1. Introduction

High-speed hot forging is a capital-intensive operation. The cost of the hot forging dies may account for about 10% of the cost of the forged component. Working life of the dies is an important consideration from the point of view of cost reduction associated with tool replacement and maintenance and improvement in productivity and product quality. The life of the tools is affected by a complex combination of high mechanical and thermal stresses. The former originates from repeated impact and high-pressure flow of the metal, and the thermal stresses are generated due to cyclic contact between die and workpiece at a temperature that is generally between 700–800°C and may be even higher. The operating parameters affecting the die damage are load, speed, temperature and environment. The damage mechanisms responsible for reduction in life of the die may include a tribo-system specific complex combination of wear, thermal fatigue, mechanical fatigue and plastic deformation. Wear and life of forging dies are studied either from industrial data or experimentally under carefully controlled conditions designed to simulate industrial practice. There is no consensus on the dominant wear mechanism(s) affecting the die life since it is a complex function of the characteristics of die materials, tribo-system and operating parameters. There are various findings regarding the nature of wear in forging dies. Metal oxide transfer from the forging stock and concurrent abrasive wear due to the oxide scale were identified as the mechanisms responsible for damage in drop forging dies. In contrast, the embedding of fine fragments of abrasive particles into the worn surfaces was found to be beneficial by Fischer in decreasing the wear. According to his findings these fragments stick rigidly to the surface and act like hard phases and protect the working surfaces against abrasion, compensating for the effect of core (matrix) softening at high temperatures. In addition to abrasive particles, oxide scale was also observed on the surface. Seidel and Luig have attributed die damage to abrasive wear. Decrease in die life due to microstructural changes and cracking has also been observed.

Studies have been made to compare the effect of salt bath nitro-carburising and plasma nitriding treatments, on the working life of hot forging dies made of H11 grade of tool steel. Working life of the surface modified dies, that are used for the production of bearing races by high speed closed die forging, was evaluated in the real plant operation. Salt bath nitro-carburised tools are found to give an average life of 12 000 races with a very wide variation between 1 000 to 35 000 races. In sharp contrast, plasma nitrided tools showed a consistent two to four fold higher life than the salt bath nitro-carburised tools. The surface of worn out dies was examined by scanning electron microscopy (SEM) to understand the nature of damage processes involved in the dies subjected to two different surface treatments. Fatigue cracks, resulting from cyclic thermal and mechanical loading during operation, are the dominant modes of damage in the case of salt bath nitro-carburised as well as plasma nitrided dies. The severity of die damage by mechanical fatigue was more in the salt bath nitro-carburised dies. Abrasive wear due to micro cutting was observed to result in significant damage of the salt bath nitro-carburised die. Die damage due to micro cutting was not observed in the plasma nitrided dies. However, signatures of chipping and plastic deformation were noticed at few locations. The results obtained on service life and wear mechanisms after the two different surface treatments are examined in the light of the characteristics of the modified surfaces.

KEY WORDS: wear mechanisms; tool steel; hot forging dies; salt bath nitro-carburising; plasma nitriding.
life. Dressler\textsuperscript{12}) has found that plasma nitriding dies have 70\% longer press time than salt bath nitrided dies. Duplex treatment, involving plasma nitriding and physical vapour deposition (PVD) of TiN, has been found effective by Navinsek \textit{et al.}\textsuperscript{13}) to increase the life of forging dies.

In the fast acting hot forging press of the ring (bearing races) plant at Tata Steel, a patented salt bath nitro-carburising process (Sursulf\textsuperscript{18}) process) is currently employed for the surface modification of the dies to enhance their service life. Inconsistent life of the salt bath nitro-carburised dies results in serious scheduling problems. As an alternative to salt bath nitro-carburising, application of plasma nitriding has been explored. Laboratory simulation tests, that provide valuable information on damage mechanisms under idealised conditions, are seldom able to predict with accuracy the actual damage of materials in the field due to the difficulty in simulating real service conditions, such as loading patterns and frequencies and environmental factors. Field-tests, in spite of being expensive, time consuming and difficult to control and monitor, are essential for a better assessment of the wear and implementation of solution to prevent or control the wear. Hence, the service life of the plasma nitrided dies was evaluated in the real plant operation. The results of a comparative study on service life and damage mechanisms in salt bath nitro-carburised and plasma nitrided dies are presented in this paper. Service life of the surface modified dies and their wear mechanisms are also examined in the paper \textit{vis-à-vis} characteristics of the modified surfaces.

