JMEPEG (1998) 7:796-800

Modified Falex Testing: A Tool for Understanding the Compound Layer Capabilities

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(Submitted 20 April 1998; in revised form 4 June 1998)

The usefulness of Falex testing in assessing the scuffing resistance of nitrocarburized steel was established by carrying out tests on treated medium-carbon and hot-working steel specimens. Though the test could be employed as a quality control measure for the compound layer thickness, it was found inadequate in bringing out the subtle variations in the compound layer characteristics of specimens of different steels. By a modified form of Falex testing, the heat resisting ability of the compound layer of different steels could be distinctly brought out.

Keywords coatings, falex test, tribology, wear

1. Introduction

Falex testing is used for evaluating wet/dry lubricants and is covered by ASTM standards D 2625 and D 2670. The machine is also used for assessing the scuffing resistance of surface-modified components, particularly that of nitrocarburized specimens (Ref 1). It is customary to carry out the test either until the specimen fails by scuffing/welding, up to the load at which the specimen extrudes, or until the loading limit of the machine is reached. Quite often in the test for nitrided/nitrocarburized specimens, the emphasis is on the nature of the failure rather than on the maximum load withstood by the specimen before failure. This philosophy is understandably governed by the fact that scuffing is essentially a surface phenomenon caused by asperity interactions leading to adhesive situations. However, the load at which extrusion takes place depends on the thickness of the compound layer; therefore, this parameter also must be considered significant in the evaluation of nitrocarburized specimens. In effect, the load can be considered an indirect measure of the thickness of the compound layer, and, hence, the test can be successfully used as a quality control tool for the processing parameters.

The standard Falex practice is to allow the load to be increased continuously until failure. This approach, though useful as stated above, has some inherent limitations. For example, the test is completed within a very short time; generally it does not exceed 120 s, and, therefore, it affords very little time to observe the progress of failure. Second, the test results do not seem to reflect the influence of the alloying elements in the compound layer characteristics as much as they are dependent on the thickness. Also, while comparing the nitrocarburized specimens of different steels, subtle differences in either the thickness or the layer characteristics are liable to be missed in the standard test. It was considered worthwhile, therefore, to modify the test in order to prolong the duration of the testing and overcome these limitations. With this rationale in mind, nitrocarburized specimens of En8 and H11 steels were subjected to both standard and modified tests, and the merits and demerits of both the tests were analyzed.

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2. Experiment

Table 1 gives the chemical composition of plain medium-carbon steel (En8) and hot-working die steel (H11) used in the present investigation. The nitrocarburizing treatments were carried out in an air and sulfur accelerated Sursulf bath under the conditions given in Table 2. The specimens from the salt bath were quenched in oil.

It can be seen from the table that for En8, the treatments at 570 °C and 650 °C are referred to as ferritic and austenitic, respectively; for H11 both are shown as ferritic. This is due to the presence of 5% chromium in H11 steel, which elevates the Fe-N eutectoid temperature from 590 °C to above 650 °C (Ref 2).

The metallographic examination was carried out in a Union Versamet microscope (Union Co.; Japan) and the same specimens were subjected to microhardness testing in a Leitz Vickers microhardness tester (Leitz; Leitz, Germany) under a load of 50 g.

Table 1 Chemical compositions of En8 and H11 steel

	Chemical composition, wt%							
Steel	C	Mn	Si	S	P	Cr	Mo	V
En8	0.43	0.70	0.25	0.02	0.02	0.03	0.01	Trace
H11	0.42	0.40	1.05	0.02	0.03	5.25	1.15	0.35

Table 2 Nitrocarburizing parameters for En8 and H11 steel

Steel	Temperature, °C	Hold time, h	Condition
En8	570	2	Ferritic
	650	2	Austenitic
H11	570	2	Ferritic
	650	2	Ferritic

The scuffing resistance of the nitrocarburized specimens was evaluated by an increasing-load test with a Falex testing machine using two methods. One method was the standard increasing-load test, the features of which are given in Ref 3. In this test, a specimen in the nitrocarburized condition, 6.5 mm in diameter and 40 mm in length, is rotated at a constant speed of 290 ± 10 rpm. A starting crushing load of 2000 N is applied to it by two stationary V-jaws made of medium-carbon steel. Figure 1 shows the schematic arrangement of the test set up. The load on the specimen is increased approximately at the rate of $100\ N \cdot s^{-1}$, which is effected through a pawl and ratchet wheel mechanism. The crushing load imposes a near-hydrostatic compression on the specimen.

