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Quality Tools to Reduce Crankshaft Forging Defects: An Industrial Case Study

Pankaj Chandna[1*] Arunesh Chandra [2]

[1]Department of Mechanical Engineering, NIT, Kurukshetra Haryana INDIA
pchandna08@gmail.com

[2]Department of Mechanical Engineering, RKG Institute of Technology, Ghaziabad UP INDIA
chandra_arunesh@yahoo.co.in

ABSTRACT

Crankshafts are the most important loaded components in the case of an automobile. In order to achieve required mechanical properties most of crankshafts for automobile are forged with micro alloyed steel. Usually, the shapes of crankshafts are complex, and many defects are induced during the process of crankshaft forging such as under-filling, laps and folds etc. In this work the forging analysis of six cylinder crankshaft produced by hot forging having engine bore of ninety-seven mm popularly known as 697 crankshaft manufactured by TATA Motors, Jamshedpur INDIA (previously known as TELCO) used in trucks and buses is being made. Forging analysis is being made to explain that how the defects appear and how to prevent them. This analysis can be easily done with the help of various quality tools used for quality improvement process. With the help of Pareto diagrams, which are mostly used to identify critical areas, the forging defects of the crankshaft have been prioritized by arranging them in decreasing order of importance. Then cause and effect diagram is being applied to explore possible causes of defects through brain storming session and to determine the causes which has the greatest effect. Corrective measures are being suggested to overcome the forging defects of the 697 integral counter weight crankshafts. Finally, few remedial measures and suggestions have been provided for the existing crankshaft production line in the forging shop. It is also concluded that the proper implementation of the proposed corrective plan may reduce the present rejection rate from 2.43% to 0.21% and rework from 6.63% to 2.15%.

Keywords: Cause and effect diagram, Crankshafts, Forging defects, Pareto diagrams.

1. INTRODUCTION

As described by Thomas et al. (1985) forging is the plastic working of metal by means of localized compressive forces exerted by manual or power hammers, presses or special forging machines for converting raw materials into desired product. According to A S M Handbook (1988) it includes many processes to be performed like heating of billet to required temperature, hammering or pressing the heated billet in multi impression dies, trimming the forged component to remove flash and coining to have final dimension. Due to the recent development of new and more advanced tools, improved materials and higher capacity machines used for the forging processes objectives

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[*] Corresponding Author

are to produce 'right first time' forged products. This requires lower scrap percentages, shorter lead times and less waste of money for the production of useless forged products. The quality of a forging product depends on several parameters such as initial shape (preform) of the billet, initial temperature of dies and material, forming velocity, friction coefficient and number and shape of intermediate dies. According to Kobayashi et al. (1989), the initial shape of the billet even for complicated parts is usually simple, therefore the material may not flow to its final shape in one stage and a designer must consider a deformation in several stages. The functions of closed die forging are the filling of die cavity of complex shape with metals at reasonable cost. The task of the forging designer is to ensure suitable die and part design, to maintain the required optimum forging conditions and by doing so he is primarily dealing with a problem of metal flow that is deformation of metal with in the die from stock to finished shape. Well-designed contour and smooth metal flow ensures complete filling of cavity, good materials properties, low die wear, enhanced die life and improved quality forged product without forging defect. Basically a forging defect is a departure of quality characteristics from its intended level or state that occurs with a severity sufficient to cause an associated forged product not to satisfy intended normal or reasonably foreseeable usage requirements. Some classifications of defects in forging operations can be found in the literature provided by A S M Handbook (1986) and Penton (2000), but generally the representation of possible defects is too poor. Furthermore, the defects are often based on very rough rules. Therefore, a more comprehensive work is required to classify defects related to forging. Common five reasons for forging defects are defects resulting from poor ingot, defects resulting from incorrect heating, defects resulting from incorrect forging conditions, defects resulting from wrong forging methods and defects resulting from uneven cooling of the stock after forging. Arentoft and Wanhein (1997) stated that the possible forging defects can be divided into six groups such as folds, shear defects, cracks, surface defects, form defects and structural defects arising due to one or combination of more than one of these above mentioned reasons.

