



Integration of Computational Intelligence and Knowledge Engineering For Design Optimization of Connecting Rod Dies

Shyamsundar D. Hivarale & Dilip R. Pangavhane

Tata Consult. Service Limited, Pune, India, Director, Prestige Inst. of Engg. & Sci., Indore (MP) India

Abstract - This paper demonstrates a cumulative use of computational intelligence and knowledge engineering to build a process automation tool for closed die forging process. A principle of soft computing has been used to develop computational intelligence with the help of Visual Basic (VB) codes. Mathematical and rule based algorithms has been developed from a relative correlation exercise between Empirical, Statistical, CAE and Experimental test analysis approaches. These algorithms have been used as knowledge base to interact with an inference engine of developed computational intelligence system. This paper also summarizes a case study to validate and review the developed process automation tool in need to get a virtual prototype die model with the prediction of forging process variables and parameters for connecting rod. This will leads to develop an automated, robust, quick, quality, accurate & decision making tool for society in order to achieve the power/cost/time/skill effectiveness even if operated by an unskilled user. This work will be worth full for forging industrial applications in estimating forging load.

Index Terms—*Computational intelligence, knowledge engineering, Expert System, Design and Optimization of connecting rod die.*

I. INTRODUCTION

After several investigation studies it has been proven that forged products are highly reliable and possess superior mechanical properties. Forging is one of the main processes used to manufacture metal components for a broad range of applications. So the increasing worldwide interest in the production of forging products leads the researchers to study on forging technology [2].

Material wasted due to the flash accounts approximately 33% of the volume of original work piece in conventional hot forging of connecting rods. It has been proved that in order to achieve the optimized topological shape parameters the forging must be

performed in a closed cavity, which finally leads to cost optimization of forged parts. Also adequate metal flow without any defect, appropriately filling of the die, no overloading of dies can be achieved by controlled volume distribution of preform in fleshless forging. So the need of process automation comes into existence to optimize the forging process, saving raw materials and energy. For the design of connecting rod and its die we have to take an assistance of some high end CAD/CAM packages like Unigraphics (NX-3) [3]-[5].

For the computer numerical simulation and optimization study we have to take an assistance of commercially available high end CAE tool like three dimensional version of DEFORM (ERC/NSM), DEFORM-3D. This thermo-mechanically coupled computer aided tool has extensively used in cold, warm and hot-forging research which obeys an elastic-plastic material law. And finally the whole man machine interaction process has being monitored by a computer controlled expert system which has been developed by visual basic language codes.

II. KNOWLEDGE ENGINEERING

Knowledge engineering is the development of knowledge base through the process of mechanism of knowledge acquisition by adapting a suitable scientific methodology.

A. Knowledge Acquisition

It has been achieved by implementing the scientific data, basic principles, related theories in the optimistic way of sequences and coded format that can be used in an automated application. Submit your manuscript electronically for review. Process of extracting the knowledge through human expertise from existing proven Theories, Methodologies, Thumb rules, Laws, Corollaries, Technical Literature, Standard Engineering Procedures, Established Engineering Equations, Experimental Data, Codes of Practice and Expert's opinions. In another way, knowledge acquisition module processes the data entered by the expert and transforms

it into a data presentation understood by the system of Computer.

B. Scientific Methodology

Here we have developed a knowledge base based on mathematical modeling techniques from Statistical, Empirical and Simulation analysis approach for the design and cost optimization of forging die for flash less forging.

C. Statistical and Empirical Analysis Approach

In this approach detailed process methodology for the determination of unknowns i.e. process parameters, variables and material properties for the flash less forging is described. Also a structured mathematical modeling has been developed by implementing the scientific data, basic principles, related theories in the optimistic way of sequences.

