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Design of combination tool for an automotive component with process optimization in metal forming

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Abstract
Selection of the tool and manufacturing equipment are the important phases of the process design in metal forming industry, as the tool development is very vital task in metal forming. The present work is focused on design and development of new combination tool used to perform three operations simultaneously on the hollow rod. The rod is used to connect the recliners of an automotive seat. A combination tool is designed based on the standard tool design approach and replaces old tools used for three different operations. A tool is used for manufacturing of a rod, which undergoes total five operations for the final product. The process has been optimized by combining three operations simultaneously in a single stroke, which ultimately increases the productivity. The study includes designing of the components, analyzing displacement and stresses for combination tool to use on the available press machine. Various forces occurred on the combination tool has been calculated and the test is carried out on an available press machine. The results found satisfactory with less defective components and improvement in productivity compared to the previous tool.

Keywords Combination press tool · Interactive approach · Tool design · Force distribution · Productivity improvement

1 Introduction

Design and development of combination tool for the sheet metal part is one of the crucial phase in sheet metal manufacturing, as for mass production, forming technology will be essential [1]. Forming industries generally uses past experience and internal techniques for tool design. The study has validated that, with the aid of CAD ability and tool designer's experience, process can be optimized by developing a combination tool. To manufacture precision tool in less time and at a lower cost is the main benefit of computer-aided engineering for combination tool design [2]. The existing system of manufacturing causes imperfect parts and rework, which results in higher cost of manufacturing, lower output and customer displeasure due to an extended production lead-time of the component. The process is carried out for manufacturing the connecting rod, used to connect recliners to regulate driver and co-driver seat in an automobile. The process consists of total five operations in sequence as grooving, flatting, serration, crimping and ID enlargement. A single tool is made for performing first three operations simultaneously.

In the earlier process chances of product quality response to process discrepancy was more. The proposed work aims to find an optimum process required for the operation and minimize the lead-time. Design of press tool used in thresher blade along with modeling, stress analysis and displacement of the component was carried out and found that fixture controls the orientation and location of parts in an assembly [3]. It appreciably supplies to process capability that determines product quality and production yield. A number of approaches developed to optimize a fixture assembly system with stiff fixture layout to deformable parts fixture layout [4]. Generation of the elegant progressive design system is the best way for cost effective product design [5]. It is demonstrated that three dimensional vision and part drawing helps the user to plan and develop the tool. The basic tasks of the process design is to select the sequence of operations and type of tools to be design [6]. To guide developments in engineering design processes and produce more valuable products,

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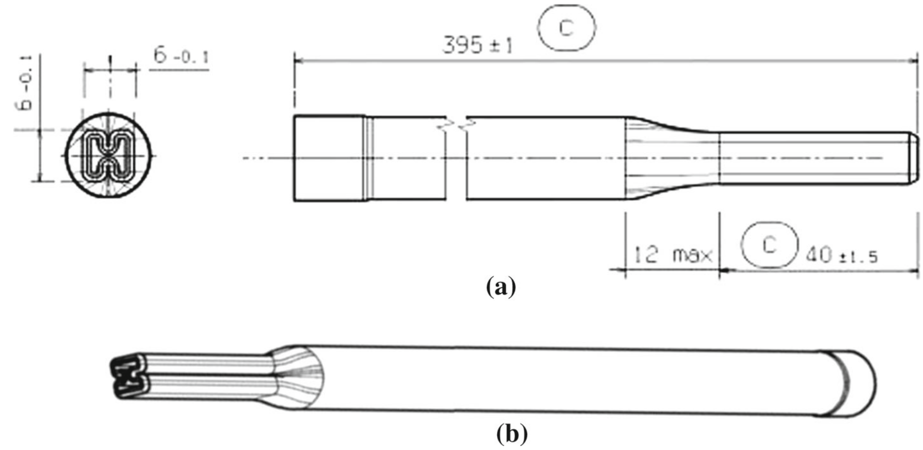

Fig. 1 **a** Connecting rod 2-D drawing. **b** Connecting rod 3-D drawing

methods for assessing the quality of engineering design processes can be used. An output of system modules includes the kind and appropriate dimensions of progressive die components specifically die block, die gages (front spacer and back gauge), stripper, punches, punch plate, back plate, die-set, and fasteners [7]. The system designed such that, the advice communicated by its modules is directly accumulated in various output data files, which utilized for regular modeling of assembly and components of a die. An intention of contributing to the improvement and facilitate the process of die design an application being developed that analyzes and values the operations to make with structuring them in order [8].

2 Operation performed

A round pipe (connecting rod) is converted into a square shape from one end up to 40 mm (+/- 1.5 mm) length as shown in Fig. 1a, b.

Previously grooving was the first operation done on the rod by converting the circular cross-section into a square shape up to 40 mm length from one end followed by flatting operation. Figure 2 shows the final required shape of the component.

Serration marks protruded on the flat surface for gripping and positioning purpose. Crimping done on the other end of the rod up to 10 mm length, followed by internal diameter enlargement by 0.3 mm up to crimping mark. Based on the intensity of defects, parts sent back to rework station or rejected after a quality check. Properties of component AISI 1010 (rod) as appended in Table 1.