Crankshafts are the most important loaded components in the case of automobile. Fiyikawa (2000) stated that in order to achieve required mechanical properties most of crankshafts for automobile are forged with micro alloyed steel. Usually, the shapes of crankshafts are complex, and many defects are induced during the process of crankshaft forging such as under-filling, laps and folds etc. In this work the forging analysis of six cylinder crankshaft produced by hot forging having engine bore of ninety-seven mm popularly known as 697 crankshafts used in trucks and buses is being made. Forging analysis is being made to explain that how the defects appear and how to prevent them. This analysis can be easily done with the help of various quality tools used for quality improvement process. With the help of Pareto diagrams, which are mostly used to identify critical areas, arranging them in decreasing order of importance has prioritized the forging defects of the crankshaft. Then cause and effect diagram is being applied to explore possible causes of defects through brain storming session and to determine the causes, which has the greatest effect. Corrective measures are being suggested to overcome the forging defects of the 697 integral counter weight crankshafts. Finally, few remedial measures and suggestions have been provided for the existing crankshaft production line in the forging shop. It is concluded that the proper implementation of the proposed corrective plan may reduce the present rejection rate from 2.43% to 0.21% and rework from 6.63% to 2.15%.

2. BACKGROUND

Hot forging, which is extensively used in metal forming, can be subdivided into three main processes, namely heating, forging and cooling. Considerable work has been reported in connection with the different design aspects of the forging process such as material waste, die design, energy conservation, lubricant design and heat treatment of forged component by Lertsirarungsun and

Ruangsilasingha (1987), Takemasu et al. (1996), Bakhshi-Jooybari et. al. (2002), Xinhai et. al. (2002), Zhichao et al. (2002) and Paul (2002). Identifying, quantifying and controlling uncertainties in the forging and cooling processes have drawn less attention. This work deals with identifying the process uncertainties that effect forging and demonstrates a trade-off method that will aid in the decision process to control process parameters for reducing part rejection and rework. Incorporation of these uncertainties into the forging and cooling process design helps in further development of better manufacturing techniques to obtain more reliable parts. To accomplish the objectives, sensitivity analysis of critical parameters has to be done. This can be achieved by first, identifying the parameters that can vary during manufacturing. A few of the listed parameters are: initial temperature of the billet before forging, variations in forging press controls (stroke length and thermal effects), friction in the dies, cooling rate, material properties (thermal expansion and flow stress), recrystallization of the material, billet positioning in the dies, scales on the billet, time required to heat the billet, die velocity, ambient temperature and so on.

During temperature measurements, the actual temperature value depends on the accuracy of the measuring equipment. This equipment has to be calibrated before use, and to a large extent that depends on the operator’s skill. Typically, the non-contact measuring instruments depend on the emissivity of the hot metal, material properties and various environmental factors. In general, mechanical, pneumatic or hydraulic presses are used in forging. These presses have moving parts which are heavy and subjected to high temperatures. The high temperatures heat the press components, inducing expansion. In addition, vibrations generated by the ram and other driving components can affect press settings, such as stroke length and die alignment. An oxide layer forms on the surface when steel is heated, above 350 ^{0}C; this oxide layer is referred as scaling and is very brittle. It has a tendency to flake away from the forged part leading to material loss. In addition, any scale particles that are inadvertently left in the die cavities lead to under-filling the die for the next part. The friction between the billet and dies has a direct relation with the forging loads required to produce the part. The quality and quantity of the lubricant used affect the amount of friction between the billet and dies. Friction affects the material flow into the dies, thereby affecting the forged part’s final dimensions. Higher friction means increased die wear, which, in turn leads to defective parts. Improper lubrication also increases die wear by generating hot spots and stress concentrations in the dies. Lubricant is sprayed on the dies either automatically or manually. Manual spraying can lead to variations in the quantity of lubrication sprayed, since the quantity and place of application has no fixed reference. In addition, scales, dust and other particles are often present in the forging plant environment. It is possible that some of these particles make their way into the lubrication tank. As a result, these particles are inadvertently pumped through the system and can temporarily block the nozzle, thus varying the quantity of lubrication on the dies. When the billets are placed in the dies manually, repeatability is an issue. Repeatability has a certain degree of error, this would add to the risks that could be coupled with the uncertainties in the manufacturing process. Statistical data could be used to develop models that would be used in the manufacturing design process to reduce the variations due to human errors. In case the billets are placed and moved by robots, accuracy of the robot is considered. Since the robots control system consists of sensors and controllers, the time taken to activate a controller to correct a slack in the system would depend on how fast the control system responds. There are millions of numerical computations that are done per second by computers in the control system. This gives a possibility of numerical errors that could accumulate with the variations in the process and thus increase the time required to correct the error by the control system. Weather conditions determine the ambient temperature and humidity on the work floor. The ambient temperature and humidity have a direct correlation on the cooling rate of the part. This can affect the hardness, stresses and geometry of the part. All the aforementioned forging and cooling factors play an important part in determining the defects of the forged part.