The overall design of forging process requires the prediction or estimation of:-

- Shape complexity and volume of the forging.
- Number of configurations of perform or blockers.
- The flash dimensions in the dies & the additional flash volume required in the stock of perform & finishing operation.
- Forging load, energy & centre of the loading for each forging operation.
- Shape Difficulty Factor

It can be calculated as:-

A Longitudinal Shape factor (α) is defined as [6];

$$\alpha = X_f / X_c$$

..... (1)

With $X_f = P_2/F$

$$X_c = P_{c2}/F_c$$

SHAPE CLASS 1 COMPACT SHAPE $L=b=h$	SUB- GROUP	101 NO SUBSIDIARY ELEMENTS	102 UNILATERAL SUBSIDIARY ELEMENTS	103 ROTATIONAL SUBSIDIARY ELEMENTS	104 UNILATERAL SUBSIDIARY ELEMENTS	
						
SPHERICAL AND CUBICAL						
SHAPE CLASS 2 DISC SHAPE $L=b>h$	SUB- GROUP	NO SUBSIDIARY ELEMENTS	WITH HUB	WITH HUB AND HOLE	WITH RIM	WITH RIM AND HUB
	21	211	212	213	214	215
PARTS WITH CIRCULAR, SQUARE AND SIMILAR CONTOURS CROSS PIECE WITH SHORT ARMS UPSET HEADS AND LONG SHAPES (FLANGES, VALVES) ETC						
	22	221	222	223	224	225
						

SHAPE CLASS 3 OBVIOUS SHAPE $L>b>h$	SUB- GROUP	301 NO SUBSIDIARY ELEMENTS	302 SUBSIDIARY ELEMENTS PARALLEL TO AXIS OF PRINCIPAL SHAPE	303 WITH OPEN OR CLOSED FORM ELEMENT	304 WITH SUBSIDIARY ELEMENTS ASYMMETRICAL TO AXIS OF PRINCIPAL SHAPE	305 WITH TWO OR MORE SUBSIDIARY ELEMENTS OF SIMILAR SIZE
PARTS WITH PRONOUNCED LONGIT. AXIS LENGTH GROUPS 1-SHORT PARTS $L=3b$ 2-MV LENGTH $L=3b$ 3-LONG PARTS $L=3b$ 4-V-LONG PTS $L=15b$ LENGTH GROUP NUMBERS ADDED BEHIND BAR - *e.g. 334/2						

“Fig. 1 Shape difficulty Factor”

Where

P = Parameter of the axial cross section of the forging.

F = Surface area of the axial cross section of the forging (surface that include the entire axis of symmetry).

Pc = Perimeter of the axial cross section of the cylinder which circumscribes the forging.

Fc = Surface area of axial cross section of cylinder which circumscribes forging.

Since the circumscribe cylinder has the maximum diameter and the maximum height of the forging, the factor represents a comparison of the shape of the forging shape with that of the cylinder

On round forging, bosses and rim placed farther away from the centre are increasingly more difficult to forge. Therefore a “lateral shape factor”, β is defined as:

$$\beta = 2R_g/R_c$$

..... (2)

Where

Rg = Radial distance from the symmetry axis to the centre of gravity of half of the cross section.

Rc = Maximum radius of forged piece which is equal to the radius of the circumscribing cylinder.

A “shape difficulty factor” (S), incorporating both the longitudinal and the lateral factor is defined as

$$S = \alpha \beta$$

..... (3)

- Flash Thickness and Weight

The most exhaustive study on flash design in steel forging appears to be that of Teterin and Ternovskij. They conducted a statistical data on more than 1500 round steel forging of various weights and established an empirical formula for flash thickness t, based on forging weight Q, using English units, inch for t and pound for Q. Their formula is [6]:

$$t = \frac{[-0.09 + 2 \sqrt[3]{Q/2.2} - 0.01Q/2.2]}{25.4} \quad \text{..... (4)}$$

Further statistical analysis based on experimental studies resulted in the following expression for the ratio of flash width w to flash thickness t :

$$\frac{w}{t} = -0.02 + 0.038 S \frac{Do}{t} + \frac{4.93}{(Q)^{0.2}} \quad \text{..... (5)}$$

Where,

w = flash land width in die in inch

Do = Diameter of the initial round stock in inch

Q = forging weight without flash loss in pounds

S = dimensionless shape difficulty factor.