In the second method of testing, a load of 1000 N is applied through the jaws to the specimen and remains constant throughout the test. The onset of red-hot condition/scoring on the surface was regarded as failure, and the time taken to reach that state was considered the end point and was designated as threshold time, t_{TH}.

3. Results and Discussion

3.1 Metallography and Hardness

The optical photomicrographs of the nitrocarburized En8 specimens treated at 570 °C and 650 °C are given in Fig. 2(a) and (b), respectively. It can be seen from the figures that a white etching compound layer of approximately 12 μm thickness had developed in the 570 °C treated specimen. X-ray diffraction studies indicated the predominant presence of $\varepsilon Fe_{2\text{-}3}(CN)$, with small amounts of $\gamma' Fe_4(CN)$ phase in the compound layer. On the other hand, in the 650 °C treated specimen, a thicker compound layer was formed (27 μm) due to higher treatment temperatures (Ref 5). Apart from the compound layer in the 650 °C treated specimen, there is another white etching subzone, identified as austenite by x-ray powder diffraction (XRD) analysis.

The microhardness traverse obtained on these specimens is presented in Fig. 3. It can be seen from the figure that the surface hardness of the 650 °C treated specimen is higher than that of the 570 °C treated specimen. This is attributed to the fact that

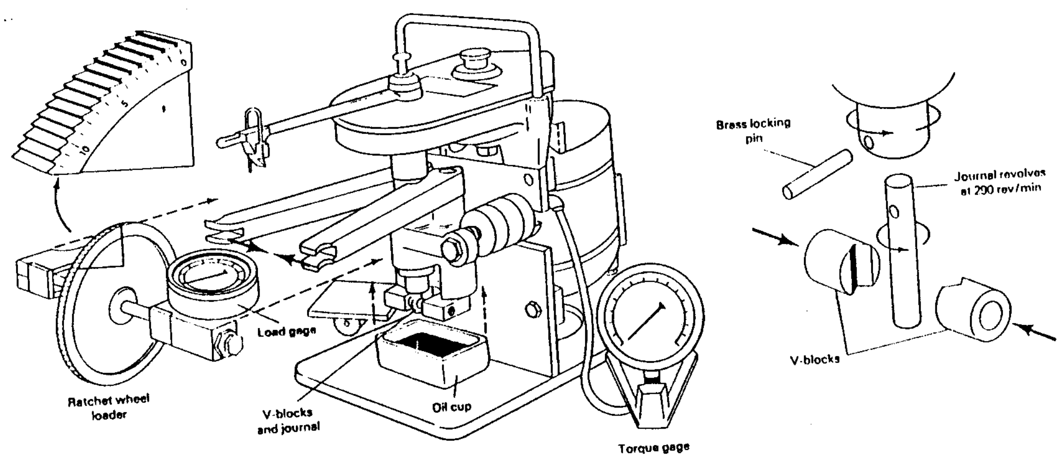
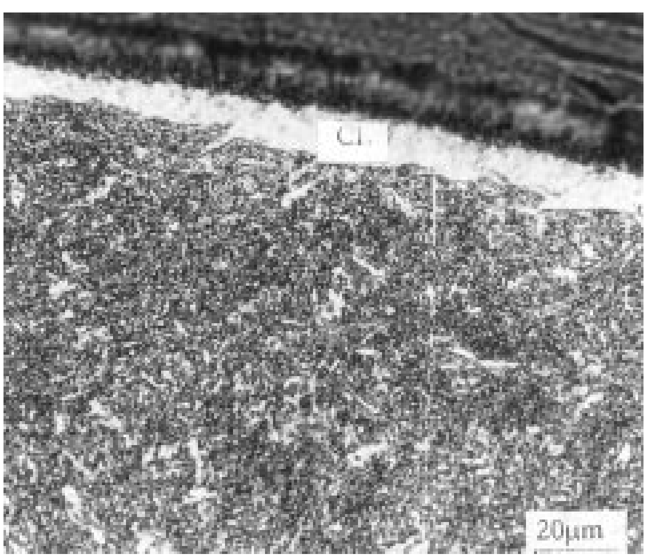
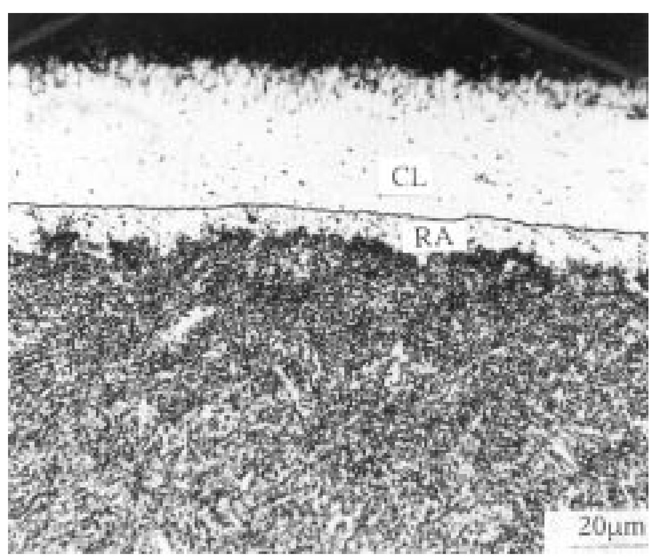