3. CASE STUDY

The present work deals with crankshaft fitted to six cylinder engine produced by hot forging having engine bore of ninety-seven mm (697 crankshafts) manufactured by TATA Motors, Jamshedpur INDIA (previously known as TELCO). The TATA motors possess wide ranging facilities in different division like automobile, foundry, forging, excavator etc. The forging division meets almost the total forging requirements of the plant and manufactures all critical forgings like crankshaft, front axle beam, connecting rod, stub axle, camshaft etc.

3.1 Production Line of 697 Crankshaft

Gravity drop hammers (DGH) having capacity of 40 tons and 25 tons (DGH 40/25) production line is used for manufacturing the crankshaft for 697 engines fitted on 1312 and 1516 TATA vehicles. The line consists of a pusher furnace for heating, DGH 25 counter blow hammer for blocker and bender die, rotary hearth furnace for reheating, DGH 40 counter blow hammer for finisher die, 1000 tons trimming press for trimming operation, 600 tons coining press for coining operation, five manipulators and seven conveyer lines for crankshaft handling from one to another hammer/ press. Figure 1 shows the arrangement of hammers, presses, furnaces and other required equipments required for the production of 697 crankshafts. Production line shown in the Figure 2 requires certain processes to be performed on raw material to get converted into final product. The processes to be followed are given in the process sheet mentioned in the Table 1, it shows the process sequence that is the series of steps required to be followed and equipment/machine on which the required process is to be done for the production of 697 integral counter weight crankshaft.

