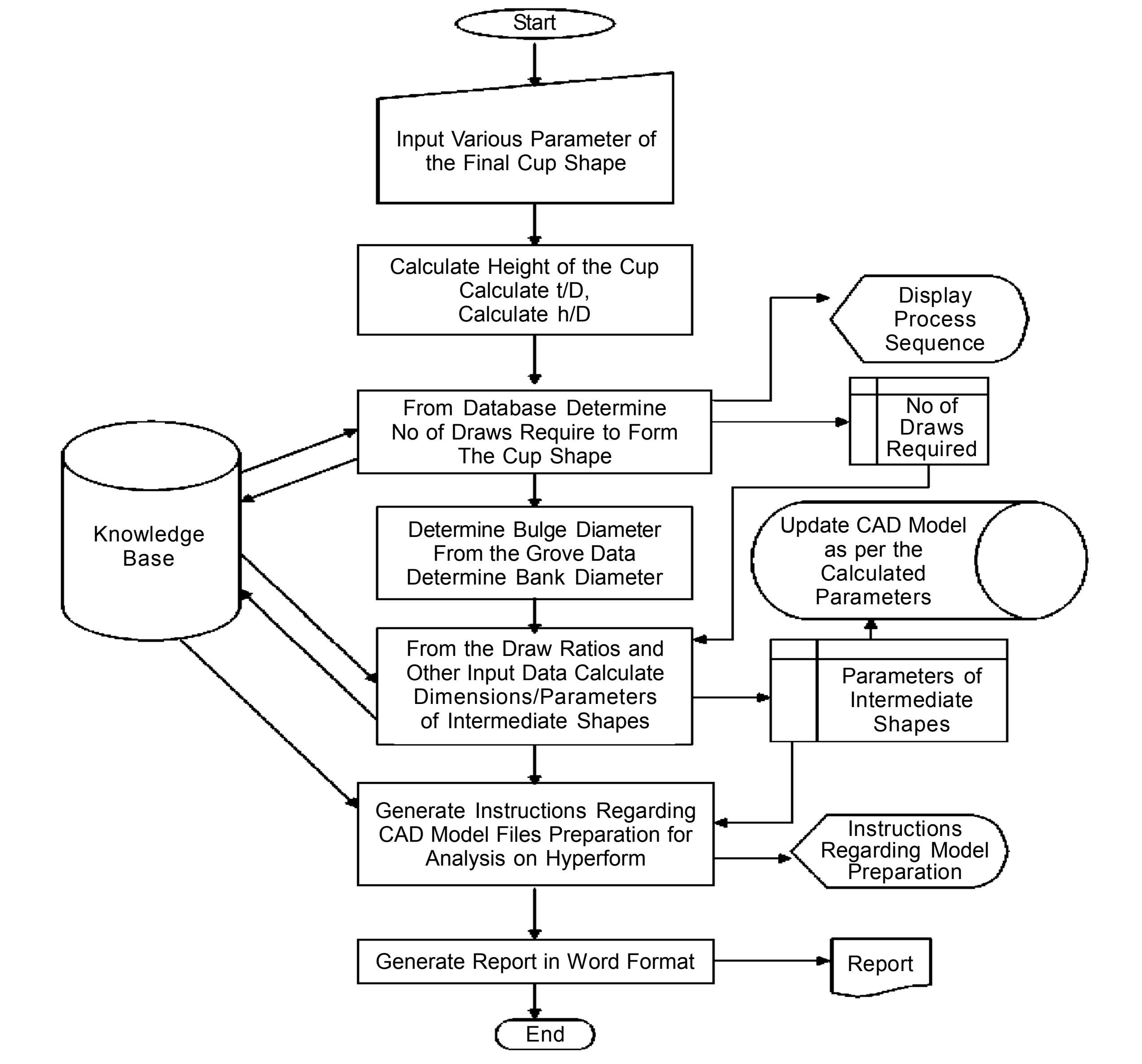
DEVELOPMENT OF PROCESS SEQUENCE DESIGN MODULE

The data required for the process sequence design, especially for deep drawing process, have been identified and arranged in the required format. Based on the requirements of the present problem the algorithm and flowchart has been developed for Process sequence Design module. The flowchart for the Process Sequence Design module is prepared as shown in Figure 4.