Fig. 1 Arrangement sketch of Falex Machine. Source: Ref 4



(a)



(b)

Fig. 2 Optical micrographs of nitrocarburized En8 specimens. (a) 570 °C. (b) 650 °C. CL, compound layer; RA, retained austenite higher treatment temperatures promote the formation of monophased compound layers consisting only of ε-carbonitride leading to higher surface hardness levels, as ε-carbonitride is reported to be harder than γ′-carbonitride.

The optical micrographs of the nitrocarburized H11 steel shown in Fig. 4(a) and (b) reveal that the compound layer thicknesses are around 6 to 8 μm and 13 to 15 μm for the 570 °C and 650 °C treated specimens, respectively. Alloying elements are known to impede diffusion of nitrogen in steel (Ref 6), and the presence of chromium, a nitride former, is responsible for the relatively lower compound layer thicknesses developed in this steel as compared to En8. Since the 650 °C treatment lies within the ferritic phase field of the Fe-C-N system for the H11 steel, the retention of austenite in the subcompound layer is conspicuously absent. The hardness profile of the specimens given in Fig. 5 indicates a peak hardness of around 1050 HV. The higher hardness of the compound layer of H11 compared to that of En8 is attributed to the formation of complex ε-carbonitride that includes chromium as well in the compound layer ($Fe,Cr_x(CN)$).