For performing above operations, three separate dies were used for grooving, flatting and serration operation. Die as shown in Fig. 3 was used for grooving operation only.

3 Design of new tool based on part geometry

For the said operation, previously three dies mounted on the same press one by one for grooving, flatting and serration operation. Die is required to change after the completion of each operation for the defined batch size. This prone to a more time-consuming affair like tool loading and unloading, set up time and fatigue for the operator. This leads to a reduction in productivity and the requirement of the product drastically increases from the customer end which became very difficult to fulfill within time. Manufacturer unable to comply with delivery commitment and causes customer dissatisfaction. The study focused on optimization of the process through replacement of existing dies with single combination tool to perform three operations i.e. grooving, flatting and serration,

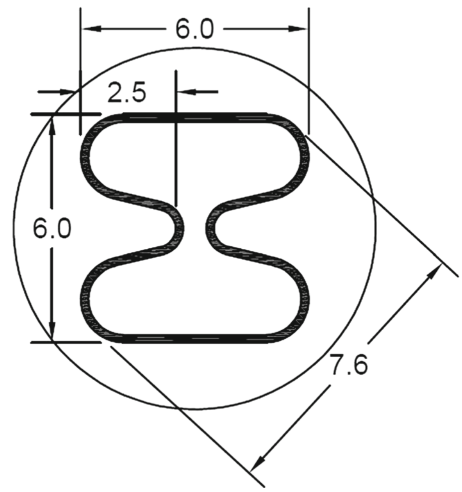

Fig. 2 Final required shape of connecting rod

Table 1 Physical and mechanical properties of rod

Property	Details
Pipe diameter, d	9.48 mm
Pipe thickness, t	0.9 mm
Ultimate tensile strength, S_{ut}	494.85 N/mm^2
Yeild strength (obtained), S_{yt}	412.37 N/mm^2

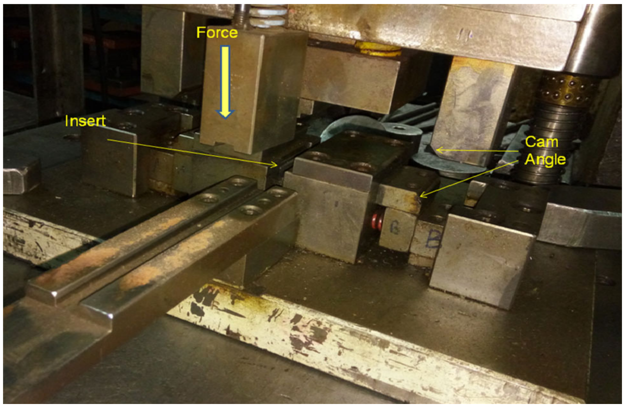

Fig. 3 Die used for grooving operation

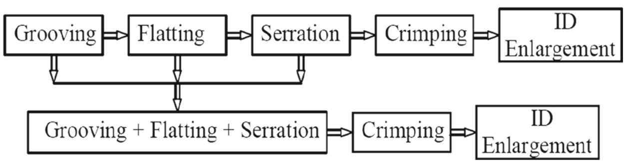

Fig. 4 Operations perform by combination tool

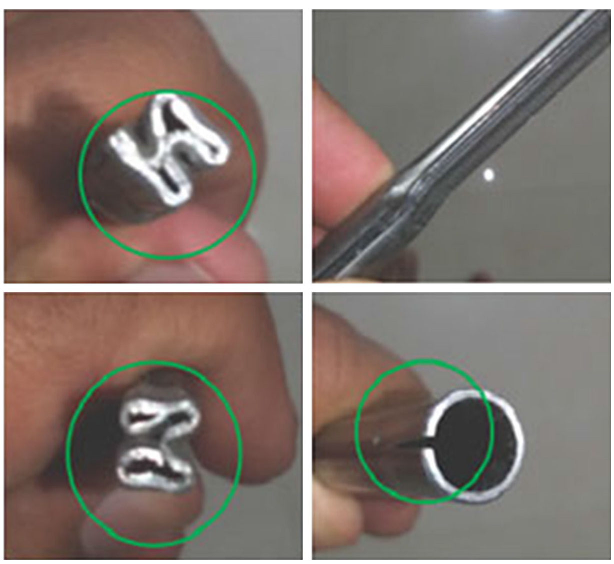

Fig. 5 Variety of defects observed

simultaniously on the connecting rod in one stroke of press as shown in Fig. 4.

In addition, previous conventional set up causes various defects in manufacturing of connecting rod as shown in Fig. 5. Defects lead to operator's fatigue at rework station, fitment problem at the customer end, increased the overall lead time which affects the productivity.

Cracks observed in the rod after grooving operation and square shape formation of 6 mm size was not perfect. A diagonal size formation of 7.6 mm was inaccurate after grooving operation. Cracks observed in the rod at the other end after ID enlargement.