While execution, first step is to input various geometrical parameters of the final shape of the cup like diameter of the cup, height of the cup, dimensions of the groove, etc. From these parameters it is required to obtain the dimensional parameters for various stages through which the product will undergo. For simple cylindrical shapes equations to estimate blank diameter is available in the literature (Duncan, 2002). For the present case final product is not simple cylinder. So it is required to find the parameters of the cup shape from the final shape geometrical parameters. Subsequently based on these parameters, blank diameter will be calculated using equations available in literature as mentioned earlier.

Calculation of the dimensional parameters of the pulley before and after each stage has been done considering geometrical similarity of the raw pulley shape before and after each

Figure 4: Flowchart for Process Sequence Design Module



stage. Seven operation stages are assumed to form the cup, namely Blanking, Three drawing stages, Trimming, Bulge forming using elastomer and Groove forming by pressing. In the present problem, bulge forming is one of the critical operation among all other operations. From the geometrical similarities Bulge diameter, height of the cup shape after each stage and other geometrical parameters have been calculated. Considering the process sequence in the reverse order, starting from final cup shape, dimensions for the bulge forming stage can be found out. The bulge diameter is to be calculated as the other dimensional parameters will remain same as before. By developing the profile of the groove the bulge diameter can be estimated as shown in the Figure 5. Subsequently for the next stage the bulge shape which is assumed semicircular in nature is developed in straight line. The shapes and the geometrical parameters for the operation stages in the reverse order are given in Figures 6 and 7. Geometrical parameters for drawing stages are governed by the h/d ratios for the subsequent stages and h/d ratio is governed by Limiting Draw Ratio (LDR) for particular material. Calculations of the geometrical parameters for different stages are given subsequently. Refer Figure 5 for input

Figure 5: Dimensional Parameters of Final Shape of the Pulley (All the Dimensions are in mm)

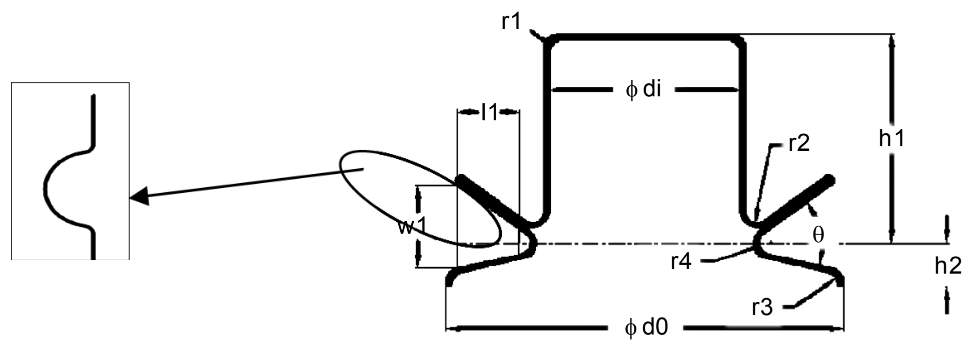


Figure 6: Dimensional Parameters After Bulge Forming and Before Bulge Forming Operation