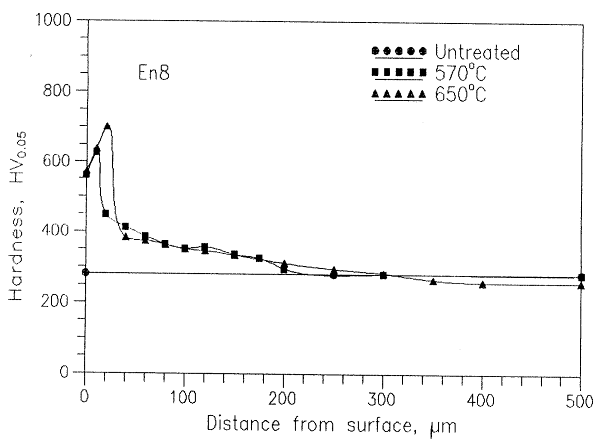


Fig. 3 Hardness profile of nitrocarburized En8 specimens

3.2 Falex Testing

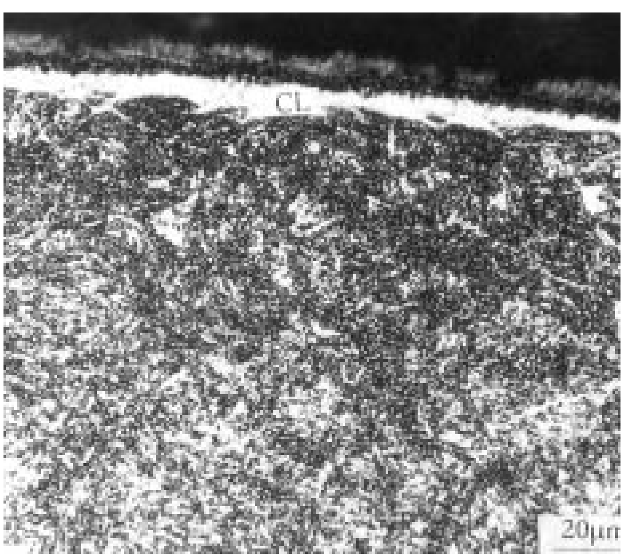
In the increasing-load Falex tests, the untreated specimens failed by severe scuffing at loads of around 3000 N, whereas the failure of nitrocarburized specimens was marked by extrusion at very high loads with no trace of scoring on the surface. The typical failure modes are shown in Fig. 6.

The failure loads of En8 specimens nitrocarburized at 570 °C and 650 °C were 7740 N and 9500 N, respectively, whereas the H11 specimens failed at 7000 N and 8750 N for the respective treatment temperatures. At the point of failure, the specimens reached a red-hot condition and extruded within a short test duration (60 ± 12 s).

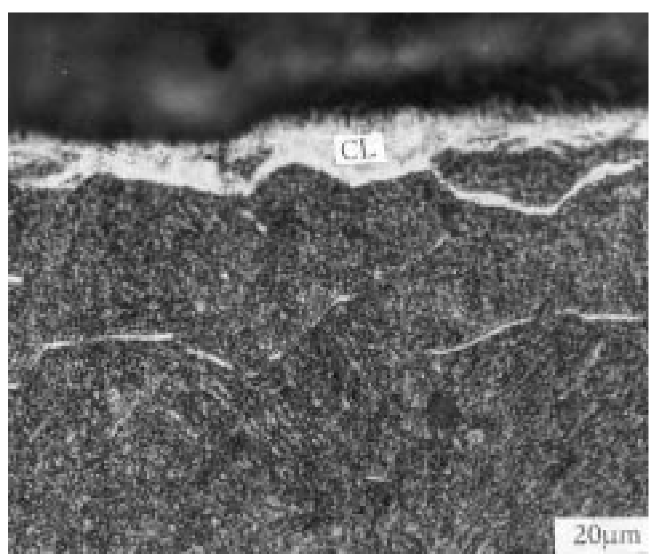
It is interesting to note that the H11 specimens, despite having only half the compound layer thickness of En8, withstood loads that were nearly 90% of the failure loads of the En8. This can be attributed to the presence of alloy carbonitrides in the compound layer of H11.

It is apparent from the above results that the failure load is affected by two factors: the compound layer thickness and the alloy content of the substrate. If considered from the mechanistic point of view, the failure load appears to be decided by the extent of working done on the specimen and the heat generation at the interface. The heat generated at the interface, in turn, is affected by the coefficient of friction and is absorbed by the core leading to softening. The working on the specimen is due to the near hydrostatic compression exerted by the jaws. The effect of working can be clearly seen in Fig. 7 in the circumferential alignment of the grains.