According to defects observed in the process, cost due to rework was examined. So it is imperative to pay attention towards designing a new tool to make defect free process which inturn increases the part productivity through process optimization by a change in setup. The combination tool design procedure determines: (i) total forming stages, (ii) stage-wise tool geometry and (iii) forming force for each stage. Since the components of the tool are designed based on the part geometry, in current methodology final drawing of the part is considered for the design of combination tool [9] .

A combination tool designed to perform:

a) Grooving with partial flatting,
b) Flatting from all sides for forming square,
c) Serration marks for gripping and positioning.

For all three stages, the single tool needed to be developed so that all operations can perform simultaneously.

3.1 Stage wise selection of material

The material selected for stage wise components of a combination tool as,

3.1.1 First stage (grooving):

Components of the combination tool for the grooving operation selected according to the material properties are appended in Table 2.

3.1.2 Second stage (flatting):

The flatting operation performed from all sides. To maintain the square shape accuracy, top and bottom flat punches kept as it is and groove punches replaced by flat punches.

3.1.3 Third stage (serration):

Serration operation performed on top and bottom surfaces. To protrude the serration marks, only top and bottom flat punches replaced by serration punch.

Material for flat punch kept same for all stages.

Design of tool based on rigidity concept and component accuracy [11,12].

3.2 Design consideration

Tool structure must satisfy the following requirements.

Table 2 Component material properties [10]

Sr. no.	Component	Material	Young's modulus
1	Groove forming punch	OHNS, Hardened at 62 HRC	172 Gpa
2	Groove punch holder cam follower		
3	Groove holder cam follower guide block		
4	Follower top support		
5	Top flatting punch		
6	Bottom flatting punch		
7	Cam		
8	Cam guide block		
9	Cam holder block	Mild Steel	206 Gpa
10	Cam guide block guide plate		
11	Cam guide block holder plate		
12	Top plate		
13	Bottom plate		

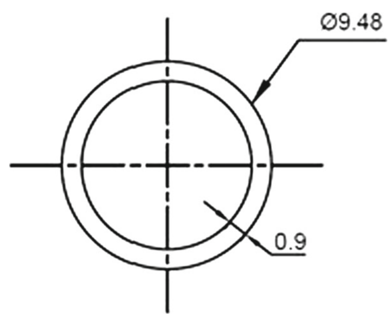

Fig. 6 Pipe diameter and thickness

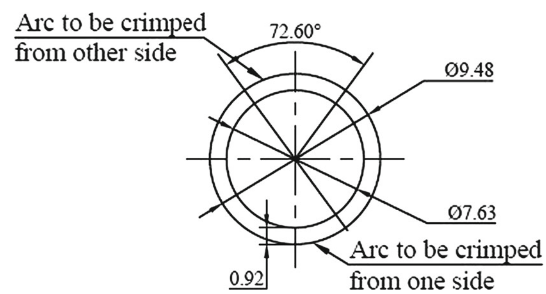

Fig. 7 Arc lengths to be crimped

a) The initial geometrical accuracy of the structure maintained for the whole life of the machine tool [13].
b) All mating surfaces of the structure machined with a high degree of accuracy to provide the desired geometrical accuracy [14]. (Accuracy of component, in this case, is +/- 0.1 mm)
c) The shape and size of the structure should not only provide safe operation but also ensure that working stresses and deformation should not exceed specific limits [15]. (Deformation of various blocks and plates, in this case, should not exceed 0.1 mm).
d) High static and dynamic stiffness of material are the fundamental requirements to fulfill mentioned necessities [16].
e) In most of the machine, the tool accuracy calculated from the component accuracy.

3.3 Pipe diameter and thickness

Pipe of diameter 9.48 mm shown in Fig. 6 needs to be converted into a square shape of 6 mm length.

To obtain a square of 6 mm, exact diameter of the pipe should be D = 7.63 mm.

Diametrically, difference per side is 0.92 mm as shown in Fig. 7. Grooving force from each side required to crimp 2.9 mm arc length inwards in the radial direction.

3.4 Angle of cam and follower

Vertical force converted into horizontal force by means of a cam and follower arrangement. With reference to Fig. 8, cam angle used has been calculated considering the coefficient of friction between hard steel as 0.4.

By calculation, cam angle should be 35^0 for the maximum efficiency.

3.5 Stage wise design of individual component

Stage wise components are designed as follows:

3.5.1 First stage

Based on the arc length mentioned in Sect. 3.3, groove forming punch thickness is calculated by considering 0.1 mm tolerance per side.