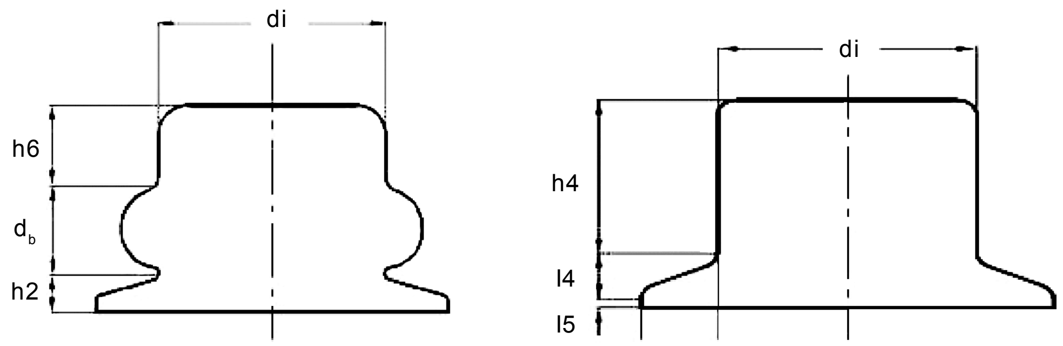
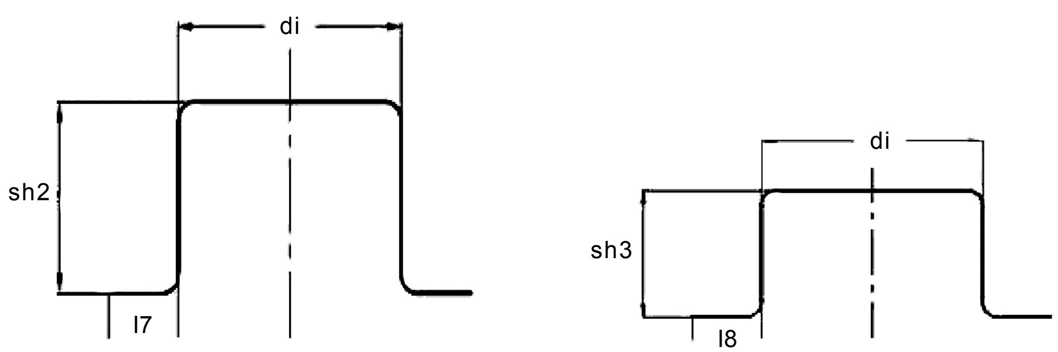


Figure 7: Dimensional Parameters After Second Draw and Before Second Draw



parameters for the KBS, which shows the final shape of the pulley to be produced.

The dimensions shown in Figure 6 will be input to the system. Based on these parameters the dimensional parameters for the other stages will be calculated.

Inputs are di, d0, l1, w1, h1, θ, r1, r2, r3, r4 (refer Figure 5).

Calculation of other dimensional parameters for the stages (refer Figures 6 and 7 for the dimensional parameters at various stages).

To get the bulge diameter the length of the groove 'l1' has been projected on the inclined groove. The inclined length of the groove is taken as the radius of the bulge. So the bulge diameter can be given as,

Bulge diameter, $d_b = 2 * l1/(\cos(\theta/2))$ ...(1)

Subsequently other parameters can be given as,

$h2 = l1 * \tan(\theta/2) + \pi * r3 + r3$ ...(2)

$h4 = h1 + d_b$ ...(3)

$h3 = h2 + h4$ (not shown in figure) ...(4)

Bulge height $hb = h1 - (r1 + r4 + d_b)$ (not shown in figure) ...(5)

$h6 = hb - db/2 - r2$ ...(6)

Now the first stage in the process sequence is to draw the cup from blank. For that it is required to estimate the blank diameter.

Equations for Blank diameter:

$h = h4 + l4 + l5$ ...(7)

$d1 = di$ ...(8)

$l6 = 0.2 * di$ ...(9)

$d2 = 2 * l6 + d1$ ...(10)

These parameters (Equations (7-10))are not shown in Figures 6 and 7.