2. The Tribo-system

The dies used in the present investigation are from the third station of a 1600 tonnes four-station close die hot forging press shop. The high-speed (60–80 strokes/min) forging shop is used for making bearing races of different size. The feedstock, a circular cross section beam of SAE52100 or 20MnCr5 steel, after initial shear to the required size, undergoes upsetting in the first station and pre-forming operation in the second station. Finish forming takes place in the third station and it is followed by piercing and separation of slug, inner race and outer race, in the last station. The entry temperature of stock in the first station is $\sim 1200^\circ$C and it drops to 900–1000$^\circ$C in the third station. The wear is maximum in the third station because 50–60\% of the total load, that is 1600 tonnes, is applied in this station. The schematic view of the third station tooling along with the work piece is shown in Fig. 1. The tribo-system under consideration consists of intermediate die as the body, workpiece as counter body and water as the coolant and lubricant. The wear of the die takes place due to a combination of impact and sliding under mechanical and thermal loads.

3. Experimental

3.1. Forging Dies, Surface Modification and Sample Preparation

The intermediate dies used in the present investigation are made of AISI H11 grade of hot working tool steel. The nominal composition of the steel is given in Table 1. The dies were available in quenched and double tempered condition. The first tempering is done at 550$^\circ$C for 2 h and this is followed by second tempering at 605$^\circ$C for another 2 h. Typical microstructure of the die steel comprises of a tempered martensite matrix with uniformly distributed carbide precipitates. In the normal plant practice, the dies are salt bath nitro-carburised at 560$^\circ$C for 2.5 h. Few sets of third station tools were plasma nitrided at 490$^\circ$C for 20 h in a commercial DC plasma nitriding system with N\textsubscript{2} and H\textsubscript{2} flow rates of 10 and 30 l/min, respectively. The tools were slowly cooled in nitrogen atmosphere after plasma nitriding. Test specimens in the form of disks, 25 mm diameter and 10 mm thickness, were cut from one of the hardened and tempered die, polished by conventional metallographic techniques and nitrided along with the dies. In addition to the test specimens, samples were also made out of used dies. The surface modified dies after their useful service life were sectioned transverse to the die surface. Metallographic samples were made from the end far away from the hot working surface.

3.2. Characterisation of the Specimens and Evaluation of Service Life

The test specimens were characterised using optical as well as scanning electron microscopy and micro-hardness measurements as described in recent paper by Devi and Mohanty\textsuperscript{14}) Microhardness depth-profiles of the nitried test samples were used to estimate the case depth. The case depth is defined as the distance from the surface of speci-
men (in case of test as well as die specimens) to the point at which micro-hardness profile reaches a value of 10% above core hardness. The thickness of compound layer was determined using optical as well as scanning electron microscopy (SEM).

Service life of the surface modified dies was evaluated in the real plant hot forging operation. The life was expressed in terms of number of bearing races made before the die surface degraded to the extent that it became unusable and required replacement.

3.3. Study of Wear Mechanisms in the Worn-out Dies

The worn out surface of the die was subjected to both macro and microscopic examinations. Microscopic examination was carried out using a JEOL-6400 scanning electron microscope. The dies after their useful service life were sectioned normal to the die cavity. The cut samples were ultrasonically cleaned twice with acetone. The cross-sectional surface through the damaged surface was polished by metallographic techniques. SEM examination of the wear in scar bearing surface was carried out to reveal the signatures of various operative damage mechanisms on the surface of the die during operation. SEM study of the polished and etched (with 2–3% Nital) cross-sectional surface was carried out to understand the nature of subsurface damage.

4. Results and Discussion

4.1. Characterisation of the Samples after Salt Bath Nitro-carburising and Plasma Nitriding

SEM micrographs presented in Figs. 2(a), 2(b) show typical microstructure of the test specimens after salt bath nitro-carburising and plasma nitriding treatments. The diffusion zone is clearly visible in both salt bath nitro-carburised and plasma nitrided samples. Salt bath nitro-carburised samples showed a compound layer of 12–16.5 \( \mu \text{m} \) thickness (Fig. 2(a)) that was found to consist of FeS, Fe\(_{2–3}\)(NC) and Fe\(_{0.98}\)O by XRD. In addition presence of butterfly networks of iron nitrides can be seen in the diffusion zone. In sharp contrast, compound layer is absent in plasma nitrided samples (Fig. 2(b)). The microstructure of the core after any of the treatments remains the same as that of the untreated specimens.