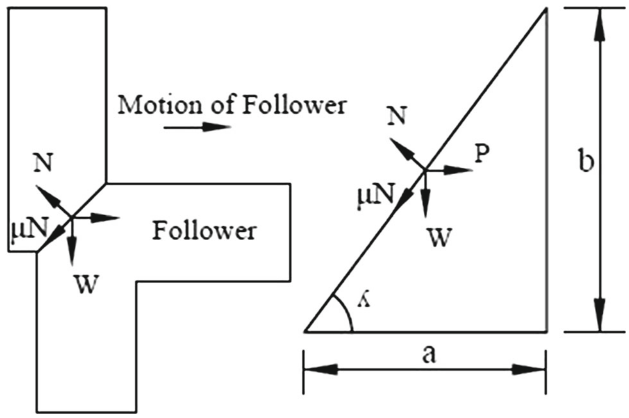

Fig. 8 Angle of cam and follower

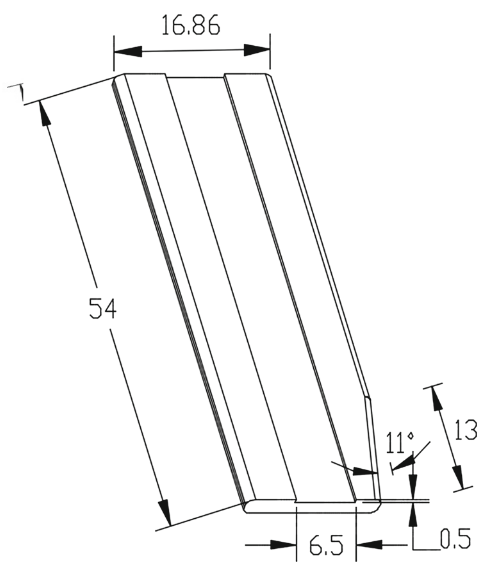

Fig. 9 Groove punch

a Groove forming punch

The groove forming punch of 2.7 mm thickness modeled by component reference shown in Fig. 9 and slot of thickness 0.5 mm is provided for fixing the punch with punch holder.

Forming or bending force required over the span of bend given by equation (Eq. (1)) [17].

$$F_b = \frac{K\,L\,S\,t^2}{W}. \tag{1}$$

Bending force,

$$F_b = 4797.91\ \text{N}$$

A total force required from both sides in grooving,

$$F = 9595.82\ \text{N}$$

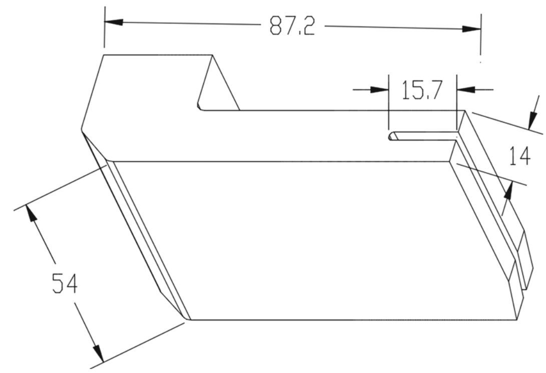

Fig. 10 Groove punch holder cam follower

Compressive stress in groove punch,

$$\sigma_{Compressive} = \frac{F}{A}.$$

$$\sigma_{Compressive} = 32.90\ \text{N/mm}^2 \tag{2}$$

Obtained stress is less than the compressive stress of OHNS at 62 HRC.

b Groove punch holder cam follower

Height, width, thickness and other geometric features generated by component reference, assembly constraints and fitment requirement during modeling as shown in Fig. 10.

Force induced compressive stress in the component.

$$\sigma_{Compressive} = 31.73\ \text{N/mm}^2$$

Another component of force act in the slot where the punch has a chamfer at 45^0 at its ends. The vertical component of force tends to expand the slot of punch holder. By shifting the force component on edge, assumed thickness for deflection (δ_{max}) was checked, which should be within the component dimensional tolerance. By calculation δ_{max}= 0.031 mm which lies within the tolerance limit of the component.

c Top and bottom flatting punch

Force calculated for making the surface flat and restricting the component deformation from top and bottom at the time of punch stroke as follows. Figure 11 shows top and bottom-flat punch used to restrict the deformation.

From Eq. (1),

$$F_b = 4797.91\ \text{N}$$

Total force required from top and bottom punch

$$F = 9595.82\ \text{N}$$

According to Macaulay's method [18], deflection of simply supported beam given by,

