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The Role of Weld-Deposited Working Layer on the Performance of Hot Forging Dies

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Abstract

The performance of hot-forging dies, in which the die cavity is weld-deposited with a layer of modified H12 hot-work tool steel, has been studied, using a continuous monitoring of the die condition as well as macroscopic and microscopic examination. It was observed that the thickness of the hard upper 'capping layer' and that of an intermediate 'buffer layer' have a pronounced effect on the life and performance of forging die. For a given size and shape of the die cavity, there was an optimal thickness of capping layer that would give the best performance; thicker capping layers are likely to exhibit brittle cracking, while thinner layer have a tendency for early deformation and wear. For buffer layer, a certain minimum thickness is needed to provide sufficient backup support.

Key Words: Hot Forging, Die Life, Flood-welding, Buffer Layer, Capping Layer

1. Introduction

The performance and the cost of forging dies are major factors which determine the quality of forged components as well as the economics of forging process. Conventionally, hardened and tempered forging dies made from H-13 hot working tool steel are no longer very popular because of their poor die-life. Additionally, the hardened/tempered and nitrided forging dies exhibit a comparatively better die life, however, these dies are generally quite susceptible to thermal fatigue cracking. Die-Life [1] proclaim that the enhanced tendency of cracking in nitrided dies is due to a comparatively soft back up material; the nitrided case is extremely hard (upto 65 HRC) while the underlying material is typically around 45 HRC. The strength and hardness of backup material cannot be increased any further as a tough core is also extremely necessary. In the circumstances, multilayer flood-welded forging dies, in which the forging cavity is weld-deposited with layers of superior die-steels, offer a good option, and are thus fastly becoming popular.

It has been reported by Hammock [2] that flood welding can increase the life of the forging die by a minimum of 50 %. Flood welding eliminates the re-sink requirement of all the features of the die, extending the life of the die and greatly reducing machining and downtime costs. Huskonen [3] is also of the view that profitability of the forging industry can be improved by using flood welding reclamation of the dies as welding can extend the die-life significantly and provides the opportunity to reuse the die repeatedly.

Liu et al. [4] in their studies using finite element analysis have shown that thermal stresses were the main cause of die failure in hot forging dies, and that die life can be improved through the deposition of various suitable heat resistant materials on the working surface of the die alongwith an intermediate layer between the parent die and the working surface layer of the die.

Jeong [5] has determined the heat transfer coefficients using various combinations of surface treatments and lubricants in warm forging. Similarly, Lee et al [6] developed techniques for the estimation of hot forging die life by studying the effects of various lubricants and surface treatments.

A typical pattern in which the die-cavity is weld-deposited with a working layer of superior-material is illustrated in Figure 1. The top layer of the working surface is called 'capping layer' and is composed of an alloy having higher strength, hardness, and wear resistance for example H12 or H21. Beneath the capping layer is a 'buffer layer' which is a lower carbon higher toughness alloy expected to buffer the high compressive impact loads of the forging operation. The thicknesses of the capping and buffer layers may have a pronounced effect on the die life, but no systematic studies have been reported in the litrature to correlate die-life with the thickness of these layers [1,7].

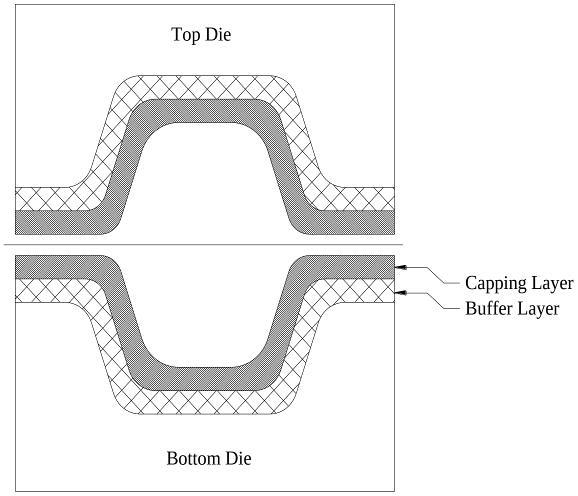

Fig.1 A schematic cross-section of multi-layered flood-welded forging die showing capping and buffer layers.