The micro-hardness depth profiles of the surface modified samples are shown in Fig. 3. The maximum (superficial) hardness of 870 HV\(_{0.1}\) was obtained after salt bath nitro-carburising. Plasma nitriding resulted in a much higher superficial hardness of \( \sim 1260 \) HV\(_{0.1}\). Thicker compound layer is porous in general and is the reason for the lower superficial hardness of the ‘Sursulf’ treated tools. The core microhardness did not show any perceptible change after either of the surface modification treatments. Typical value of case depth was 160 \( \mu \text{m} \) for the plasma nitrided samples. The salt bath nitro-carburised samples showed a much lower case depth of the order of 40 \( \mu \text{m} \). The low case depth developed in salt bath nitro-carburising is due to the slow kinetics of diffusion reactions in the liquid state giving rise to lower carbon-, nitrogen potential at the tool-bath interface. However, in plasma state the diffusion rate of ions into the substrate is high, due to high nitrogen potential at the part surface and higher case depths can be attained at lower temperatures that are far below the tempering temperature.

4.2. Working Life of Surface Treated Forging Dies

The service life of the nitro-carburised 3rd station tooling was analyzed statistically over a few months period and typical results for intermediate dies are presented in Fig. 4. The service life distribution of the intermediate die shows a bi-modal distribution (similar for ring dies); the first maxima is at 4 000–6 000 strokes and the second peak at 12 000–14 000 strokes, with life ranging between 1 000 to 35 000 strokes and weighted average life around 12 000 strokes. The uncontrolled Sursulf\(^\text{®}\) bath chemistry is suspected to
be the prime reason for this kind of variation in the die life. Besides, there could be other plant factors e.g., tool alignment, variations in the applied load etc., and their effect are under investigation. Service life distribution of plasma nitrided dies is also presented in Fig. 4. Here press times are segregated primarily above 24,000 strokes. The dies, which had a case of 155–200 μm failed only after a life of more than 24,000 strokes. The maximum life observed for the plasma nitriding dies was 50,000 strokes. Thus plasma nitriding is found to increase the service life of H11 steel forging tools 2–4 times compared to salt bath nitro-carburised tools. In addition, the scatter in the service life of the tools is also minimized.

The physical interaction between moving surfaces in a tribo-system originates and continues on a microscopic scale leading to macro-level damage. To understand the microscopic damage mechanisms, SEM studies were carried out on the working surface of the worn-out dies. The working area was scanned from surface to the interior of the cavity of the die and the results are compiled and compared in Fig. 6 for the nitro-carburised and plasma nitrided dies. The approximate locations of the typical microscopic damage areas examined in the die and correspondence with the microphotographs are indicated in Fig. 6.

At the open end of the intermediate die, where the metal flows inwardly, under the pressure of punch sleeve and punch nose, there is a severe abrasive wear (Fig. 6(a)) due to micro cutting in the salt bath nitro-carburised die. This scoring due to micro cutting was absent in the plasma nitrided die. The absence of abrasive wear in the plasma nitrided die is due to the development of consistently higher surface hardness (1260 HV0.1) and a thicker (155–200 μm) hardened case, compared to salt bath nitro-carburising (~40 μm hardened zone). A magnified view of a single micro-cut is shown in Fig. 6(b). The debris remnants (shown in Fig. 6(d)), which were the product of scoring, were found adhered around the step of the intermediate die (step can be seen in Fig. 5) of salt bath nitro-carburising treatment. The morphology of the debris is similar to the product of machining process. This kind of debris was not found on the entire working surface of the plasma nitrided die. The surface of the salt bath nitro-carburised tools developed a compound layer with cracks (Fig. 2(a)). As a
consequence of the rubbing of the die working surface with the work piece under load, the compound layer breaks into pieces. It appears that resultant particles along with the mill scale from the oxidation of the work piece surface, act as an abrasive third body and cause abrasive wear of the die surface during sliding.