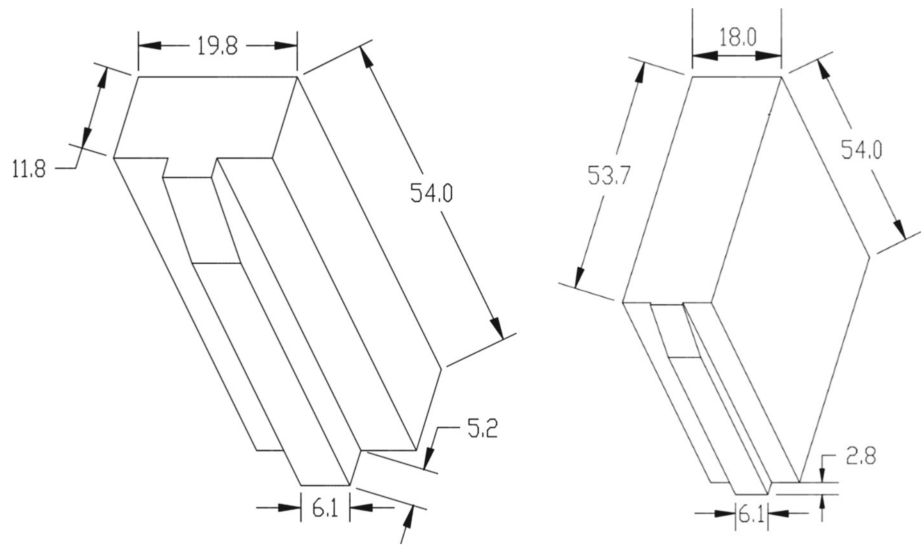

Fig. 11 Top and bottom flatting punch

$$\delta_{max} = \frac{WL^3}{48EI}. \quad (3)$$

For top punch,

$$\delta_{max} = 0.001 \text{ mm}$$

For bottom punch,

$$\delta_{max} = 3.38 \times 10^{-4} \text{ mm}$$

Total force required in the first stage

$$F_{total} = 4797.91 \times 4 = 19191.64 \text{ N}$$

d Cam

The cam subjected to a load of 4797.91 N during operation. Consider this as cantilevered at cam holder plate shown in Fig. 12, deflection obtained $\delta_{max} = 0.0032$ mm.

e Cam Guide block guide plate

Shaded region of this element (cam slot) subjected to a horizontal force of 4797.91 N and a vertical of 4797.91 N. Assume shaded portion shown in Fig. 13 as cantilever support for horizontal force, deflection obtained $\delta_{max} = 0.0085$ mm.

Considering the plate as a simply supported member under a vertical load of 4797.91 N, maximum deflection obtained δ_{max}= 0.15 mm.

This deflection is above the tolerance limit of the component, so extra 24 mm plate (as standard) added below the same plate. Extra 24 mm plate will support bottom-forming block. Final deflection obtained after adding this plate, δ_{max}= 0.018 mm.

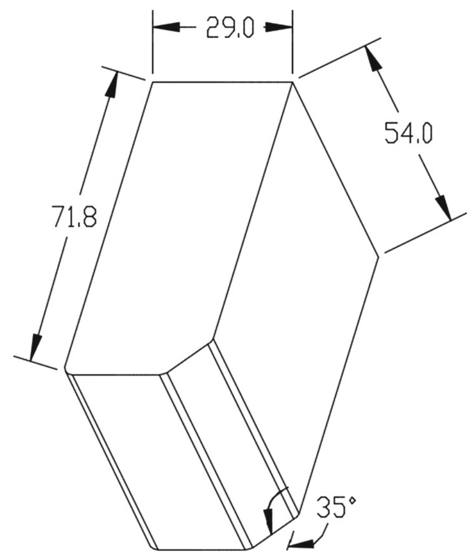

Fig. 12 Cam

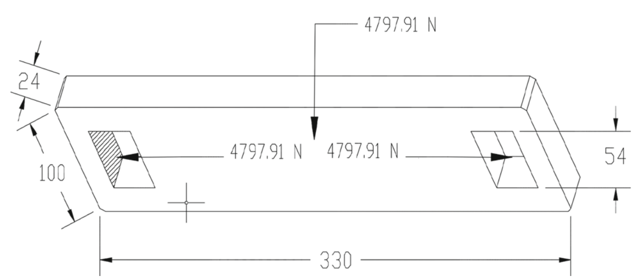

Fig. 13 Cam Guide block guide plate

f Spring calculation

During groove forming, both the groove punches remain within the formed groove at the same time, springs (set of 12 springs) will compress the rod from top side to deform it partially. The force produced by spring to bend the top during forming is 4797.91N. These springs also ensure the locking of the rod from the top during the stroke. This force also exists at the end of the stroke and creates a bite force on both sides of groove punch.

Bite force assumed to be 5% of the total force [19].

$$\text{Bite force} = 0.05 \times \text{Applied force.}$$

$$\text{Bite force} = 239.89\ \text{N}$$

$$\text{Total bite force } F_b = 479.78\ \text{N} \quad (4)$$

Coefficient of friction between punch & part = 0.4

Apply frictional principles

$$F_{(rev)} = \mu \times N = 191.91\ \text{N.} \quad (5)$$

The force required to produce by springs,

As explained two types of springs need to design.

a) Gang spring (i.e. Spring in parallel):
   A total force required to produce by springs is 4797.91 N. As total 12 springs used, hence force required to produce by each spring is 399.82 N.
b) Springs for follower reversal:
   From (Eq. (7)) total force required for the follower reversal is 191.91 N. Total 2 springs used in parallel, hence force required to produce by each spring is 95.95 N.

3.5.2 Second stage

In the second stage, there is a flatting process to make the component perfect square shape. Flat punches are used instead of groove punches, rest all components remain same in design since same force is required for the operation as in the first stage.

3.5.3 Third stage

In the third stage, all components remain same as in the second stage only top and bottom punch are replaced by serration punch. Serration marks to be punched of size 6 mm x 0.2 mm on the part. Force required for serration from the top side (same will be required from bottom side) is given by

$$\text{Force} = s_{ut} \text{x A} \ldots\ldots\ldots\ldots \quad (6)$$

After flatting operation, total 40 serration marks protruded on top and bottom flat surface of the component. The force required from the top serration punch is 23752.8 N. Obtained serration force is greater than forming force; hence, it needs to check the top serration block and bottom serration block for deflection.