The above results obtained by Teterin and Tarnovskij, agree well with those results obtained from above equation given in English units.

$$t = \frac{(1.13 + .89\sqrt{Q/2.2} - 0.017 Q/2.2)}{25.4} \quad \text{..... (6)}$$

And

$$\frac{w}{t} = 1.25 \exp[-1.09(Q/2.2)] + 3 \quad \text{..... (7)}$$

In most of the practical cases when a shape difficulty factor is difficult to calculate, the equation 1.3 and 1.4 are quite satisfactory for predicting flash dimensions.

• Flash Weight

Teterin and Tarnovskij also conducted statistical studies on round forging in order to develop formulas for estimating the flash losses. A dimensionless parameter γ is defined as [6]:

$$\gamma = H_s / (h_0 + h_A) \quad \text{..... (8)}$$

Where

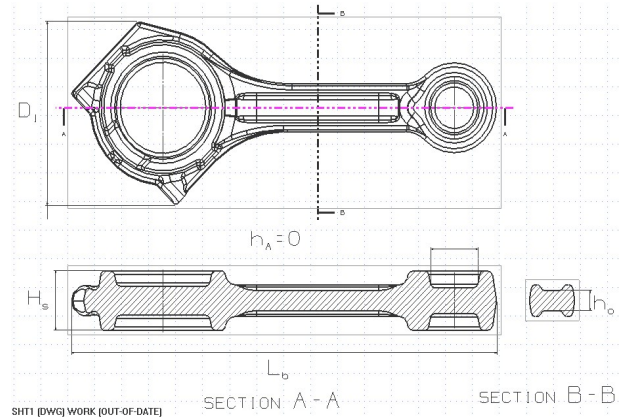
H_s = Final height of the forging.

h_0 = Minimum distance between flat surfaces upon which stock was resting when Dies closed. Refer Fig. 2.

h_A = Distance between internal and external parting line.

The flash weight is given by:-

$$Q_f = [(K_1 + K_2)/100] Q$$



“Fig. 2 Top & side view of connecting rod die showing dimensions used in calculations of flash weight”

Where

Q_f = Weight of flash

Q = Net weight of forging (without flash)

$$K_1 = 0.54 + 15.44(Q/2.2)^{-0.2} (1 + 0.00757\eta)$$

$$K_2 = 0.7026 (1 + 0.01969 \eta) \frac{w}{t}$$

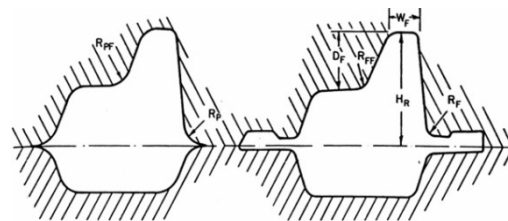
The ratio w/t is obtained from equation (7). the parameter η is a dimensionless expression for shape that incorporate the shape difficulty factor, S , the shape change parameter, γ and the dimension of the stock Do and the final forging dimension $D1$ thus [7]:

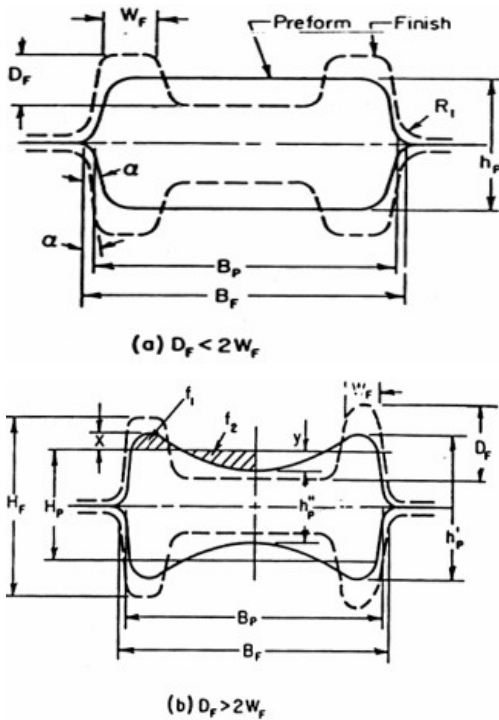
$$\eta = S(Do/D)^2 \gamma^2 \quad \text{..... (10)}$$

Where, S is obtained from equation (3) γ is obtained from equation (4)

• Preform Design Considerations

“Prototype of final forged component having slightly larger dimensions than that of finished product.”