During the present work, a series of experiments were performed on hot-forging dies of various components and the effect of buffer and capping layer's thickness on the service life of die was studied. In the present paper, the results of experiments conducted on hot-forging dies for 'connecting rod' are presented and discussed.

2. Experimental Setup

2.1 Materials of Die-block and the Buffer and Capping Layers

The material of dies in all the experiments conducted during the present work was H13 steel. A 10 % Cr alloy with low-carbon content was used as buffer layer, while modified-H12 was used as the capping layer. The compositions of die and the buffer and capping layers are given in Table 1.

Table 1 Chemical composition of Die steel and of Buffer and Capping Layers

	Chemical Composition						
	C	Mn	Ni	Cr	Mo	V	W
Die	0.35	-	-	5.00	1.50	1.00	-
Buffer	0.18	0.97	3.86	11.38	2.42	-	-
Capping	0.29	1.02	-	6.00	1.83	0.63	1.53

2.2 Heat Treatment of Dies

The H-13 dies used during the present study were prepared using a sequence involving rough-machining, heat-treatment, and final-machining. The heat-treatment was employed according to the information provided by Cubberly et al [8] which consisted of: (a) Hardening by austenitising at 1010°C followed by air quenching, (b) First tempering at 565 °C for 1 hour per inch of ruling section, and (c) Second tempering at 580 °C for 1 hour per inch of ruling section. The final hardness of the dies was ~ 44-45 HRC.

For the first production run, the forging dies were put to use without any flood-welding.

After the first production run, when the dies were sent back to the die-section for re-work, the die-cavity was scarfed and then flood-welded for the first time. The weld-deposited die-cavity was then machined in the conventional manner. These flood-welded dies were then put to use and their performance and service life was monitored and recorded.

2.3 Flood-welding Procedure

For flood-welding the dies were first scarfed. It is relevant to mention that the scarfing depth is of immense importance as it has to be equal to the total thickness of capping plus buffer layers to be deposited. Photograph of a typical scarfed cavity is shown in Figure 2(a), while Figure 2(b) shows the configuration of the forged component.

Scarfing of dies was carried out with carbon electrodes using high amperage. Magnetic Particle Inspection (MPI) of the scarfed cavity was mandatorily carried out to ensure the absence of cracks. The dies were then ready for flood welding which was performed using the parameters as shown in Table 2. For flood-welding the dies were first pre-heated to a temperature of 450 °C.

Table 2. Parameters of Flood-welding.

Wire Dia (mm)	Voltage (Volts)	Current (Amperes)	Shielding Gas	Shielding Gas Flow Rate (L/min)	Wire Feed Rate (m/min)
2	30-32	475-500	Argon : 75 CO2 : 25	16 - 18	5

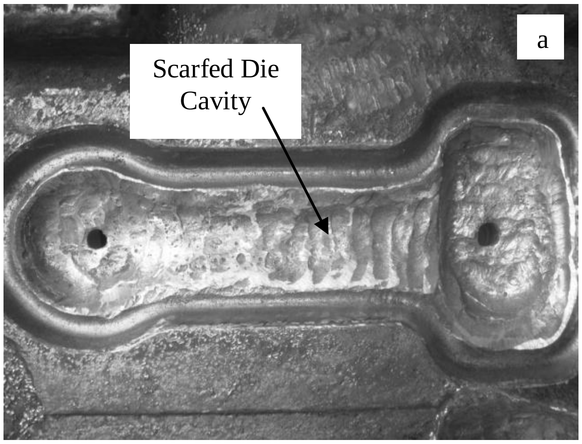

Fig.2 Photograph of Scarfed die of Connecting Rod (a), and forged Connecting Rod (b)