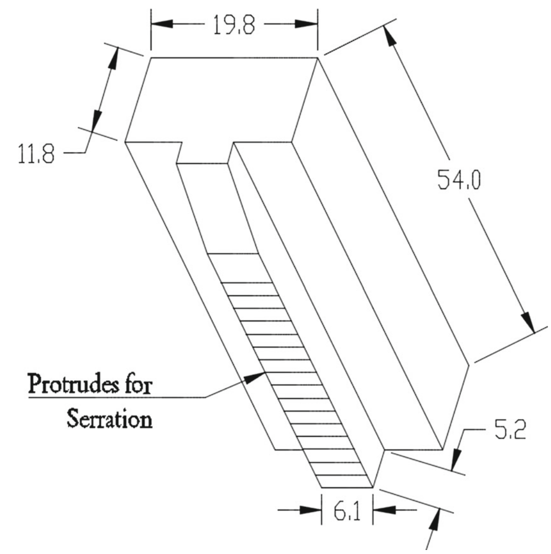

Fig. 14 Top serration block

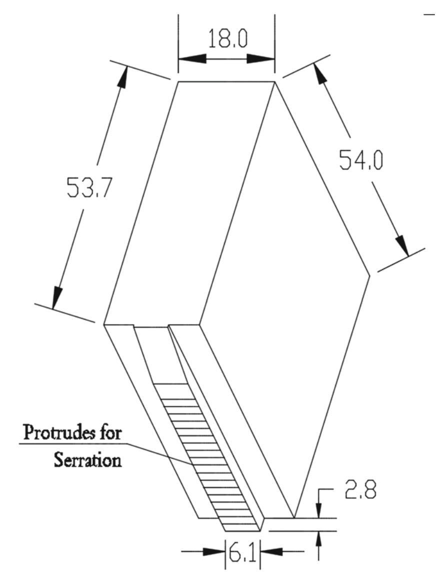

Fig. 15 Bottom serration block

a Top serration block

Consider a top serration block as the simply supported element as shown in Fig. 14, subjected to force of 23752.8 N, deflection obtained $\delta_{max} = 0.05$ mm.

b Bottom serration block

Consider bottom serration block as the simply supported element as shown in Fig. 15, subjected to force of 23752.8 N, deflection obtained $\delta_{max} = 0.00167$ mm. This lies within the tolerance limit of the component.

The force required from top and bottom

$F_1 = 23752.8 \times 2 = 47505.6$ N

The force required from both sides

$F_2 = 2 \times 4797.91 = 9595.82$ N

Hence, total force required in the third stage

$F_{total} = 57101.42$N

3.6 Design of spring

3.6.1 For load of 400 N

Wire diameter

Calculate using Wahl factor

$$Kw = \frac{4C-1}{4C-4} + \frac{0.615}{C}.$$
$$d = 3.35mm \tag{7}$$

Number of coils are 10 Nos.

By considering square and ground ends,

Total 12 turns, having solid length is 39.2 mm and free length is 74.9 mm.

3.6.2 For follower reversal

Wire diameter

$d = 3.35$ mm

Number of coils are 20 Nos.

By considering square and ground ends,

Total 22 turns, having a solid length is 73.03 mm and free length is 118.9 mm.

3.7 Calculation of forces for combination tool

Force in the first and second stage is equal.

$$\begin{aligned}
\text{First stage (grooving) } F &= 4797.91 \times 4 = 19191.64 \text{ N} \\
\text{Second stage (flatting) } F &= 4797.91 \times 4 = 19191.64 \text{ N} \\
\text{Third stage (serration) } F &= (23752.8 \times 2) + (4797.91 \times 2) \\
&= 57101.42 \text{ N}
\end{aligned}$$

The maximum force required for all three stages is 57101.42 N. The operator has to observe stroke height setting for the perfect stroke of serration during the third stage only. When serration depth achieved, the machine stroke will be locked i.e. same stroke height maintained during the production [20]. Setting the stroke height for serration will confirm the forming force requirements for another two stages (already maintained during tool design). The minimum capacity of press required to perform an operation using combination tool.