Blank diameter, $D = (d_2^2 + 4 * d1 * h)^{1/2}$ (Duncan *et al.*, 2002) ...(11)

$LDR = di/D$

$l3 = 2 * t$ ...(12)

$l4 = l1 * \tan(\theta/2)$ ...(13)

$l5 = 3 * t$ ...(14)

These Equations (12-14) are given for three stage drawing operation, which depends upon $dr = h3/di$

$sh1 = dr * di$ ...(15)

(where *dr* is draw ratio for third stage, $dr = h3/di$)

$sh2 = 0.7 * di$ ...(16)

$sh3 = 0.4 * di - l1/\cos(\theta/2) + \pi * r3/2 + \pi * r4/2$ ...(17)

$l7 = D - 2 * h2 - di/2$ ...(18)

$l8 = D - 2 * h1 - di/2$ ...(19)

For process sequence determination, it is required to know Limiting Draw Ratio (LDR) for the material considered. LDR data for various materials is available in the literature (Avitzur, 1983; and Anne *et al.*, 2007). The material which the manufacturer of the pulley is using has been identified. The database regarding the limiting draw ratio for that material has been fetched from the available standard metal forming handbooks (Avitzur, 1983; and Anne *et al.*, 2007). Values for h/D ratios corresponding to t/D ratio taken from the standard databooks are shown in Table 1.

Table 1: h/D Ratio for Different Deep Drawing Stages

	t/D Ratio in Percent		
	0.6-0.3	0.3-0.15	0.15-0.08
	Maximum h/D Ratio		
1st Draw	0.62-0.5	0.52-0.42	0.46-0.38
2nd Draw	1.13-0.94	0.96-0.83	0.9-0.7
3rd Draw	1.9-1.5	1.6-1.3	1.3-1.1
4th Draw	2.4-2.0	2.4-2.0	2-1.5
5th Draw	3.3-2.7	3.3-2.7	2.7-2.0

Based on the h/D ratio obtained, various parameters for subsequent drawing stages will be calculated. The height of the cup before the bulging operation will be derived from the final geometry of the pulley. Based on the h/D ratio, number of drawing stages will be obtained. After that the final process sequence will be identified, as the other operations like blanking, trimming, bulge forming and groove forming will remain the same.

It is also required to develop CAD models of the shapes after each operation. These models can be utilized for preparation of the drawings of the part at various intermediate stages. Also it will be used to analyze the model files on FEA software. For that IGES files of the models, prepared by the KBS, are required.

Only drawing operation and bulging will be simulated in FEA software. So parametric CAD models of the shapes for drawing and bulging has been prepared. After calculations of all the dimensional parameters for different stages, the data will be stored in database, which was linked with CAD models of shapes of the cup at various stages. When the database will be updated, all the models will be updated accordingly.

Now it will be required to generate the instructions for the model preparations for the user as user may not be aware of the process of updating of the model in CAD software. Also it is required to generate IGES files form the CAD models, which will be further used for FEA analysis. So the database has been prepared for the model preparations with respect to the various process sequence results. After determination of the process sequence and updating of the database, instructions regarding model preparations will be given to the user and user will be guided for the generation of IGES files from the CAD models. The report also will be generated of the parameters of the models in plain text format.

The programme coding has been done using Visual Basic and Access Data Base, and KBS has been developed for process sequence design.

TESTING OF THE DEVELOPED KBS

After completion of the development of the application, the testing is done with three case studies. These case studies are taken of three pulleys having different dimensional parameters, being manufactured at the shop floor. The data related to the production of the pulleys was available. The results given by the developed KBS have been compared with the practical results available.

Case-1

Dimensional parameters entered for Process Sequence Design module:

Refer Figure 6 for the dimensional parameters;

Cup inner diameter (*di*) = 83.3 mm

Cup height upto the groove (*h*1) = 39.4 mm

Length of the groove (*l*1) = 12.5 mm

Width of the groove (*w*1) = 15.4 mm

Angle subtended by the groove (θ) = 360

Cup outer diameter (*d*0) = 120.07 mm

Thickness of the sheet (t) = 4 mm

Values of various fillet radii,

*r*1 = 4 mm, *r*2 = 4 mm, *r*3 = 2 mm, *r*4 = 3.46 mm.

