Improvement of rolls service life using plasma nitriding in cold and hot roll forming process

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Abstract. Plasma nitriding is known to improve and rectify the service life of rolls; thus this amendment also depends on the type of the steel. AISI D3 tool steel is widely used in Cold Roll Forming (CRF) and AISI H13 tool steel is widely used in hot Forming process. In this researches the structure and Wear properties of plasma nitrided D2 steel is evaluated. Plasma treatments are carried out using an industrial size furnace in appropriate nitrogen–hydrogen mixture and Pin-on-Disk Wear Tester Machine is employed to obtain the Wear behavior according to ASTM G99. The micro hardness profiles were used to demonstrate the case depth. The structures of surface layers and diffusion zone is examined by optical and X-ray diffraction (XRD). It is found that thermochemical processing significantly increased the micro hardness and improved wear behavior and service life of D3 and H13 rolls. also the structure and fatigue properties of plasma and gas nitrided Ck45 steel were evaluated and compared with standard nitriding steel. Plasma treatments were carried out using a semi-industrial size furnace in appropriate nitrogen–hydrogen mixtures and a rotating–bending fatigue machine was employed to obtain the fatigue limits. The microhardness profiles were obtained and used to demonstrate the case depth. The structures of surface layers and diffusion zone were examined by optical and scanning electron microscopy and X-ray diffraction. It was found that thermochemical processing significantly increased the microhardness and fatigue limit of Ck45 steel; increasing the fatigue limit to more than 50% was noticed after 70-h gas nitriding; similar improvements were achieved using plasma treatment in a 5-h cycle. XRD results indicated that the compound layer formed in plasma nitriding was mono-phased and thinner than the two-phase layer formed by the gaseous method which also contained iron oxide.

Introduction

Many automotive items and engineering components are not heavily loaded but nevertheless require high surface hardness which may be obtained by case hardening techniques [1]. Traditionally, gas nitriding and ferritic nitro carburizing have been used in improving wear resistance and endurance characteristics when the components have been manufactured from Cr–Mo bearing steel [2]. The properties of a nitrided steel component are determined by both the core strength and the structural characteristics of the compound layer and the diffusion zone [3]. Whilst it is possible to nitride many steel grades, very high hardness is only obtained when using special nitriding alloys containing aluminum, chromium, molybdenum or vanadium; elements which form hard and stable nitrides as soon as they come into contact with nitrogen atoms at the surface of the work piece.

It is well established that nitriding of plain carbon steels would produce a case of only moderate hardness. This is largely because nitrogen diffuses fairly quickly beneath the surface forming iron nitrides dispersed at greater depths so that surface hardness is comparatively reduced. Since the nitride forming elements have a higher affinity for nitrogen, they prevent diffusion of the latter to a greater depth but instead form very hard stable particles near the surface; giving an extremely hard but shallow case. Another argument concerning nitriding of plain carbon steel is that nitrogen diffusion occurs to a significant depth and it is difficult to achieve any sharply defined hardening limit. Therefore, properties such as fatigue strength which rely on the generation of surface compressive residual stresses by a distinct case–core interface are not as significantly improved as in processing of nitriding steels. On the other hand, due to long process times, increased material and treatment costs of such alloys and a lack of sufficient control over the process, gas nitriding has never been developed to its full potential [4]. The advent of plasma nitriding [5] has led to an increased interest in the application of the process to plain carbon (non-alloyed) steels for obvious Advantages offered by these materials. Such treatment would affect the surface related properties such as resistance to applied loads, to adhesive and abrasive wear, to rolling contact fatigue, and to corrosion. The purpose of the present paper is to explore the fatigue behavior of a plain carbon steel after plasma nitriding and to compare that with a conventional nitriding alloy.

Steel	% C	% Si	% Mn	% Cr	% Mo	% Ni	% Fe
Ck45	0.46	0.19	0.7	–	–	–	Bal.
En40B	0.26	0.25	0.7	3.0	0.5	0.2	Bal.