“Fig. 3 Preform design Considerations”

It assists achievements of:-

- Adequate metal distribution
- Defect free metal flow
- Complete die filling

Where,

RF = Blend radius of final forging at the parting line

BF = Overall width of final forging

HF = Height of final forging

HP = Height of preform

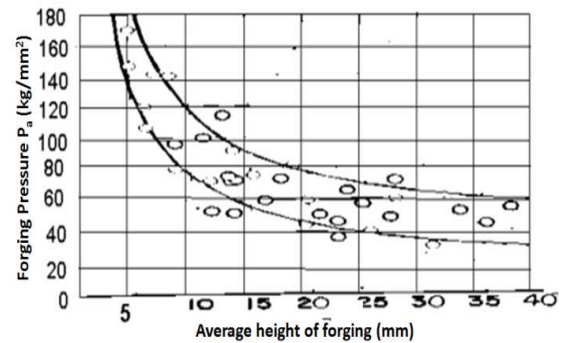
DF = overall rib height

PREFORM DIMENSIONS RECOMMENDED BY VARIOUS COMPANIES FALL IN FOLLOWING RANGES:-			
Dimensions of finished forging	Dimensions of preform		
	Al alloys	Titanium alloys	Steel & its alloys
Web thickness (t_f)	$t_p = (1 \text{ to } 1.5) t_f$	$t_p = (1.5 \text{ to } 2.2) t_f$	$t_p = (1.7 \text{ to } 3) t_f$
Fillet radii (R_{FF})	$R_{PF} = (1.2 \text{ to } 2) R_{FF}$	$R_{PF} = (2 \text{ to } 3) R_{FF}$	$R_{PF} = 1.2 R_{FF} + 0.125$
Corner radii (R_{FC})	$R_{PC} = (1.2 \text{ to } 2) R_{FC}$	$R_{PC} = (2) R_{FC}$	$R_{PC} = 1.2 R_{FC} + 0.125$
Draft angle (a_f)	$a_p = a_f (2 \text{ to } 5^\circ)$	$a_p = a_f (3 \text{ to } 5^\circ)$	$a_p = a_f (3 \text{ to } 5^\circ)$
Width of Rib (W_f)	$W_p = W_f - 1/32$	$W_p = W_f - (1/16 - 1/8)$	$W_p = W_f - (1/8 \text{ to } 1/4)$
Blend radius of the preform at the parting line	$R_p = R_f + C$		
Overall width of preform	$B_p = B_f - (0.008 \text{ to } 0.4)$		
The additional preform height is determined by	$X = 0.25 (H_f - H_p)$ or $X = (0.6 \text{ to } 0.8) * D_f$		

“Fig. 4 Preform dimensions recommended by forging industries”

- Pressure and Load in closed die forging

The Fig. 5 shows experimental graphical correlation of role of average height of forging in determining the forging or normal load acting on forged steel connecting rod die.



“Fig. 5 Average height of forging”

Based on this sensitivity study Schey has developed an empirical formula for calculating forging P_a –

$$P = C_1 \cdot \bar{\sigma}_a A \quad (11)$$

$$h_a = \frac{Q}{A_t \cdot P} \quad (12)$$

$$P_t = A_t P_a \quad (13)$$

$$P_a = 1422 \left(14 + \frac{618}{25.4 h_a} \right) \quad (14)$$

$$P_a = 1422 \left(37 + \frac{781}{24.5 h_a} \right) \quad (15)$$

Where,

$\bar{\sigma}_a$ = Average flow stress at a given forging temp.

A = C/S area of the forging at parting line

C1 = Constant depends on complexity of forged part

h_a = Average height

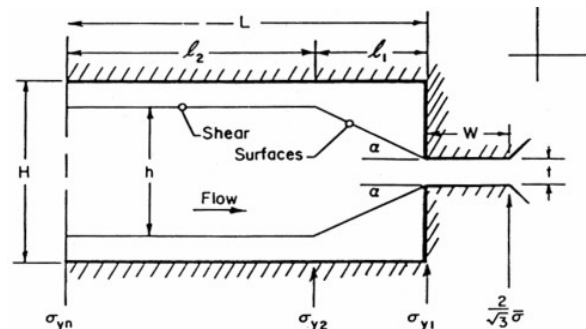
P_a = represents average forging press.