Damage due to thermal fatigue is dominant in the dies treated by both the treatments. This feature can be observed in the micrographs Figs. 6(b), 6(f) and 6(g). This is a universal damage mode in the hot forging tools. Summerville et al. also found out cracks in the industrial hot forging dies due to alternate thermal cycles. In nitrocarburised intermediate die, horizontal thermal cracks could be observed even inside the scored regions (Fig. 6(b)). The other major mode of damage in both the dies was mechanical fatigue. This damage due to alternate me-

Fig. 6. View of the microscopic surface damage on the working surface of the intermediate die: (a) to (e) correspond to salt bath treated die; (f) to (j) correspond to plasma nitrided die.
Mechanical loads can be seen in Figs. 6(c), 6(e), 6(h), 6(i) and 6(j). It is well established in the literature \(^{17-21}\) that plasma nitriding improves fatigue life of components. The nature of the damage due to mechanical fatigue is distinctly different in the die surface modified using nitro-carburising and plasma nitriding. In salt bath nitro-carburised die after the initiation and growth of the fatigue cracks, spalling of the die surface has taken place as chunks, as is evident in Figs. 6(c) and 6(e). There appears to be no plastic deformation of the working surface of the Sursulf\textsuperscript{®} treated dies due to their inability to absorb the mechanical stresses. Coalescence of small \(\sim 10 \mu m\) cracks (Fig. 6(e)) led to the chipping of the die surface. These chips adhering to the wall of the die can be seen in Fig. 6(c). However, plasma nitrided die working surface absorbed the mechanical shock, by deforming the surface and subsurface as can be seen from the morphological features of the micrographs in Figs. 6(h), 6(i) and 6(j) and the extent of chipping is also low in this case. Detailed studies on the elasto-plastic behavior of plasma nitrided surface and subsurface are in progress and beyond the scope of this paper.

The nature of subsurface damage in worn-out dies is elucidated in the cross sectional SEM micrographs presented in Figs. 7 and 8 for salt bath nitro-carburised and plasma nitrided dies, respectively. From the cross-section (SEM) micrographs of salt bath nitro-carburised intermediate die (Fig. 7), it appears the cracks nucleated at the surface due to the tensile stresses generated by thermal and mechanical loads are propagated mostly normal to the die surface (Fig. 7(a)). These cracks could go as deep as 90 \(\mu m\) inside the die. However, there is no material damage due to these normal cracks. The transverse cracks which are in the direction of metal flow, (Figs. 7(a), 7(b)) aided in the chipping resulting from the coalescence of cracks. Inside the cracks, the oxidation of tool steel appears to take place (Fig. 7(c)). But surface oxidation and intermixing of oxide scale and tool steel were not found in the worn dies of both the nitriding treatments as was observed in the simulated laboratory high temperature experiments.\(^{9}\) Microstructural changes were not observed in any of the worn dies. In plasma nitrided
die, coalescence of cracks, which ultimately led to spalling of die surface as shown (cross-section (SEM) micrograph in Fig. 8(a), is also a major damage mechanism. The maximum size of the spall was a 200 μm. At very few places (Fig. 8(b)) plastic deformation of the plasma nitrided die surface in the direction of metal (stock) flow was observed. It can be seen that a surface layer of 10–17 μm thick has been deformed for a distance of about 50 μm in the direction of metal (work piece) flow. But the extent of surface damage due to plastic deformation is low. Cracks nucleated at the surface of plasma nitrided die could not grow beyond 70 μm and oxidation of the crack interior was observed as shown in Fig. 8(c).

5. Conclusions

1. Salt bath (Sursulf®) nitro-carburised tools characterised by a compound layer of 12–16 μm and a case depth of ~40 μm give a wide variation in service life from 1000 strokes to 35,000 strokes. Typical service life of Sursulf® treated tools is 12,000 strokes.

2. Field trials on closed die hot forging (finish forming) tools established that plasma nitrided tools give consistently 2–4 fold improvement in service life compared to salt bath nitro-carburised tools, when the tools developed a diffusion zone of 155–200 μm without any compound layer.

3. The common damage modes in the die surface treated by salt bath nitro-carburising and plasma nitriding are thermal fatigue (heat checks) and mechanical fatigue.

4. Wear by micro-cutting mode is an additional dominant damage mechanism observed in salt bath nitro-carburised dies.

5. Minor damage modes of plastic deformation, chipping resulting from the coalescence of cracks are observed in plasma nitrided dies.

6. Plasma nitriding can be used to tailor a blend of surface mechanical properties to suit the functional requirement of closed die hot forging tools.

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