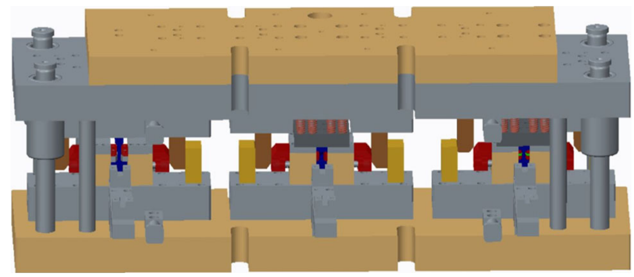

Fig. 16 New combination tool

$F_{min} = 95484.7$ N or 9.77 ton

3.8 Assembly model of combination tool

Design basis aims to capture the product design information from the early stage as those decisions have impacts in terms of time, cost and quality [6]. The IGES data of component drawing is taken in modelling software (in present case Pro-E wildfire-5) for designing the combination tool. Interactive design is a practical method that tends to ensure improvement by user-integration in the design process. CAD model of component is studied in 3D space and number of stages are formulated to obtain finished component as per the component drawing provided by the customer. Software based solution is a common method in industry to search the support for analytical design [21]. In present case groove profile is un-grooved, this will be the first stage followed by flatting and serration. For first stage, groove profile is taken as reference to develop grooving punch. Data is modelled and structured for supporting development activities to lead in innovative solutions. Grooving punch is then modified for the fitment requirement and constraining the motion in all direction. For follower, grooving punch will be treated as reference during geometric modelling and so on. The new combination tool is modeled by considering all the operations, forces required for the respective operations and designs parameters [22,23]. Compression springs are provided at the grooving and flatting operations only, since the force required for the serration is quite high compared to grooving and flatting. Figure 16 shows the assembly model of new combination tool.

From the technical drawing and CAD tools final component geometry that needs to be manufactured is studied and the tool components are developed for the respective processes in order to improve and optimize geometry of the combination tool. Drafting generated from this mentioned design criterion, for the fabrication of combination tool as shown in Fig. 17.

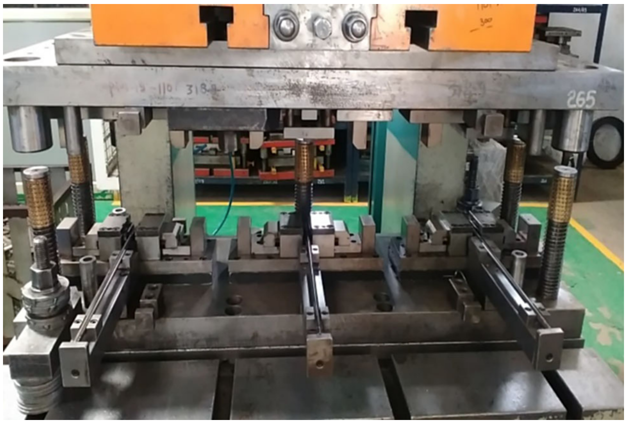

Fig. 17 Fabricated combination tool

Fig. 18 SEYI SN1 110 C-frame mechanical press

4 Experimental details and observation

Considering the required force mentioned in Sect. 3.7, 10-ton capacity press was sufficient to carry out the experimentation. The available press of required capacity has a bed size of (432 × 228) mm^2, which was not suitable to carry out the experimentation for the designed bottom plate and top plate (bed) size (1110 × 324) mm^2 of the combination tool. Hence, the higher bed size press required to be selected for the experimentation. Another press of higher capacity (110-ton) was available with the bed size (1150 × 680) mm^2, which matches the designed bed size for the experimentation. Experiments were carried out using the new combination tool mounted on 'SEYI SN1 110' C-frame mechanical press having 110-ton capacity as shown in Fig. 18.

Fig. 19 Experimental setup of combination tool

For fixed speed, the press is having 55 strokes per minute. Press is equipped with active photoelectric protective devices such as safety thru-beam sensors and safety light grid sensor that a stop applied on detection of unauthorized access or someone reaches into a danger zone. Die height of 350 mm provided with digital die height indicator of 0.1 mm increment.

Experimentation performed in one of the leading sheet metal manufacturing industry, Fig. 19 shows the actual working of the newly designed tool.

Time study for the manufacturing of connecting rod using the old conventional tool is mentioned in Table 3. It shows total cycle time for all the five operations including rework of defective parts is up to 43.65 seconds.

Previously for each operation separate stroke was required, out of which three combines in a single stroke using combination tool. Cycle time reduced significantly up to 20.79 seconds as appended in Table 4.

5 Results and discussion

Results obtained from the experimentation for manufacturing connecting rod using new combination tool are compared with the old tool as mentioned in Table 5.

From the comparison, it can be seen that total cycle time reduces up to 22.86 seconds. More than 50% reduction in cycle time compared to the old tool additionally reduces the number of workers as predicted from Table 6.

This huge reduction in cycle time was due to less material handling, minimum operation time and reduction in component rejection as shown in Fig. 20. New tool minimizes various defects observed in the component, which reduces rework and operators' fatigue.