P_t = maximum total forging load.

Q = total forging weight

• FLOW STRESS ANALYSIS

The Fig. 6 shows the design variables used in determining the flow stresses at various sections of connecting rod die based on research data review.



“Fig. 6 Flow Stress Analysis”

$$\sigma_{y1} = \frac{2\tau}{t}b + \frac{2}{\sqrt{3}}\bar{\sigma} \dots\dots\dots (16)$$

$$\sigma_{y2} = \frac{k_2}{k_1}l_n \left[\frac{t}{h} \right] + \sigma_{y1} \dots\dots (17)$$

$$\sigma_{yn} = \frac{2\tau}{t}l_2 + \sigma_{y2} \dots\dots\dots (18)$$

l1, l2, h, w, t, a = Geometrical parameters

K1, K2 = constants

f = frictional stress

σ = shear stress

τ = shear stress

• Forging Load

Based on this sensitivity study Schey has developed an empirical formula for calculating forging load P –

Load Edger-

$$B = \frac{A}{L}$$

$$P = 4 \times [1 - (0.001 \times D_s)] \times \left[1.2 + \left(\frac{20}{D_s} \right)^2 \right] \times \left[1 + 0.1 \sqrt{\frac{L}{B}} \right] \times \left[\frac{A \times y}{1000} \right] \quad (19)$$

Load Finisher-

Load require for forging component in finisher die is approximately (2/3) of load require for forging component in blocker die.

$$P_{FINISHER} = \left(\frac{2}{3} \right) \times P_{BLOCKER} \quad (20)$$

III. COMPUTATIONAL INTELLIGENCE

The following steps shows the use of computational intelligence in building a expert system to design a connecting rod die for forging process in need to achieve or predict optimum process variable parameters.

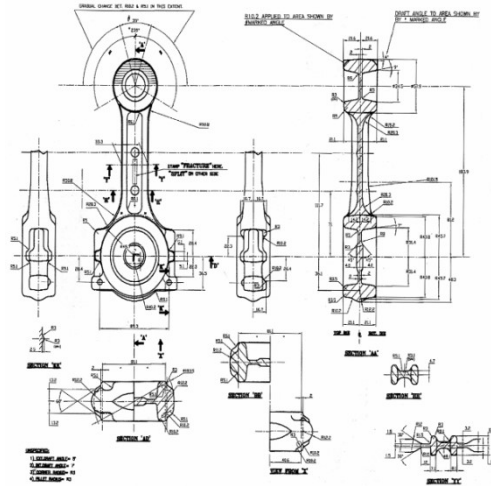
A. Component Review (2D Drawing):

In this process user has to review the 2D drawing of component being forged received from customer to analyze and predict process for 3D modeling technique (see Fig. 7).

B. 3D CAD Modeling:

This process involves conversion of received 2D drawing sheet into a live 3D CAD model using a high end 3D modeling too like UNIGRAPHICS NX-2. It is useful to design & create virtual die blocks model by subtracting the geometry of component being forged

with forging allowances from standard available metal die cubes about parting line (see Figure 9)



“Fig. 7 2D drawing model of connecting rod”

C. Geometry or Profile Recognition for component being forged:

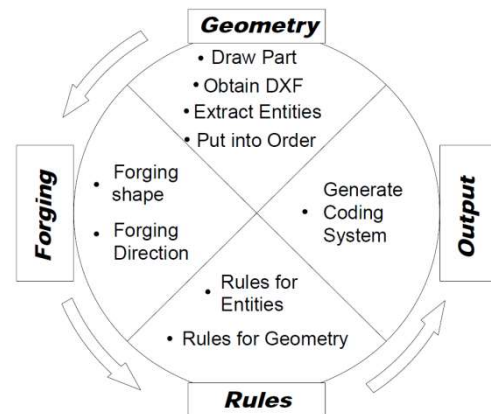
A high CAD package UGNX-2 can easily recognize the required topological parametric values of extreme peripheries of component being forged [8]. This can be done automatically by a developed coded auto control program. The outcome of this program generates a datasheet (See Appendix-I-II).