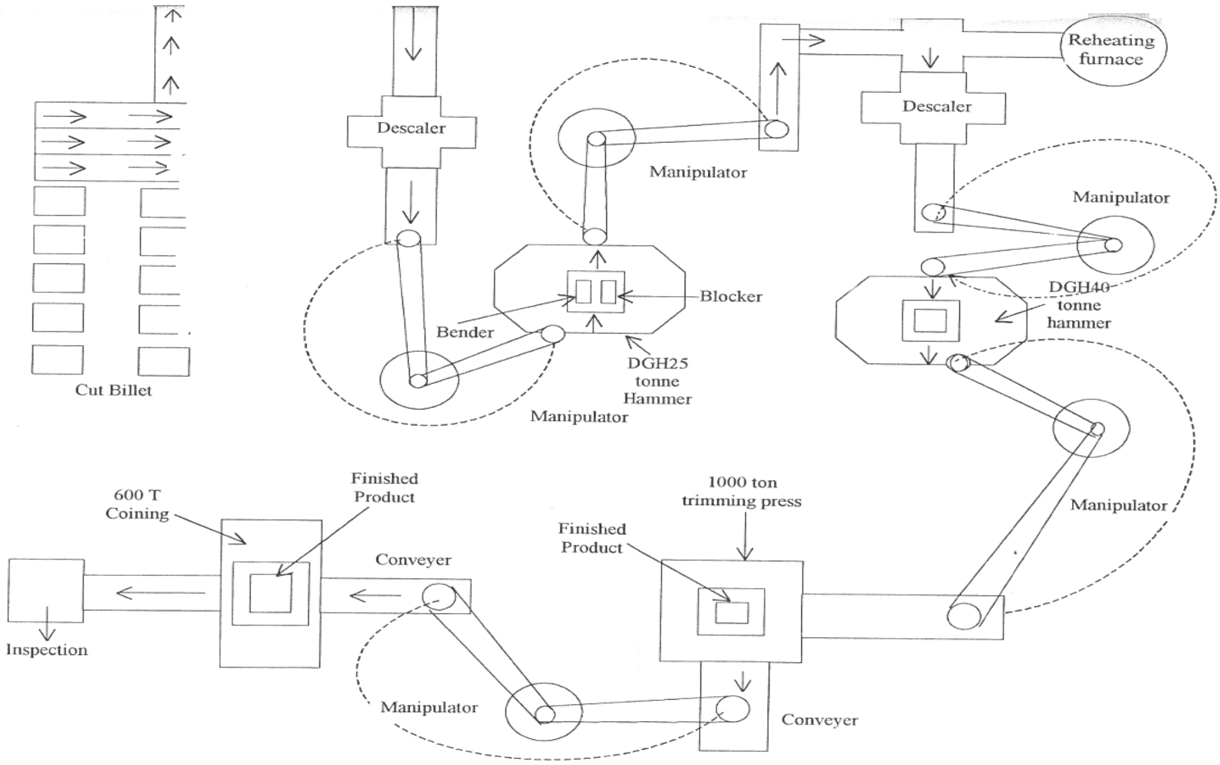

Figure 1. Production line of 697 integral counterweight crankshaft

Table 1. Process sequence of 697 integral counter weight crankshaft

Process Sequence	Specification	Equipment
Billet Cutting	$42Cr_4Mo_2$ 125 RCS X 785-$_2^{+3}$	Sawing
Heating	Furnace Temp.1st Zone- 1100 ^{0}c 2nd Zone-1250$^+_-$50 ^{0}c	Pusher Furnace
Bender& Blocker	As Per DRG. NO. 50:DH-1	DGH25
Reheating	Furnace Temp 1st Zone- 1100 ^{0}c 2nd Zone – 1250$^+$_ 50 ^{0}c	Rotary Furnace
Finisher	As Per DRG. NO. 50:DH-2	DGH 40
Hot Trimming	As Per DRG.NO.50: HT-1	100T Banning Press
Hot Coining	As Per DRG.NO.50: HT-2	600T Nigra Press

Table 2. Defects data of 697 integral counter weight crankshaft

Month	Submitted	Accepted	Burnt	Dent	Foreign Body	Overlap	Pitting	Shop Scrap	Under Filling	Under Size	Reject -ions	% Rejecti ons
November,02	2320	2290	0	2	7	10	2	0	9	0	30	1.29
October,02	1874	1833	3	0	11	13	1	0	13	0	41	2.19
September,02	2122	2076	2	2	5	7	9	6	15	0	46	2.17
August,02	1242	1213	1	0	4	2	1	5	16	0	29	2.33
July,02	1481	1446	1	2	3	2	10	8	9	0	35	2.36
June,02	1142	1118	1	1	6	6	0	0	10	0	24	2.10
May,02	1605	1565	0	1	4	9	6	6	11	3	40	2.49
April,02	1044	1020	0	0	0	3	5	0	16	0	24	2.30
March,02	1029	1005	1	0	0	17	1	0	5	0	24	2.33
February,02	546	513	0	0	0	33	0	0	0	0	0	6.04
January,02	699	682	0	0	1	5	0	7	4	0	17	2.43
December,02	353	353	0	0	0	0	0	0	0	0	0	0
November,01	351	311	6	0	1	10	8	0	8	7	40	11.39
October,01	79	79	0	0	0	0	0	0	0	0	0	0
September,01	148	146	0	0	0	1	0	0	1	0	2	1.35
August,01	112	105	0	0	0	0	4	0	3	0	7	6.25
Total	16147	14755	15	8	42	118	47	32	120	10	392	2.43
% contribution			3.82	2.04	10.71	30.10	11.99	8.16	30.6	2.55		