In the initial running-in period of the test, the coefficient of friction value increases to around 0.40, during which the leveling of asperities takes place at the specimen surface. This stage also contributes to removal of a portion of the compound layer by the wearing process. As the test proceeds with the load continuously increasing, the coefficient of friction reaches a relatively low, steady value of approximately 0.26; the working effect predominates with heat generation at the interface, lead-



(a)



(b)

Fig. 4 Optical micrographs of nitrocarburized H11 specimens. (a) 570 °C. (b) 650 °C. CL, compound layer ing to compaction of the remaining portion of the compound layer. Since the compound layer is made of refractory carbonitrides, the heat generated at the interface reaches the core at a very slow rate with the layer acting as a thermal barrier. Upon reaching the red-hot condition, the specimen is no more able to withstand the crushing load by the jaws and, hence, fails by extrusion. The thicker the compound layer is, the longer it takes for the specimen to reach this red-hot stage. This is why a 650 °C treated specimen with its higher compound layer failed at a higher load than the one treated at 570 °C.

H11 steel, with its ability to retain its core hardness, appears a better candidate despite its marginally lower failure load. This choice may seem to be a compromise but is actually not so, as can be seen from the results of the modified Falex test discussed subsequently.

In Fig. 7, part of the compound layer is seen to be still intact. This indicates that conditions of compacting or near-hydrostatic stress rather than of wear predominate in the Falex test. Though it is an accelerated form of destructive testing, and therefore ought to be necessarily a severe one, there are only a few industrial applications in which such severity is encountered. On the other hand, there are several applications wherein the surface is subjected to wear under dry sliding conditions. Therefore, it was determined that if the Falex test method is modified to simulate dry sliding conditions, it would become yet another useful tool for assessing the wear resistance of material. With this rationale, the test was run at a constant load of 1000 N. Another distinct feature of this modified “constant-load” test is that, unlike the conventional increasing-load Falex test, the testing duration is prolonged. The extended duration of the test by itself affords an opportunity for both closer observation of the phenomena that happen during testing and comparative evaluation of specimens whose properties (particularly surface properties) differ only marginally. The compound layer of nitrocarburized specimens undergoes gradual wear in this test, and the build-up of frictional heat at the interface causes