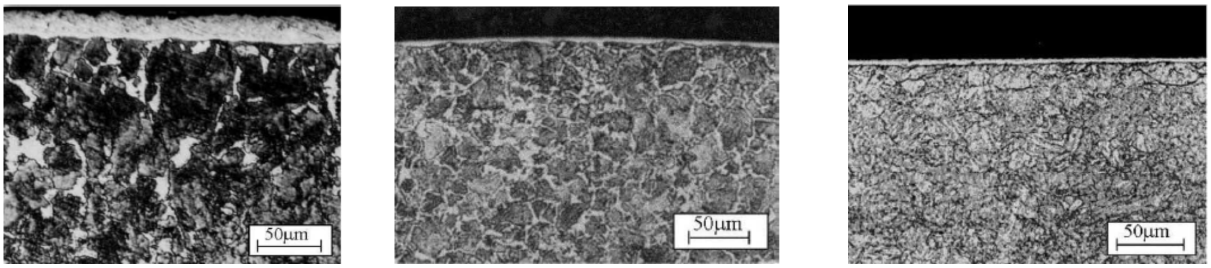
Table.1. Chemical composition of steels

Material and Methods

Experimental procedures and conditions. The Wohler fatigue specimens were machined from 10 mm diameter bars of the steels shown in Table 1.Plasma nitriding was carried out in a medium size 5kW furnace operated by DC voltage. After loading, the chamber was evacuated to 0.1 mbar pressure before the power was switched on. The treatment gas, the composition of which was selected according to the preliminary experiments, was slowly introduced at the required pressure. In all experiments a heating time of 1 h was used during which sputter cleaning was performed in Argon gas. After each treatment the power was switched off to allow the samples to cool to below 150 8C before being removed from the chamber. Specimens for gas nitriding were treated in sealed quenched furnace under industrial conditions, typically 70 h. The plasma nitrided samples were sectioned, mounted, and prepared for metallographic examination and the measurement of microhardness gradients. The compound layers produced on the surface were studied by scanning Electron microscopy and the phases were identified by X-ray diffraction. Using hardness profile is perhaps the most convenient technique to determine the case depth. Where strong nitride formers are present in sufficient amount, the hardness drop at the case–core interface is steep and abrupt, enabling an easy determination of the case depth. In Ck45 steel, however, the alloy–nitrogen interaction is weak and the case hardness drops rather gradually. Consequently, the effective case depth is less well defined. Therefore, it was decided to select hardness value 10% above the core hardness as ameasure of the case depth [6].

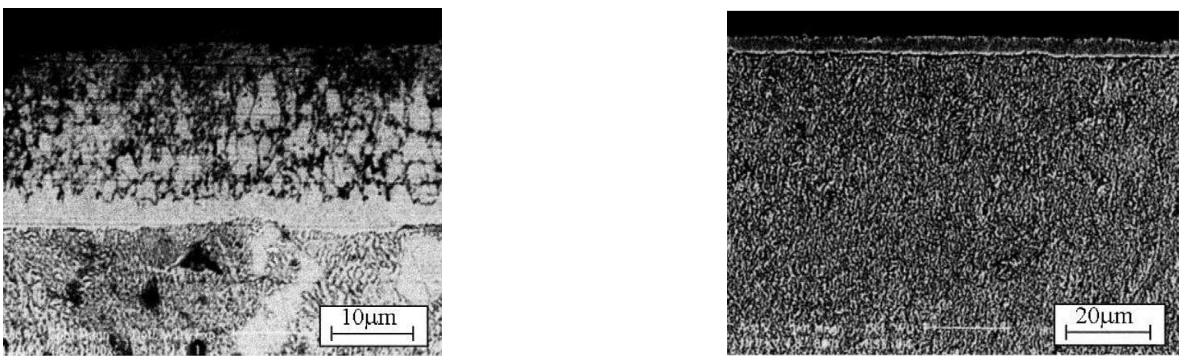
Results and discussion

Microstructure and hardness profiles. Fig. 1 shows optical microstructures of typical nitrided specimens. A white layer of a few microns thickness and a relatively thick diffusion layer were formed at the surface; the compound layer in gas nitriding is much thicker than in plasma nitriding. In the case of plasma nitriding, the growth rate of the compound layer deviates from a parabolic diffusion law and that after a nitriding time it is thinner than a gas nitriding compound layer, due to the effect of material removal from the surface by cathode sputtering in glow discharge [7]. Under equal treatment conditions as to nitrogen supply and nitriding time, the compound layer of plain carbon steel is always thicker compared with alloy steels containing nitride forming elements [8] because nitrides or carbonitrides formed with alloying elements contain more nitrogen than those formed with iron. This is obvious from SEM micrographs of Fig. 2, although nitriding time was longer for En40B steel specimens.