During the production of 697 integral counterweight crankshaft it is observed that all the produced forged crankshafts do not conform to the desired quality requirements. Due to the forging defects some of them are rejected completely and few of them are considered for rework. After rework they attain the desired specification and quality requirement and finally accepted. The present work deals with the objective of reducing of complete rejection and rework due to the forging defects. The rejection data due to defects occurred during the forging process has been taken from Quality Audit’s monthly rejection reports for fifteen months starting from August 2001 to November 2002 and is given in Table 2. It gives the details regarding the quantity of forged component produced, accepted, rejected and also the reason of rejection because of different forging defects like burnt, dent, overlap, underfilling, pitting, shop scrap, undersize. Total number of rejections and the percentage rejections of the crankshafts for every month has been calculated. The contribution of individual defect in terms of percentage has also been calculated. The overall rejection of Crankshaft for fifteen months due to forging defects is 2.43%.

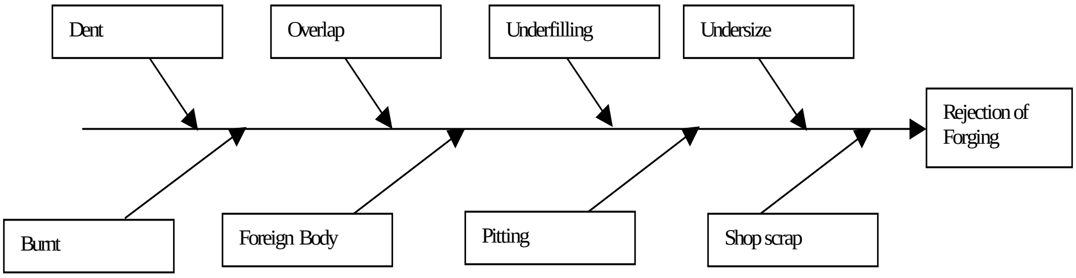

Figure 2. Trivial many defects responsible for rejection of Crankshafts

Bagchi (1997) suggested that statistical tools like cause and effect diagram and Pareto diagram are hereby used for problem solving and quality improvement. The analysis of data, information and use of statistical tools are mainly focused over here for continuous improvement practice by cause and effect analysis through process improvement and identifying most promising factors for rejection. Further in Table 3 forging defects are prioritized on the basis of their contribution towards rejection of the crankshafts as calculated in Table 2.

Table 3. Ranking of defects

Defects	Priority	Defects	Priority
Under filling	1	Shop scrap	5
Overlap	2	Burnt	6
pitting	3	Under size	7
Foreign body	4	Dent	8

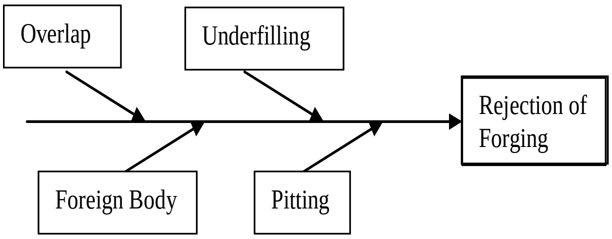

Figure 3. Vital few defects responsible for rejection of crankshafts

Grant and Leavenworth (2000) stated that Pareto diagram helps to separate out the vital few from the trivial many to decide which of the defect to work out first. Analysis of information and data under this system is therefore a key to the system effectiveness. Based upon Pareto (80-20) rule and his theory which states that 'the vital few and trivial many'. Trivial many are represented in Figure 2 and vital few are represented in Figure 3.

Cause and effect diagram is used for analysis here because its strength lies in analyzing relationship in a structured way in by using causing and their component which helps in focusing to root rather than symptoms. Thus four out of eight defects, which are the most promising factors for rejection of crankshafts, are under filling, overlap, pitting, and foreign body. Cumulative percentage of rejection due to these defects raises upto 83.41% which make to study the causes of these four defects more important.