When compared with percentage rejection of components, it founds that around 2% rejection with combination tool

Table 3 Time study for the manufacturing of connecting rod (Old Tool)

Sr. no.	Process/operation	Loading time/ batch (Hr)	Cycle time (S)	No. of operator	No. of helper
01	Grooving	0.5	8.73	1	1
02	Flatting	0.5	8.73	1	1
03	Serration	0.5	8.73	1	1
04	Crimping	0.5	8.73	1	1
05	Enlarging	0.5	8.73	1	1
	Total	2.5	43.65	5	5

Table 4 Time study for the manufacturing of connecting rod (New Tool)

Sr. no.	Process/operation	Loading time/ batch (Hr)	Cycle time (S)	No. of operator	No. of helper
01	Grooving + Flatting + Serration	0.5	3.33	1	NA
02	Crimping	0.5	8.73	1	1
03	Enlarging	0.5	8.73	1	1
	Total	1.5	20.79	3	2

Table 5 Comparison of time study

Sr. no.	Process/ Operation	Loading Time(Hr)		Cycle time (S)		No. of operator		No. of helper	
		Old	New	Old	New	Old	New	Old	New
01	Grooving	0.5	0.5	8.73	3.33	1	1	1	NA
02	Flattening	0.5		8.73		1		1	
03	Serration	0.5		8.73		1		1	
04	Crimping	0.5	0.5	8.73	8.73	1	1	1	1
05	Enlarging	0.5	0.5	8.73	8.73	1	1	1	1
	Total	2.5	1.5	43.65	20.79	5	3	5	2

Table 6 Reduction in cycle time

Sr. no.	Process/ Operation	Total reduction in			
		Loading time/ batch (Hr)	Cycle time (S)	No. of operator	No. of helper
01	Grooving	1.0	22.86	2	3
02	Flatting				
03	Serration				
04	Crimping	0	0	0	0
05	Enlarging	0	0	0	0
	Total	1.0	22.86	2	3

whereas 10% rejection with old tool. This shows around 8% saving in rejection of components and reduced cycle time, improves productivity with process optimization. Figure 21 shows the rise in the rate of production by using new combination tool.

Though the combination tool is validated for the improvement in productivity by optimizing the process having restriction of the material being used, thickness of component, geometric tolerances and final shape of the component. Type and numbers of operations performed on the blank must be known before starting the tool design.

6 Conclusion

The study focused on optimization of the process by performing three operations in a single stroke of the press. A new combination tool was designed to perform three different operations simultaneously for replacement of existing tools. Mostly compression as crushing was the major mode of failure for designing the machine tool, which was considered while designing the new combination tool. The material used for the tool is (OHNS) hardened at 62 HRC have a compressive yield of 1800 N/mm^2, which is higher than the yield

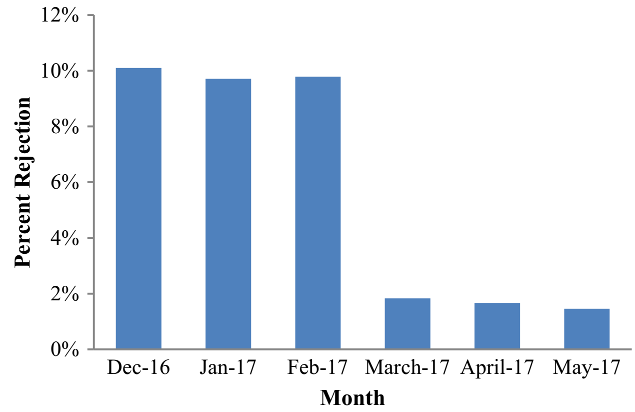

Fig. 20 Monthly percent rejection

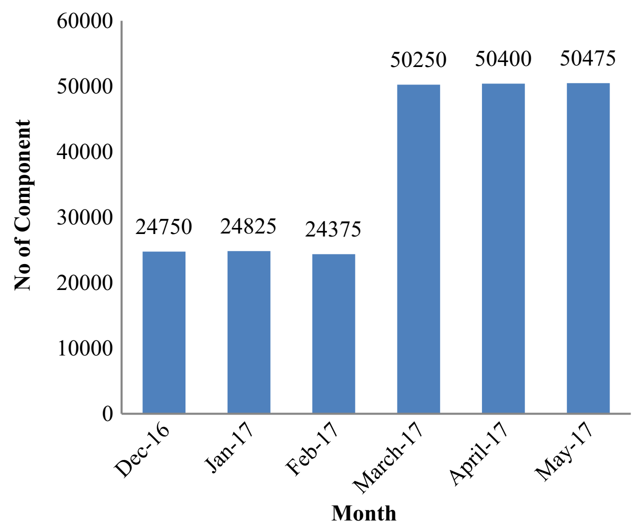

Fig. 21 Monthly improvement in production

strength of component material (SAE-1010). Forces required for all the stages have been calculated. It was observed that the total minimum 9.77-ton force required for forming. Due to large bed size, the tool cannot fit on a press having capacity of 10-ton, hence trials were carried out on 110-ton capacity available press with required bed size that permits the tool assembly.

Design experimentally validated in one of the leading sheet metal manufacturing industry. As seen from the observations, monthly percentage rejection rate with new tool reduces and ultimately increases the productivity. Total cycle time reduced by more than 50%, as three operations performed simultaneously with minimal material handling, compared to the previous conventional tool. Furthermore, workers required to carry out the operation also reduces.

The same methodology can be implemented to develop the generalized approach for other industrial process to design a combination tool for the component having more than one operations, where separate tool was required to perform these operations. Analytical design procedure will be changed according to type of operation required. The proper care shall be taken regarding forming force required for each operation considering type of material and component thickness, while designing the tool.

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