(a) Ck45 gas nitrided (b) Ck45 Plasma nitrided (c) En40B steel plasma nitrided

Fig. 1. Optical micrographs of typical nitrided specimens.



(a) Ck45 gas nitrided (b) Ck45 Plasma nitrided

Fig. 2. SEM micrographs of typical nitrided specimens.

The results of X-ray diffraction proved that the compound layer was single γ' phase in plasma nitriding, but in gas nitriding it contained both ε and γ' phases together with some iron oxide (Fe3O4). These characteristics of the surface layers are usually observed in gas nitriding of steels [9]. Beneath the compound layer, in the diffusion zone, nitrogen is dissolved in ferrite at nitriding temperature and forms nitride precipitates during cooling as a result of decreasing solubility of nitrogen. For En40B steel, alloying elements with a higher affinity for nitrogen than iron form precipitates in this region. The extent of nitrogen diffusion is not very clear from the optical micrographs, but could be made visible by means of an adequate etching technique. The hardness gradients of typical specimens are shown in Fig. 3. One common characteristic of nitrided or nitro carburized microstructures is the hardness gradient with its parameters case hardness, hardness difference between case and core, and case depth. Such data, obtained from the hardness profiles, are presented in Table 2. Accordingly, the maximum hardness of plasma nitrided Ck45 steel is 470 HV and that of En40B is above 900 HV with a steep gradient. The compound layers of plain carbon steels, which form iron nitrides or carbonitrides, reach a hardness of 500–800 HV; those of alloyed steels in which the iron in the nitrides is replaced by alloying elements reach approximately 900– 1100 HV. However, the hardness of the compound layer cannot be measured accurately owing to inadequate thickness of the layer. A considerable increase in the hardness of the diffusion zone is achieved by increasing the amount of supersaturated dissolved nitrogen (solid solution strengthening) and is decreased again to the values characteristic of the slowly cooled diffusion zone.

Steel (treatment)	Core hardness (HV)	Case hardness (HV)	Depth of nitriding (10% above core hardness) (mm)	Compound layer
Ck45 (gas nitrided)	280	470	0.40	25 μm ($\varepsilon+\gamma'$)
Ck45 (plasma nitrided)	290	470	0.36	3 μm (γ')
En40B (plasma nitrided)	310	900	0.22	5 μm (γ')

Table.1. Hardness and nitriding depth of specimens

Comparison of the hardness profiles indicated that they had different parameters. Since the nitride precipitates in the nitriding steels contain more nitrogen, a more shallow case depth with higher hardness is obtained in En40B as compared to Ck45 steel. The concept of nitridability defined as the ability of the steel to absorb nitrogen and to increase the hardness, may be applied to these steels; obviously, the plain carbon steel has a lower nitridability. The depth of nitriding decreases with increasing content of nitride forming elements; the reason for the inhibiting effect of the alloying elements is that they bind the nitrogen as nitrides. In this respect, Ck45 steel must have a much deeper case depth. On the other hand, this alloy has a higher carbon content than En40B steel and carbon, too, has a strong inhibiting effect on the diffusion of nitrogen. Therefore, provided the plasma nitriding time is not too long, the diffusion depth of Ck45 steel may be controlled to be comparable to nitriding steel.