Table 4. Rework data of 697 integral counter weight crankshaft

Month	Production	Underfilling	Overlap	Dent	Pitting	Offset	Miscellaneous	Total	% Rework
August,02	2072	79	3	5	2	20	7	116	5.6
September,02	1873	75	10	7	3	12	30	137	7.7
October,02	1496	55	13	15	6	10	21	112	7.49
November,02	2144	85	5	10	4	26	8	138	6.94
Total	7585	294	31	37	15	68	66	503	6.63
% contribution		58.45	6.16	7.36	2.98	13.52	13.12		

Table 5. Ranking of defects

Defects	Priority
Under Filling	1
Offset	2
Miscellaneous	3
Dent	4
Overlap	5
Pitting	6

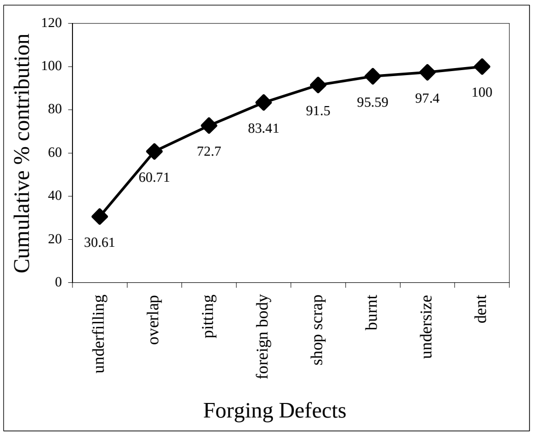

Figure 4. Defect analysis of rejections through Pareto diagram

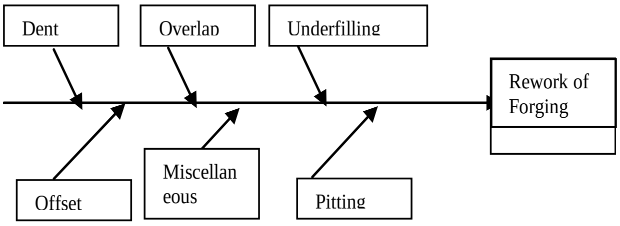

Figure 5. Trivial many defects responsible for rework of crankshaft

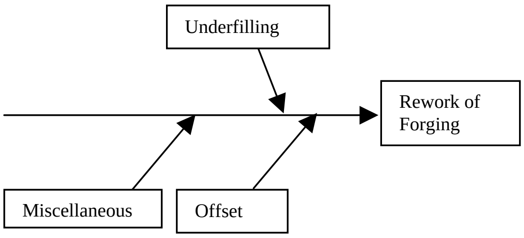

Figure 6. Vital few defects responsible for rework of crankshaft

As discussed earlier, that every crankshaft produced by forge department at TATA motors is not accepted; some of them get finally rejected due to forging defects. Few of the rejected crankshafts during first stage can be made accepted by undergoing certain amount of rework, so the study of rework is also required to produce product right at first time and to minimize rework. Rework data of crankshaft is taken for the four months from August 2002 to November 2002 as shown in Table 4. It represents monthly production data, rework data, data of forging defects which can be rejected if not reworked and percentage of rework data. Overall Rework of Crankshaft for four months due to forging defects is 6.63%. Cause and effect diagram for analyzing the trivial many and vital few reasons of the rework are represented in Figure 5 and Figure 6. Further according to above mentioned rework data defects are prioritized according to Pareto (80-20) rule as shown in Figure 7 based upon Table 5.

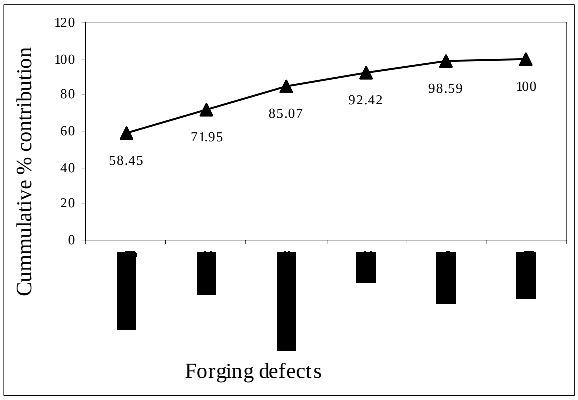

Figure 7. Defect analysis of rework through Pareto diagram

Figure 7 shows that 85.07% rework required is due to forging defects like underfilling, offset and miscellaneous. The analysis of rejection and rework data of forging defects shows that *six* out of *ten* defects are major contributor of either rejection or rework. Thus the authors decided to overcome these mentioned defects and to know the cause of these defects hence it is required to know the location of these mentioned defects.