Output values for the process sequence design are:

Blank diameter = 206.17 mm

Bulge diameter = 26. 285 mm

There are seven stages required to produce the component namely: Blanking, Three drawing stages, Trimming, Bulging using elastomer, and Groove forming.

Output window for above module is shown in Figure 8. The process sequence suggested by the KBS can be seen in Figure 9.

The database and model files have been updated. From that updated model files IGES files have been exported for further analysis on Hyperform, as per the instructions given by the system. The report has been generated as given in Figure 10.

Figure 8: Process Sequence Suggested by KBS for Case-1

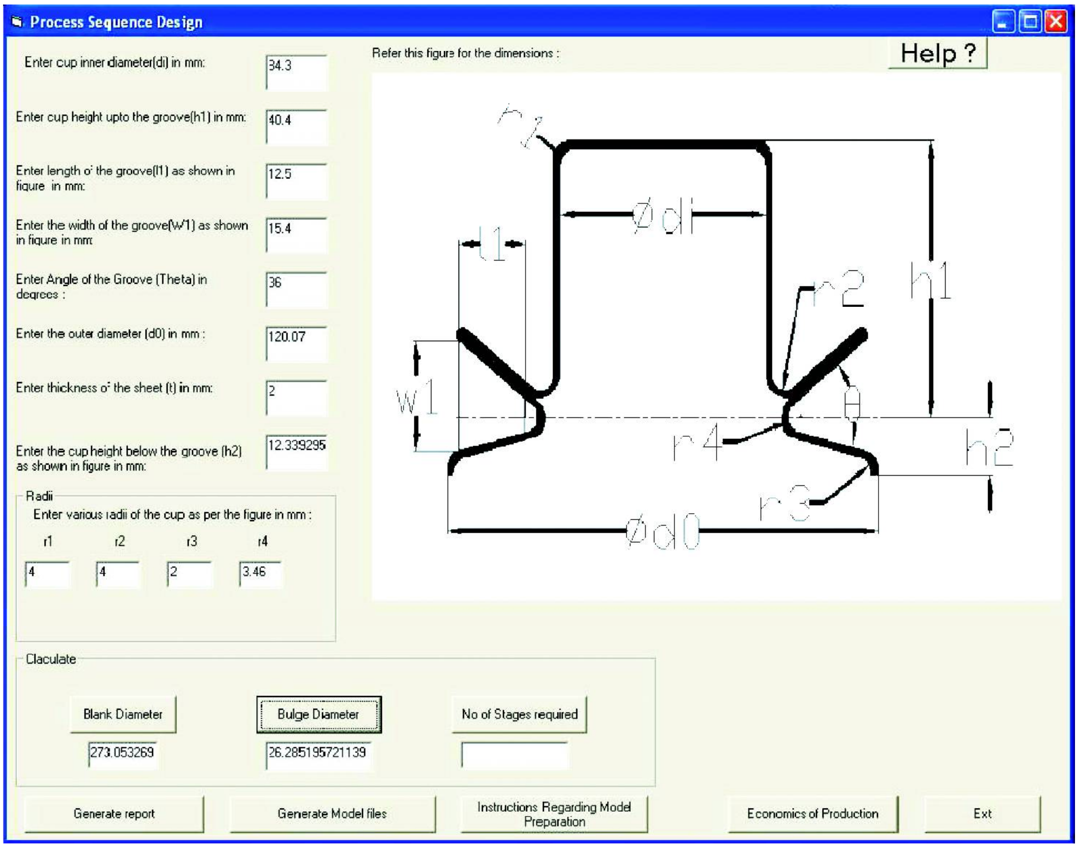


Figure 9: Output Showing Process Sequence for Case-1

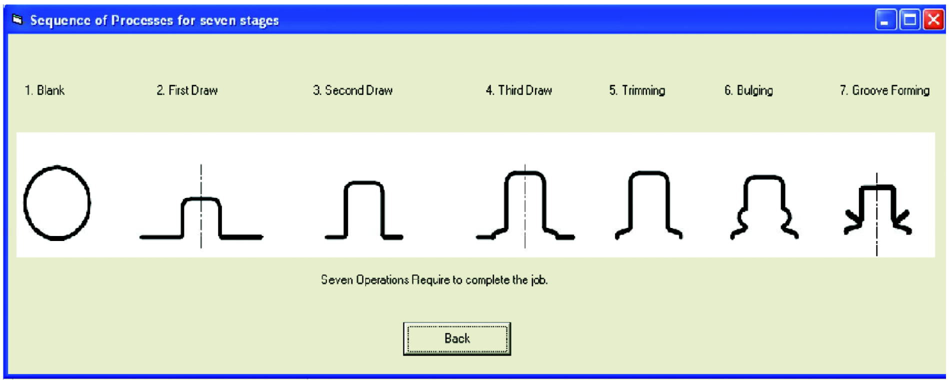
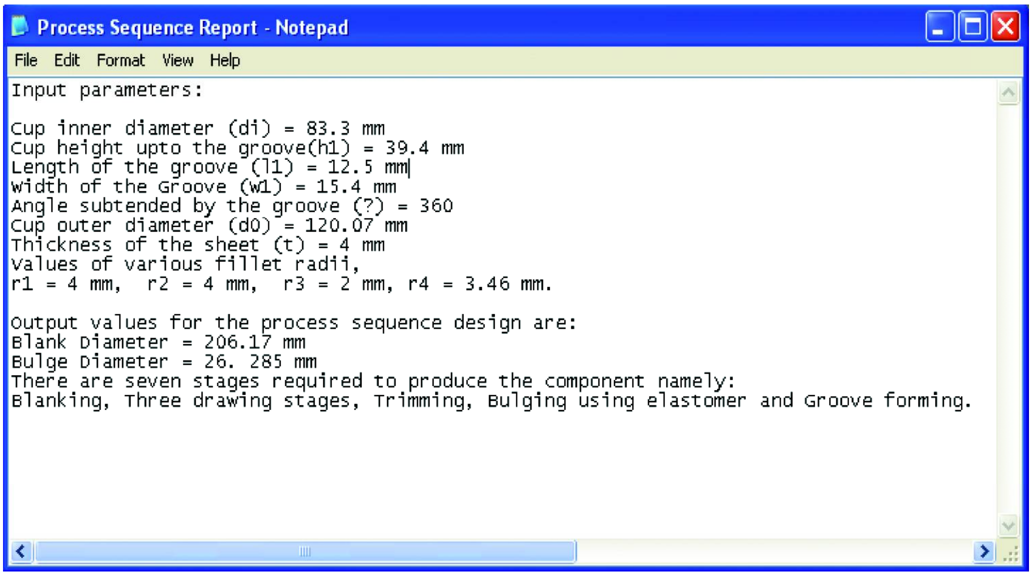


Figure 10: Report Generated by KBS for Case-1



Process Sequence Report - Notepad

File Edit Format View Help

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Input parameters:

Cup inner diameter (di) = 83.3 mm
Cup height upto the groove(h1) = 39.4 mm
Length of the groove (l1) = 12.5 mm
width of the Groove (w1) = 15.4 mm
Angle subtended by the groove (?) = 360
Cup outer diameter (d0) = 120.07 mm
Thickness of the sheet (t) = 4 mm
Values of various fillet radii,
r1 = 4 mm,  r2 = 4 mm,  r3 = 2 mm, r4 = 3.46 mm.

Output values for the process sequence design are:
Blank Diameter = 206.17 mm
Bulge Diameter = 26. 285 mm
There are seven stages required to produce the component namely:
Blanking, Three drawing stages, Trimming, Bulging using elastomer and Groove forming.
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The analysis has also been done for two other models of the pulleys. The input parameters and output results for these two pulleys are shown in Table 2 as Case-2 and Case-3.