Upon removal from the pre-heating furnace the die was wrapped with ceramic fiber to minimize the heat losses. The welding table was provided with a preheating hearth that continuously heated the bottom of the table so as to maintain the temperature of the die around 450 °C, but in no case below 400 °C. During the entire flood-welding process, especially during the deposition of capping layer, the temperature of the die was essentially maintained around 450 °C and was continuously monitored by infrared thermometer. The significance of this temperature for H12 steel, during post-weld cooling, can be understood from the continuous cooling transformation diagram[9]. As per this diagram, the H12 steel during cooling can be held for long time as austenitic phase, without transformation. After each successive welding pass, the weld-layer was peened with a hammer while it was in dull- red state [10]. The significance of this peening operation [11] is that it reduces the shrinkage stresses and refines the microstructure. Following the peening operation, the scale was removed from the surface of weld deposition by using a pneumatic -needle type de-scaler and an air gun, after which the next welding pass was employed. After the completion of weld deposition the temperature was equalized at 450 °C by placing the die in a furnace. The die was then air cooled to ambient temperature.

The die was then tempered twice. First tempering operation (which was carried out at 565°C for 1 hour per inch of ruling section) aimed at transforming the martensite in the as-welded die to tempered martensite. The second tempering which was carried out at just above the first tempering temperature (around ~575 °C) intended to coarsen the already formed carbide particles thereby increasing the toughness of the die. The flood-welded dies were then machined on CNC machining centre to form the component impression in the die. The finished machined dies were then ready for use.

3. Results and Discussion

he forging company at which the present study was carried out produces ‘connecting rods’ for Massey Ferguson tractor in large volume and hence the connecting rod dies were selected for the present work. Extensive experimentation with different thickness combinations of buffer and capping layers were carried out. The same dies were used repeatedly after reworking /reclamation with flood-welding. During this entire study the material to be forged was heated to forging temperature by using an induction heater of 250 KW.

In addition to the increased die life, a significant advantage of reclamation with flood-welding is that the thickness of the die-block remains unchanged which eliminates the need for any packing plate/ shims to correctly position the die within the shut height of the forging press. Further, in conventional quenched and tempered dies, the repeated rework gradually reduces the thickness of the die to the extent that the die-block has to be eventually discarded when the thickness reduces below a certain limit.

3.1 The influence of varying thicknesses of Capping and Buffer Layers

The data obtained from different experiments conducted on connecting rod dies is given in Table 3. Initially, keeping in view the thickness of the connecting rod, an arbitrary combination of 25 mm thick capping layer and a 15 mm thick buffer layer was adopted. However, this combination resulted in brittle cracking of the die at very early stage, suggesting that either the hard capping layer may be too thick or the buffer layer may be too thin. Accordingly, in the next experiment the thickness of capping layer was decreased to 20 mm while that of the buffer layer was increased to 20 mm. As a result, the die life marginally improved and failed under brittle cracking. Hence in the next experiment the thickness of capping layer was further decreased to 15 mm while the thickness of buffer layer was also decreased to 10 mm. This combination resulted in a significantly longer die life. The die showed no brittle cracking, but instead, after producing around 20,000 forgings, showed wear as well as some fine thermal fatigue cracks. In order to validate the results, this thickness combination was repeated two more times with the results that around 20,000 forgings were produced.

It was important to note (Table 3) that as the thickness of capping layer was gradually reduced from 25 mm to 15 mm, the mode of failure had changed from brittle cracking to wear and thermal fatigue. In order to see whether the thickness of capping layer could be reduced any further, the thickness was decreased to 10 mm but the results were deteriorated; wear and deformation took place in these dies after producing only 6000 forgings.

Table 3 Experimental Data of Connecting Rod Dies

Expt. No.	Thickness of Buffer Layer (mm)	Thickness of Capping Layer (mm)	Surface Hardness (HRC)	Number of Forgings Produced	Remarks
1	15	25	54	1219	Brittle Cracking
2	20	20	53	7692	Brittle Cracking
3	10	15	54	18637	Wear and Thermal Fatigue Cracks
4	10	15	55	21483	Wear and Thermal Fatigue Cracks
5	10	15	54	19172	Wear and Thermal Fatigue Cracks
6	10	10	53	6051	Deformation, Wear, De-shape
7	10	20	55	10321	Brittle Cracking

In order to verify whether or not 15 mm was the optimum thickness for capping layer, another experiment was performed by increasing the capping layer to 20 mm while keeping the thickness of buffer layer at 10mm. Again, a severe brittle cracking took place which confirmed that the optimum layer thickness combination for this component is 10mm buffer layer with a 15 mm of capping layer.