Thus after thorough investigation of one thousand of crankshaft location of above mentioned six defects are identified and shown in Table 6. It shows critical defects along with their occurrence zone on the production line of the crankshaft. Once the critical defects and critical location of above-mentioned six defects are identified next course of action is to overcome these mentioned defects. The authors suggested some corrective measures required along with the area at which action is required. Table 7 shows the detailed action to be taken when different causes are responsible for rejection and rework of 697 crankshafts. It has also been observed from the Table 2 that only two forging defects namely overlap and underfilling are responsible for 60.71% of total rejections of the crankshafts.

Table 6. Location of important forging defects

Forging Defect	Occurrence Zone
Underfilling	On bottom die at flange and at counter weight 1, counter weight 2, counter weight 11 and counter weight 12 On top die at mount number 3, 4, 9 and 10 and at crankpin 2 and crank pin 5
Pitting	On top die at shank On bottom die at shank, main bearing 1, and at circular web 3, 4, 9 and 10
Overlap	On top die at crank pin 3, crank pin 1, and extended web 8 On bottom die near parting line at web number 11 and web number 12 On parting line at web number 1
Offset	Longitudinal offset at flange
Dent	On bottom die at circular web 3, circular web 4, circular web 9, circular web 10 and at mount number 12
Miscellaneous	Oversize and fin mark at mount number 7 and mount number 8

Table 7. Actions required overcome vital forging defects

Forging defects	Area of action	Corrective action required
Overlap	Crankpin / web	Remove deformation of blocker die by dressing with template.
Underfilling	Temperature	Modify burner position and calibrate furnace for temperature.
	Die deformation	Grinding of blocker die as per template.
	Delay	Preventive maintenance of conveyors and manipulators for smooth movement of billet from furnace to die.
	Die design	Modify blocker die design by mapping unfilled zone.
	Lubricant	Select the best lubricant for die.
Pitting	Scales	Remove scales in blocker forging or finisher forging through preventive maintenance of descaler.
Foreign body	Unwanted material	Remove foreign body from sawdust through checking of sawdust while mixing with water.
	Chips	Air should be blown properly before placing hot billet both in blocker and finisher die.
Shop scrap	Temperature	First zone temperature to keep higher side for better soaking.
	Delay	Preventive maintenance of conveyors and manipulators for smooth movement of billet from furnace to die.
	Billet	Place billet properly at bender and check billet to touch stopper on flange side.

On the basis of study made authors have also suggested few measures which can reduce the rejection and rework of 697 integral counterweight crankshaft caused by the above two defects. The first defect overlap can be minimized with the help of two actions:

(a) Top blocker division at Crankpin 1 should be dressed to give one mm more volume towards shank side.

(b) Crankpin 3 and Crankpin 4 of bottom blocker die dressed to provide more volume of 2 mm.

Similarly second defect underfilling can be minimized by these two actions:

(a) More volume of 3 to 4 mm should be given in bottom blocker die at mount 1, mount 2, mount 11 and mount 12.

(b) Flash checks should be provided in bottom finisher die at Crankpin 1 & Crankpin 6.

As shown in the Table 2 that controlling of vital few forging defects i.e. underfilling, overlap, pitting, foreign body and shop scrap will reduce the present rejection rate from 2.43% to 0.21% as 2.22% rejection take place because of these forging defects only. Similarly Table 4 indicates that controlling of vital few forging defects i.e. underfilling, overlap and pitting will reduce the present rework rate from 6.63% to 2.15% as 4.48% rework takes place because of these forging defects only.

4. CONCLUSION

In this work the forging analysis of six cylinder crankshaft produced by hot forging with the help of quality tools is being made. The analysis shows that more than 80% of rejection and rework are due to forging defects like overlap, underfilling, pitting, foreign body and shop scrap. Corrective measures are being suggested to overcome the forging defects of the 697 integral counter weight crankshafts. Finally, few remedial measures and suggestions have been provided for the existing crankshaft production line in the forging shop and controlling vital few forging defects will reduce the present rejection rate from 2.43% to 0.21% and rework from 6.63% to 2.15%.

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