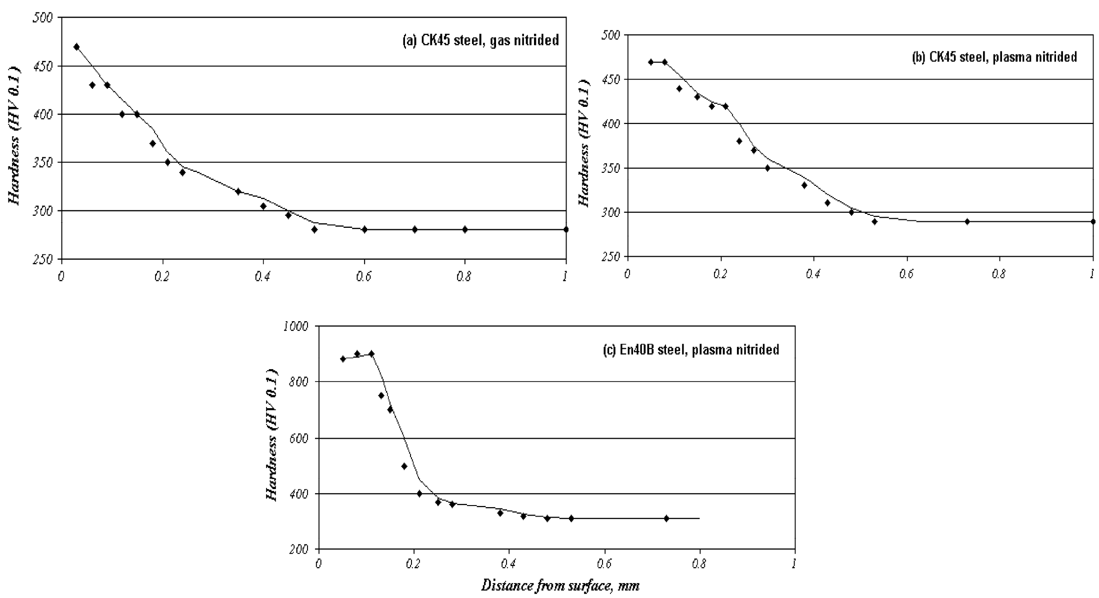


Fig. 3. Hardness gradients of nitrided specimens

Fatigue behavior. Typical fatigue limits of the untreated and nitrided steels are presented in Fig. 4. The improvement in fatigue limit for Ck45 steel was 52% and for En40B was 46% and higher depending on the treatment time.

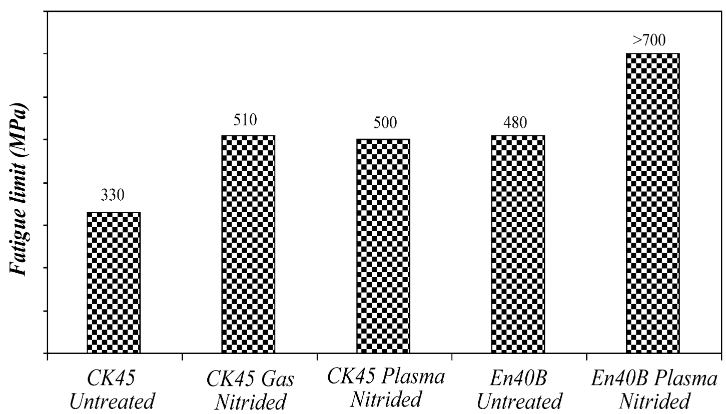


Fig. 4. Fatigue limits of specimens.

Indeed, increasing the fatigue limit up to 75% has been reported for this alloy with a nitrided case 0.56 mm thick [6]. In Ck45 it was noticed that there was no substantial increase in fatigue limit at longer nitriding times. This was also true for gas nitriding specimens with 70-h treatment cycle. The possible explanation could be the relative case–core depth and the distribution of residual stress on both sides of the interface. The tests demonstrated that compound layer had no significant influence on the fatigue limits, but instead it was the diffusion case which had the dominating effect on the fatigue behavior of plasma nitrided specimens. This has been explained in terms of the fatigue fracture mechanism for En40B steel [10]. From the results of the fatigue tests, the best effect is expected with approximately 10% case depth relative to the component size. The comparison graphs which are shown in Fig.5 prove that the effect of feed rate on surface roughness was significant.

The fatigue strength of nitrided components is improved by the combined effect of higher case hardness and compressive residual stresses, which result in a local endurance limit. Owing to the lower density of alloy nitrides than the iron matrix, compressive residual macro- stresses develop during nitriding. This also reduces the unfavorable factor of the notch effect which is extremely marked on fatigue limit. The growth of residual stress is caused by nitrogen being taken into solution in the matrix and the formation of nitride precipitates. The residual stress has been reported for nitriding steels [11], but there is no published work on plain carbon steels. Comparison of experimental results of Ck45 with En40B as a typical nitriding steel demonstrated that plasma thermochemical treatments are candidate processes for improving the fatigue strength of Ck45 material although it is a plain carbon (non alloyed) steel. Gas nitriding, however, requires very long treatment times and results in rather thick compound layer which is undesirable for some components. Therefore, plasma nitriding is recommended as the feasible process and it is expected that surface treated Ck45 in some applications will be cost effective and advantageous.

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