3.2 Sectioning of 'used' Die for examination

In order to evaluate the hardness changes (if any) in the flood-welded layers resulting from the production cycle, one die of connecting rod was sectioned after it had given full production of about 20,000 forgings and was due for next rework. A photograph of this die before sectioning indicating the surface condition after producing 20,000 forgings is shown in Figure 3. Then a section of the die was metallographically prepared and etched with 10 % Nital. Photograph of this section of connecting rod die after macro etching showing buffer and capping layers is given in Figure 4. Then hardness profile through the flood-welded layers was measured on Rockwell Hardness Tester and these hardness indentations are also shown in Figure 4.

In order to assess the hardness profile on an un-used die (i.e., before the die is put to use) a test sample was produced in which buffer and capping layers were weld-deposited on a block of H13 steel. The thicknesses of these layers were kept the same as that in the die shown in Figure 4. This test sample was taken as a substitute for the un-used die, so as to avoid the sectioning of a new die without taking any production from it.

Figure 5 shows the two hardness profiles plotted on the same scale for comparison. HRC1is a hardness profile before forging production and HRC2 is a hardness profile after forging production. It may be noted that the hardness of the capping layer (and also that of the buffer layer) decreased as a result of use of the die for producing ~20,000 forgings. Micrographs taken from the two samples are given in Figure 6 (a) and (b). The comparison between the two microstructures and the hardness profiles clearly indicate that capping layer has been gradually 'tempered' as a result of continual contact with the hot metal during the production run.

Clearly, the temperature of a thin layer on the working surface of die-cavity has been rising to 'red-heat' level ~ 600 °C during each forging stroke. The magnitude of the heat transfer from forging into the surface-layer of die is also dependent upon the time for which the 'hot' forging effectively remains in contact with the die, i.e., the efficiency with which the forged component is ejected out is also a very important factor. It also follows that any event of difficulty in ejection can have a very intense tempering effect on the die.

As the die is gradually tempered during the production, the hardness of the working surface drops to a level where the wear and deformation start to occur putting a limit on the die life. This consideration emphasizes the need for an efficient ejection of the forging, and also an effective spraying of coolant on the die-surface between the forging strokes.

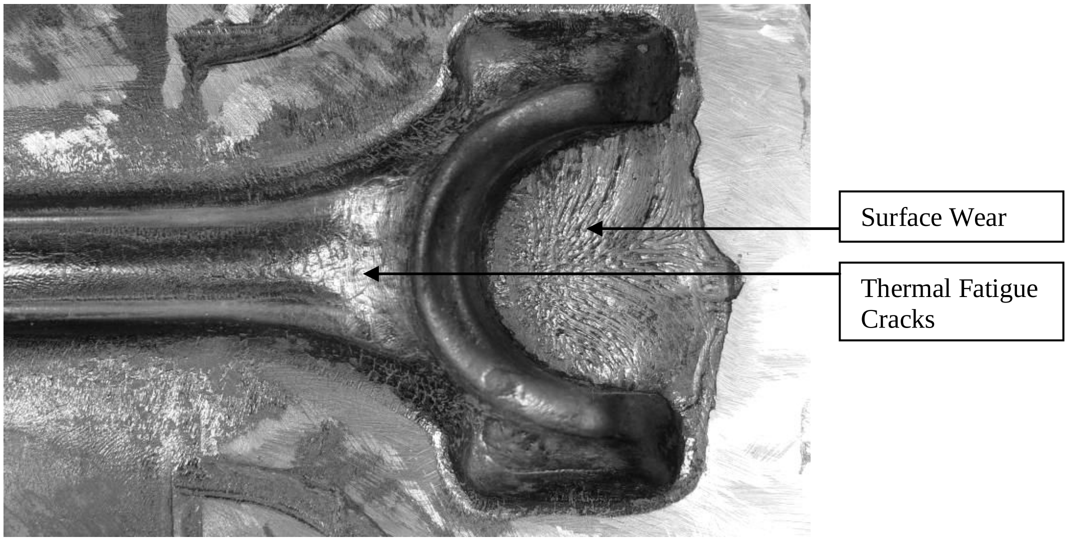

Fig.3 A photograph of flood-welded die impression after 20,000 pieces showing surface wear and thermal fatigue cracking