COMPARISON OF THE KBS RESULTS WITH PRACTICAL RESULTS

To validate the developed KBS, comparison has been done of KBS result with actual field results. As three case studies have been reported in present paper, the result of comparison is shown in Tables 3, 4 and 5.

It is observed that the error in the result is maximum, of the order of 1.85%, for the blank diameter for Case-1. The reasons of this error may be because of the variation of draw ratio taken for the deep drawing stages in KBS and practical conditions. It may be also because of the trimming allowance provided

Table 2: Input Parameters and Output Results for Case-2 and Case-3

Parameters	Case-2	Case-3
Cup inner diameter (*di*) in mm	92.60	89.00
Cup height upto the groove (*h*1) in mm	65.80	33.60
Length of the groove (*l*1) in mm	9.78	11.18
Width of the groove (*w*1) in mm	11.65	11.71
Angle subtended by the groove (θ) in degrees	38.00	36.00
Cup outer diameter (*d*0) in mm	146.00	153.00
Thickness of the sheet (*t*) in mm	2.00	4.00
Values of Various Fillet Radii, in mm		
r1	7.00	5.00
r2	4.00	4.00
r3	2.00	2.00
r4	4.30	4.00
Output Results		
Blank diameter in mm	232.15	168.00
Bulge diameter in mm	20.68	23.50
Number of stages required	7.00	6.00
	Blanking, Three drawing stages, Trimming, Bulge forming and Groove forming	Blanking, Two drawing stages, Trimming, Bulge forming and Groove forming

Table 3: Comparison of the Results for Case-1

	Case-1		
	Calculated	Actual	Error (%)
Blank Diameter	206.170	210	1.85
Bulge Diameter	26.285	28	6.52
No of Stages Required	7.000	7	–

Table 4: Comparison of the Results for Case-2

	Case-2		
	Calculated	Actual	Error (%)
Blank Diameter	232.15	235	1.22
Bulge Diameter	20.68	22	6.38
No of Stages Required	7.00	7	–

Table 5: Comparison of the Results for Case-3

	Case-3		
	Calculated	Actual	Error (%)
Blank Diameter	168.0	170	1.19
Bulge Diameter	23.5	24	2.12
No of Stages Required	6.0	6	–

in KBS and practical conditions. Further when comparison is made for the bulge diameter, error is higher in order of 6.52%, for Case-1. This error may be because of the assumption of the development of the bulge and groove surfaces. In the KBS it is assumed that thinning doesn't occur in the sheet metal while bulging, but in actual conditions it is bound to happen.

CONCLUSION

Sheet metal forming industry is becoming very competitive. Because of the competition in the market the manufacturers need to shorten the lead times for their products. KBS is one such tool to assist the manufacturers in shortening the lead times. It can be used effectively as decision support system. An attempt has been made to develop KBS for Process Sequence design for manufacturing pulley, which is used for power transmission in automobile cooling applications. Following conclusions can be derived from the present work:

- Algorithms and flowcharts have been developed for the Process sequence design module. Coding has been done for development of KBS based on the flowchart and validation of the KBS has been done comparing the results with the practical data available from the manufacturer. The data produced by KBS are found in good accordance with the practical data. As we can see in the comparison all the errors are positive. Estimation of Blank diameter and Bulge diameter is lesser than the actual data. This variation is acceptable. Again the errors can be corrected as and when it is encountered by providing some positive allowance as the errors are all positive. It will assist in quick decision making to the manufacturer as the results can be achieved in very short time with satisfactory accuracy.
- Developed KBS can be further enhanced by automating the FEA analysis by suitable codes developed using API support for FEA software. This can be done in two ways, either incorporating KBS in FEA software or incorporating FEA software support in the developed KBS (Venkatesh, 2007).
- The present KBS gives costing solution for only one stock-strip layout with single press working. It can be further enhanced by providing options for the selection of various possible stock-strip layouts.
- The developed KBS doesn't give any detail regarding die designing. A die design module can be prepared using parametric data derived in process sequence design module.

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