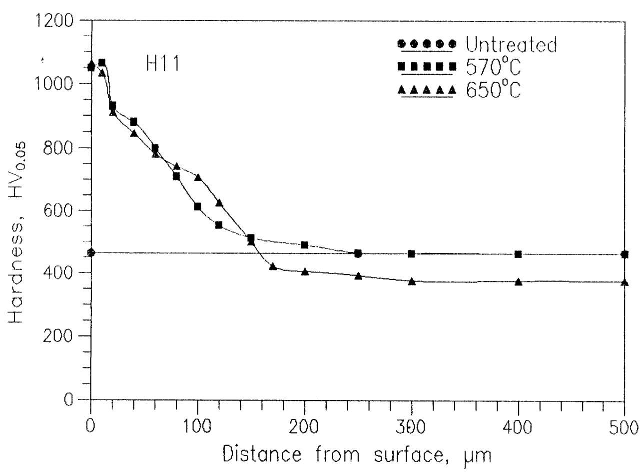


Fig. 5 5 Hardness profile of nitrocarburized H11 specimens

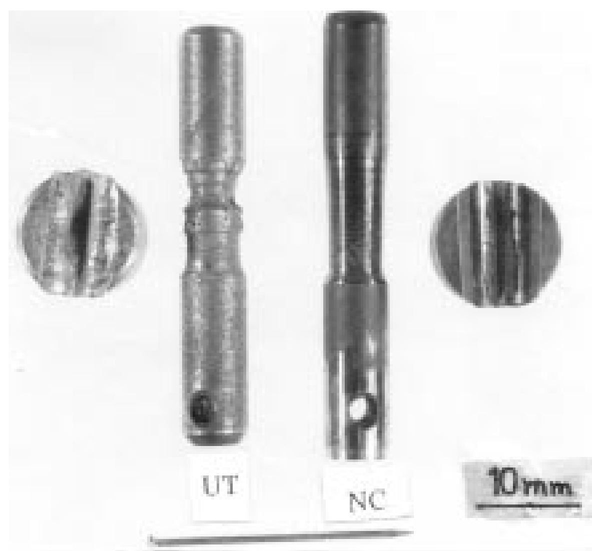


Fig. 6 Modes of failure in Falex test. UT, untreated; NC, nitrocarburized

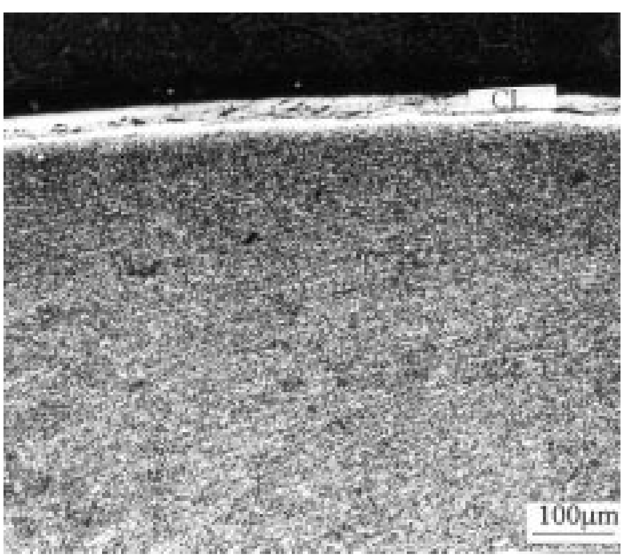


Fig. 7 Optical micrograph of the cross section of the Falex tested specimen. CL, compound layer

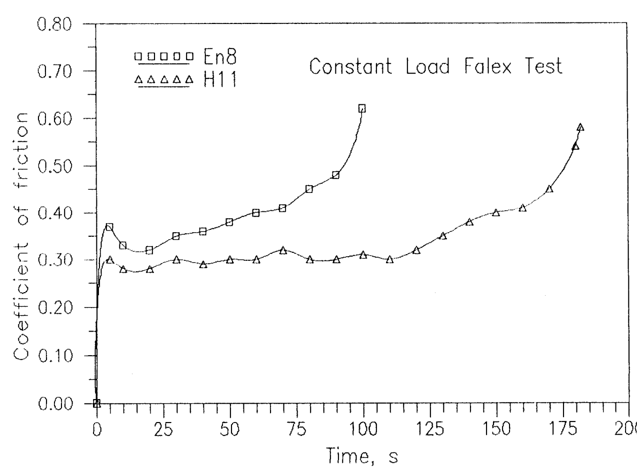


Fig. 8 Plot of time versus coefficient of friction obtained during Falex testing

the specimen to reach red-hot condition. Upon complete removal of the compound layer by the wearing process, surface scoring marks appear, at which point a sudden rise in the friction coefficient is noticeable. The time it takes to reach this point is designated as the threshold time, t_{TH}.

In this test, the untreated specimens failed within 3 to 5 s with severe scuffing without reaching red-hot condition. On the other hand, the nitrocarburized En8 specimens reached a t_{TH} of 67 s and 132 s, respectively. The H11 specimens nitrocarburized under similar conditions ran for relatively longer periods, with t_{TH} values of 100 s and 182 s, respectively, despite the compound layer thickness being only half that of En8.

Apparently, the superiority of the H11 specimens is due to the compound layer resisting the wearing process under the running conditions due to its higher hardness. Further, the presence of chromium carbonitride in the compound layer, which is known for its low friction coefficient levels (Ref 7), seems to have helped in prolonged running as well.