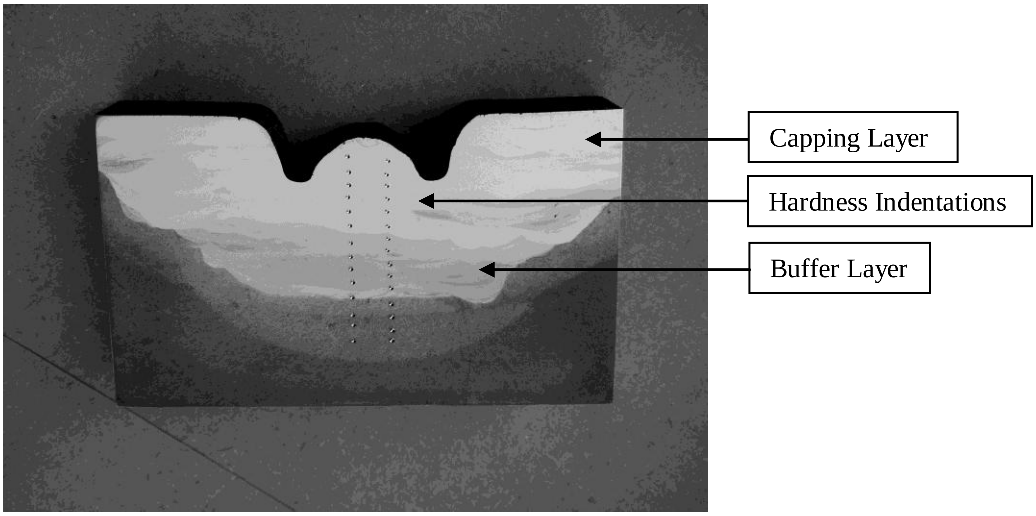

Fig.4 Cross section of connecting rod die, showing buffer and capping layers and Rockwell Hardness profile on a section taken from a die that has produced 20000 forgings.