D. User Interface:

User has to give the required inputs manually to the inference engine iFORGE. These required inputs are values generated by datasheet in last step (See Appendix-III-V).

E. Inference Engine:

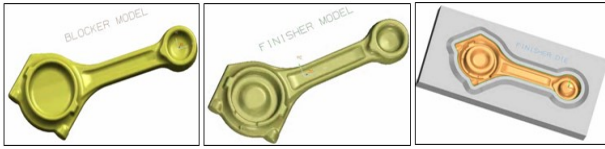
The developed inference engine has being driven by an intelligent agent i.e. the codes of Visual Basic Language. It calculates optimum values of all forging process variable parameters for the geometry being forged (See Fig. 8) [1].



“Fig. 8 Mechanism of Inference Engine”

F. 3D Die modeling:

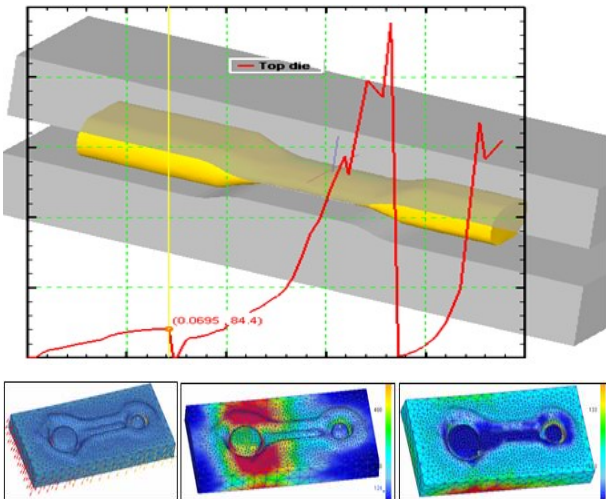
User need to scale the 3D geometry of the component being forged with respect to the optimum forging allowances given by the iFORGE in last step. This scaled geometry of component being forged has to be subtracted from standard available metal die cubes about parting line to design & create virtual die blocks model (See Figure 9).



“Fig. 9 3D UG Part models of connecting rod die”

G. CAE Analysis (Finite Element Analysis Method):

The performance of forging dies have been checked through CAE simulations in order to predict the optimum values for required forging load, die stress, limits of deformation, initial preform temperature, die life against number of forging cycles and frictional forces at die preform interfaces (See Figure 10).



“Fig. 10 Structural, thermal, & mould flow analysis of connecting rod die”

H. Feedback Loop:

If there is a remarkable deviation seen between CAE and iFORGE results, then user has to go for trial and error method by varying shape difficulty factor and which is also less time consuming.

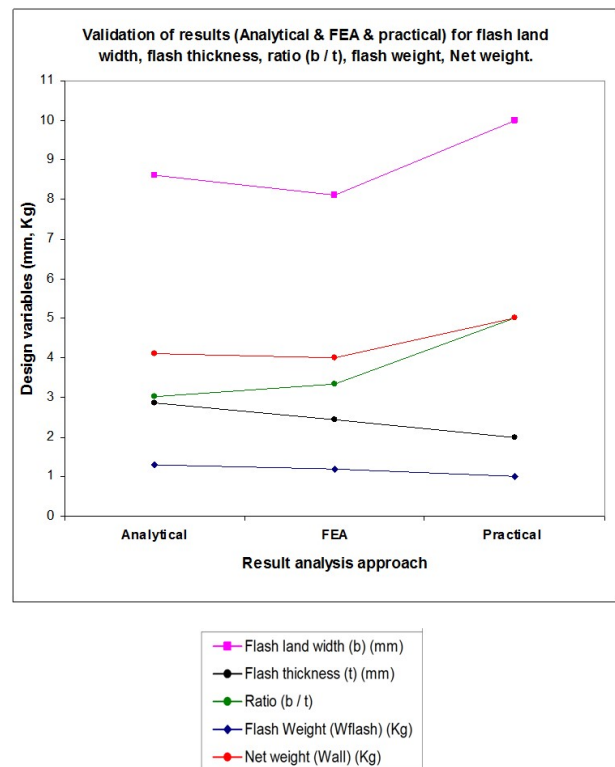
IV. RESULTS AND DISCUSSION

Following table shows the variation of design variables with the different analysis approaches (i.e. Analytical, FEA). Following table shows that these values show good conformity with both the analysis approaches taken under considerations.