Figure 8 shows the time versus coefficient of friction plot obtained for the above tests. It can be seen from the figure that the coefficient of friction was slightly higher for the En8 specimens. The value remained relatively steady during testing for the H11 specimens, whereas for En8, a gradual increase in the coefficient of friction is observed. This can be attributed to the porosity level being slightly higher for the En8 specimens, causing relatively higher wearing rates of the compound layer. As the wearing process continues, the continuous heat generation at the interface causes the friction value to increase gradually, reaching 0.65 at the point of failure. In the H11 specimens, the presence of chromium carbonitride and higher hardness levels allowed for a longer running duration with reasonably steady and relatively low coefficient of friction values.

A comparative analysis of the results obtained in the above two methods of Falex testing brings out the specific applicability of each method. The increasing-load test is undoubtedly useful for assessing the scuffing resistance of nitrocarburized steels; however, the load at which extrusion takes place upon reaching red-hot conditions cannot be considered solely dependent on the compound layer property but also on the strength of the core because the core provides the back-up to the layer to resist the increasing near-hydrostatic compression exerted by the jaws. The influence of core strength can be appreciated because the H11 treated at 650 °C withstood a failure load of 8750 N, which is about 90% of the failure load of 9500 N of En8 despite having only half the compound layer thickness of the latter.

The modified constant-load test, on the contrary, slowly wears out the compound layer while maintaining a nominal crushing load and brings out the properties of the near-surface layers; in particular, heat resistance. The extended duration of the test and the gradual frictional heat development provide opportunities for studying the response of the compound layer to situations that can be expected in hot-working applications.

If one were to consider only the results of the increasing-load test, En8 would be rated superior to H11. The superiority of H11, particularly its heat resisting ability, is best demonstrated by the constant-load test. In this test, H11 steel, nitrocarburized at 570 °C, survived for 100 s with a 6 μm compound layer compared with treated En8 with a 12 μm layer, which failed in 67 s.

4. Conclusions

- The standard Falex test method, though primarily intended for assessing the properties of lubricants, can effectively be used for qualitative evaluation of nitrocarburized components.
- Though the conventional increasing-load test is successfully employed to determine the scuffing resistance, it is limited by the inability to bring out subtle differences in the properties of compound layers with thicknesses that vary only marginally. This limitation has been overcome by a modified Falex test method, in which the crushing load is constant.
- The modified test is also found to be useful in assessing the refractory capability or the heat resisting ability of the compound layer.
- By the judicious use of both the methods, the abilities of the compound layer to meet specific service situations can be established.

Acknowledgments

The authors wish to express their sincere thanks to M/s Tribology India Limited, Madras, for providing the necessary facilities to carry out this research.

References

1. T. Bell, Ferritic Nitrocarburising, *Heat Treat. Met.,* Vol 2 (No. 2), 1975, p 39-49
2. G. Wahl, Component Properties after Salt Bath Nitrocarburising by the Tufftride Process, *Heat Treat. Met.,* Vol 22 (No. 3), 1995, p 65-73
3. N. Krishnaraj, "Surface Layer Characterisation and Wear Behaviour of Nitrocarburised Steels," Ph.D. dissertation, Indian Institute of Technology, Madras, 1997
4. "Study of the Influence of Steel Composition on the A_c1 Temperature of Nitride Layer," *Heat Treating,* Vol 4, *ASM Handbook,* ASM International, 1991
5. B. Edenhofer and H. Trenkler, Beitrag Zum Enifluss der Stahlzusammen Setzung auf die Lage der Acl-Temperatur von Nitrier-Schichten, *Härt.-Tech. Mitt.,* Vol 35 (No. 4), 1980, p 175-181
6. L.J. Dijekstra and R.J. Sladek, Effect of Alloying Elements on the Behaviour of Nitrogen in α-Iron, *Transactions of AIME,* Vol 197, 1953, p 69-72
7. M. Keyes, Balzers High Vacuum Limited, trade literature, 1989