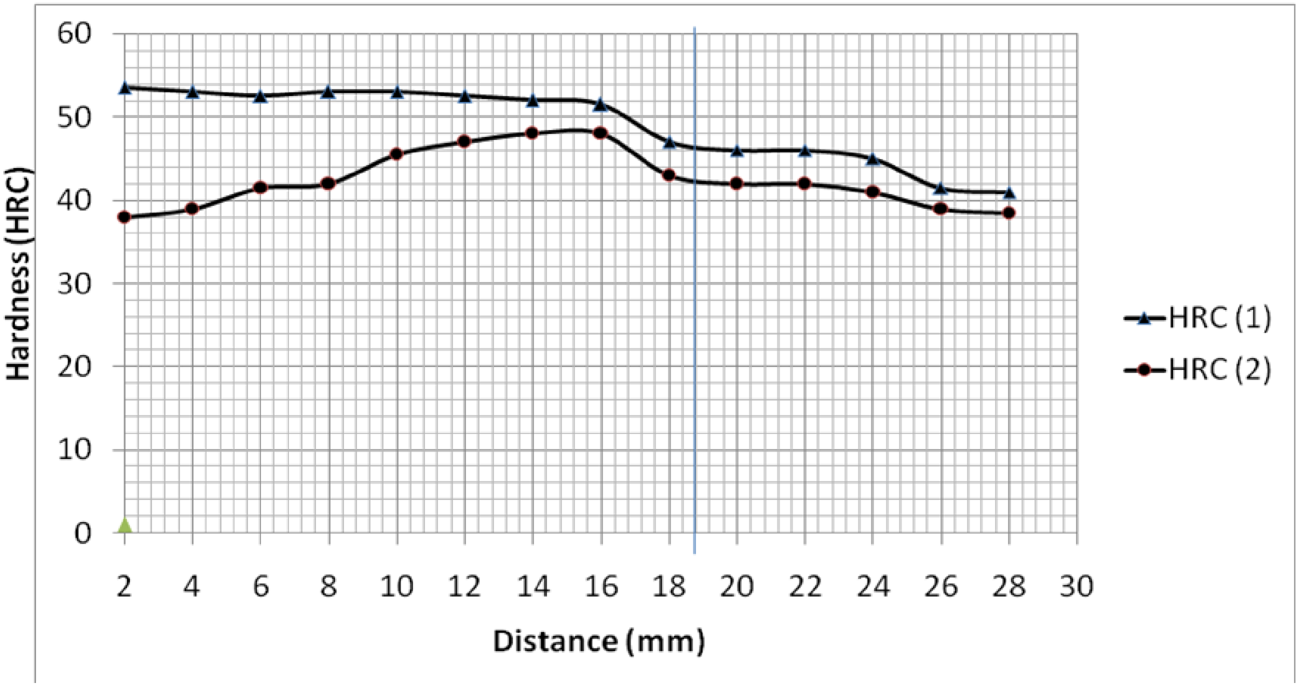

Fig.5 HRC1 - Hardness profile before forging production
HRC2 - Hardness profile after forging production

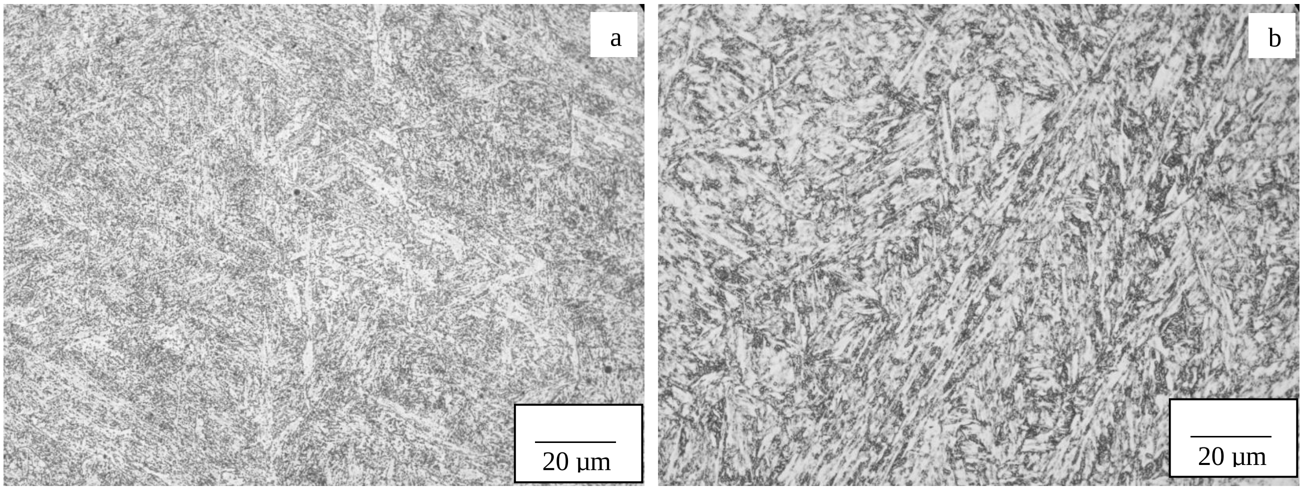

Fig.6 Microstructure of capping layer (a) before, and (b) after producing 20,000 forgings showing fine and coarse tempered martensite respectively.

4. Conclusions

The results of present study show that:

1- Other factors kept aside, there is a suitable combination of capping and buffer layer's thickness for the best life of the die of a given size and shape .

2- For a given die, when the thickness of capping layer is greater than a certain limit, it has tendency to brittle cracking.

3- On the other hand, if the thickness of the capping layer is lower than the optimum level, it will have a tendency to premature deformation and wear.

4- Buffer layer is a lower carbon higher toughness alloy which serves to buffer the effect of high compressive impact loads of the forging strokes. A minimum thickness of the buffer layer is thus required to have any effect on die life. Any greater than the optimum level thickness of the buffer layer will neither have any beneficial nor any undesirable effect on the die life but will un-necessarily involve extra cost.

5- Use of coolant and its proper application on the entire working surface is very important for improving the die life.

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