Table – 1 : Validation of FEA with Analytical method

Design Variables	Test Methods		
	Analytical	FEA	(%) Error
Flash Land Width (b)	8.926	8.121	5.1

Design Variables	Test Methods		
	Analytical	FEA	(%) Error
(mm)			
Flash Thickness (t) (mm)	2.968	2.426	14.5
Ratio (b/t)	3.16	3.34	10.2
Flash Weight (Wflash) (kg)	1.43	1.2	8
Cut Weight (Wall) (kg)	4.23	4.34	3
Load Edger (N)	12.98*10E5	8.28*10E5	34
Load Blocker (N)	10.93*10E6	9.73*10E6	7
Load Finisher (N)	06.98*10E6	6.31*10E6	9
Maximum Principle Stress(N/mm2)	386.57	350	11
Deformation/Strain Rate (mm)	0.31	0.33	10
Average Flow Stress (N/mm2)	115.2	104.75	8
Flow Stress at Flow Zone1 (MPa)	271.52	240.23	12.1
Flow Stress at Flow Zone2 (MPa)	599.52	543.39	8.4
Flow Stress at Flow Zone3 (MPa)	649.52	610	6.5



“Fig. 11 Validation of results (Analytical, FEM & practical) for forging process variables”

From the above results review it is clear that the forging process variables which have been predicted by this automated tool show good conformity against both analytical and FEA approaches by small marginal error.

V. CONCLUSION

Thus in this study structural topology optimization of forged steel connecting rod die has been achieved with the help of computational intelligence and knowledge engineering. The developed process automation tool can able to predict the forging process variable parameters with precision and accuracy. The developed tool is linked with the commercially available high end CAD/CAM/CAE packages. Also in order to predict the forging load and die stress values combination of Statistical, Empirical and Simulation analysis approaches have been used and verified by FEM. After the identification of geometry, the design rules have been stored in the knowledge base in such a way that every industry (designer) can define and add its own values. The developed inference engine uses Visual Basic programming codes to interact with the developed knowledge base and user interface. It has been proved and validated by comparing the output results with both experimental and Finite Element Analysis methodologies. The experimental and Finite Element results show good conformity. The advantage of developed tool is that no tooling has to be built and the number of experimental tryouts can be significantly reduced. The future scope of this dissertation may lead on to develop an Expert System with the help of Artificial Intelligence to reduce the total design cycle time.

VI. ACKNOWLEDGEMENT

The authors would like to thank all the employees involved in this particular task of Shivsai Enterprises (Tool Room) Pune, Maharashtra, India for their excellent technical support to carry out this work.

VII. REFERENCES

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APENDEX (01) -DATA SHEET SHOWING VALUES OF GEOMETRICAL PARAMETERS OF CONNECTIN ROD DIE USING CAD TOOL UNIGRAPHICS NX-2.

Information listing			
created by	:	Administrator	
Date	:	4/16/2006	
Current work part	:	\\ug3\l\1150_D1300\1278\FIN\REV_B\1278_FTN_B.pr	
Node name	:	ug4	
Measurement of Mass Properties			
Displayed Mass Property Values			
Volume	=	379650.327458619 mm ³	
Area	=	66787.911855445 mm ²	
Mass	=	2.980496127 kg	
Weight	=	29.228708712 N	
Radius of Gyration	=	98.983632085 mm	
Centroied	=	-143.071544256, -0.131530722, 0.014873938 mm	
Detailed Mass Properties			
Analysis calculated using accuracy of 0.990000000			
Information Units in Area			
Density	=	0.000007851	
Volume	=	379650.327458619 mm ³	
Area	=	66787.911855445 mm ²	
Mass	=	2.980496127 kg	
Plan Area	=	2363 mm ²	
First Moments			
Mxc, Myc, Mzc	=	-426.424458203, -0.392027059, 0.044331742	
Center of mass			
Xcbar, Ycbar, Zcbar	=	-143.071544256, -0.131530722, 0.014873938	
Moments of Inertia (Work)			
Ixxw, Iyyw, Izzw	=	1937.279514651, 88499.576499231, 89986.065551308	
Moments of Inertia (Centroidal)			
Ixx, Iyy, Izz	=	1937.227291661, 27490.370096099, 28976.808243961	
Moments of Inertia (Spherical)			
I	=	29202.202815861	
Products of Inertia (Work)			
Pyzw, Pxzw, Pxyw	=	-0.036717793, -9.759975559, -19.143670671	
Products of Inertia (Centroidal)			
Pyz, Pxz, Pxy	=	-0.030886807, -3.417364788, -75.231587435	
Radii of Gyration (work)			
Rxgw, Rygw, Rzg	=	25.494806628, 172.316226450, 173.757360631	
Radii of Gyration (centroidal)			
Rxg, Ryg, Rzg	=	25.494462995, 96.038611510, 98.600893998	
Radii of Gyration (spherical)			
R	=	98.983632085	
Principal Axes			
Xp(X), Xp(Y), Xp(Z)	=	0.000126459, 0.000027179, 0.999999992	
Yp(X), Yp(Y), Yp(Z)	=	0.002944081, 0.999995666, -0.000027552	
Zp(X), Zp(Y), Zp(Z)	=	-0.999995658, 0.002944084, 0.000126379	

DATA SHEET SHOWING VALUES OF FINITE
ELEMENT ANALYSIS OF CONNECTIN ROD DIE
USING SIMULATION TOOL DEFORM F3 ver. 6.0.

Information listing		
created by	:	Administrator
Date	:	4/16/2006
Current work part	:	//ug4/d/D1150_D1300/D1278/FIN/REV_B/D1278_FTN_B.pr
Node name	:	DEFORM F3 ver. 6.0
Measurement of Mass Properties		
Displayed Mass Property Values		
Volume	=	379650.327458619 mm^3
Area	=	66787.911855445 mm^2
Mass	=	2.980496127 kg
Weight	=	29.228708712 N
Radius of Gyration	=	98.983632085 mm
Centroied	=	-143.071544256, -0.131530722, 0.014873938 mm
Detailed Mass Properties inputs		
Analysis calculated using accuracy of 0.990000000		
Information Units in Area		
Work piece Material	AISI 1060	
Die Material	H-14	
Temperature	1650 ~ 2200 F	
Density	= 0.000007851	
Volume	= 379650.327458619 mm^3	
Area	= 66787.911855445 mm^2	
Mass	= 2.980496127 kg	
Plan Area	= 2363 mm^2	
Component weight	= 2.54 Kg	
Component Length	= 316.3 mm	
Component width	= 128.6 mm	
Component thick.	= 41.8 mm	
Detailed Design Properties outputs		
Process	Hot	Step 53
Die temperature type	Hot (150-250)	Step 53
Object shape complexity	= 0.196	Step 53
Mesh	Elem. 38707, Nodes 9638	Step 62
Top Die	Rigid 150	
Geometry	Poly 27190, Points 13597	Step 62
Top Die	Rigid 151	
Geometry	Poly 27380, Points 13791	Step 62
Moments of Inertia (Centroidal)		
Ixx, Iyy, Izz	= 1937.227291661, 27490.370096099, 28976.808243961	
Load prediction	= 992.17265368 Ton	Step 52
Deformation rate	= 0.24721527	Step 53
Maximum principal stress	= 350.02168531 MPa	Step 53
Flow stress effective	= 600.11498256 MPa	Step 53
Flash design properties		
	Land width	= 8.12172854 mm Step 67
	Thick	= 2.42621232 mm Step 67
	Weight	= 1.17285432 Kg Step 67
Average flow stress	= 103.75237141 MPa	Step 73
Error estimates		

