Surface & Coatings Technology 236 (2013) 2–7

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Development of advanced duplex surface systems by combining CrAlN multilayer coatings with plasma nitrided steel substrates

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ARTICLE INFO

Available online 13 July 2013

Keywords:
Duplex treatment
Plasma nitriding
Interface
Plastic deformation
Wear

ABSTRACT

Both modelling analyses and experimental work have recently confirmed that the failure of thin coatings on steel, especially under high loads for some demanding applications, is related to the lack of mechanical support from the substrate, which means that the exceptional hardness, toughness and wear resistance of state of the art PVD coatings cannot be fully exploited. To this end, two types of new duplex surface systems have been developed from this research: i) PVD (specifically Closed Field UnBalanced Magnetron Sputter Ion Plating, CFUBMSIP) CrAlN multilayer coating deposited on ex-situ, 20-h active-screen plasma nitrided (ASPN) steel samples, and ii) in-situ 3-h, high power medium frequency pulsed plasma nitriding (HPMFPPN) treatment, followed by a similar CrAlN coating, but performed in a serial, single batch process in an otherwise conventional CFUBMSIP equipment. The microstructures of these two duplex surface engineered systems were characterised using XRD and SEM, while their hardness, adhesion, load bearing capacity and tribological properties were compared by micro-hardness tests, scratch adhesion tests and pin-on-disc sliding wear measurements. Post-test examinations were conducted and the results confirmed that a hard coating on a nitrided substrate can fully exploit the advantages of both the nitrided sub-surfaces for increased load bearing capacity and of the PVD coating for increased hardness, high temperature stability and extreme wear resistance. Finally, the advantages and disadvantages of these two new duplex surface systems were compared and their potential applications were discussed.

1. Introduction

There is a continuously increasing demand for highly efficient mechanical transmission components that require high load bearing capacity on the contact surfaces of the parts concerned. Problems arise, as plastic deformation is encountered on the surface due to high contact stress and so the performance of components is progressively reduced as a result of fatigue and wear, therefore degrading the precise geometry of the installed parts.

Surface treatments have been widely reported to improve the surface properties of such components to increase their resistance against plastic deformation, fatigue and wear. Among these techniques, surface nitriding, coating, and a combination of both treatments were the typical methods used to deal with the surface deterioration problems induced by heavy duty operation of such mechanical components.

Gas nitriding in an ammonia atmosphere was described [1] as a ferritic thermochemical method of diffusion which was based on the solubility of nitrogen in iron, dependent on the temperature from 450 to 490 °C. According to this mechanism, a process [2] was created that makes nitrogen diffuse into iron-based steels to improve the surface hardness, wear resistance and corrosion resistance. Plasma nitriding employs the glow discharge plasma technique to ionize the nitrogen molecular gas and to generate energetic nitrogen ions which react with the treated surface to enhance the nitrogen diffusion. Plasma source ion implantation at low pressure (0.1 Pa) as well as the use of conventional glow discharge plasma at high pressure (500 Pa) has been reported [3] to nitride stainless steel at a lower temperature of 380°C whilst pulsed-DC glow discharge plasma was also reported [4] to nitride stainless steel at temperatures ranging from 375 to 475 °C. These plasma nitriding processes were claimed to offer treated steels with strengthened surfaces with increased hardness and stiffness, and increased resistance against fatigue, wear and plastic deformation.

Refractory thin hard coatings can be produced by using techniques of either chemical vapour deposition (CVD) or physical vapour deposition (PVD) to form compound materials of, for example, transition metal nitrides, carbides or carbo-nitrides [5]. The high hardness of the coatings can be employed to improve the properties of soft substrates by preventing ploughing induced wear on the surface and thus high surface hardness is useful in limiting wear in an abrasive environment [6], unless a coating has poor adhesion when it may break up and cause further wear through enhanced three-body

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0257-8972/$ – see front matter
http://dx.doi.org/10.1016/j.surfcoat.2013.07.017

abrasion. Although a hard coating can provide enhanced wear resistance in sliding contact friction environments, its performance is often limited when normal loading is increased, especially when the bearing stress is high enough to cause the substrate to suffer plastic deformation.

The combination of nitriding and PVD coating to create a duplex treated surface system has been investigated both via two separate, sequential batch processes in separate equipment and as a single batch duplex treatment process [7–12] in which plasma nitriding was carried out as the first stage of the process followed by the deposition of the hard coating as the second stage treatment, within the same vacuum chamber.

Industrial applications of the duplex treatment need routine, fast, efficient and low cost processes that can be readily justified economically and be acceptable to a wide range of end users. Accordingly, the single batch duplex treatment is expected to be more suited to the needs of industrial end-users, unless the higher capacity of the separate ASPN process is of prime importance. The selection of the most appropriate techniques for the two process stages, from those which have already achieved industrial acceptance, will be critical to the rapid future adoption of the new duplex treatment.

Traditional gas nitriding uses various types of heaters to raise the temperature of the component, usually to more than 500°C, and needs a long nitriding process time (which can exceed 24 h, dependent on temperature). Radiant heating in a vacuum is not efficient and extra power requirements can further increase the cost, which combined with the long nitriding cycle time result in high depreciation charges for duplex treatment in relatively costly PVD equipment.

Commercial PVD equipment adapted for plasma nitriding was reported [13] as being able to complete a duplex treatment in a single, sequential batch process of plasma nitriding followed by CrN hard coating. The nitrided sub-layer supported the hard coatings and exhibited desirable properties but the process still required an additional heater to raise the temperature of the components before carrying out the plasma nitriding step using an external plasma source.

This paper reports the properties of plasma nitriding combined with CrAlN hard coating made in a single, sequential batch duplex treatment without previous heating. The resulting coatings were compared to similar coatings produced by two separate, state of the art batch processes, combined to produce a similar duplex treatment, but carried out in separate vacuum chambers. The potential for the industrial application of these duplex treatments is also discussed.

2. Experimental

Discs of stainless steel (SS) AISI316 and low alloy carbon cast steel (ACS) were used as substrate materials and their chemical composition and hardness are listed in Table 1. Discs of these two materials were cut to a size of 25 mm diameter by 3.0 mm thick. These discs were polished with 1200# SiC paper and then cleaned with ultrasonic assistance in acetone for 10 mins.

Three treatments were carried out on the prepared discs: 1) The as-prepared samples were nitrided by the use of an industrial active screen plasma unit (ASPN) [14] in a 25%N_2 + 75%H_2 atmosphere at 430 °C for 20 h. 2) A 6.0 μm CrAlN multilayer hard coating [15] was deposited in a semi-industrial size (TCL UDP 550, diameter 550 mm, high 600 mm, substrate turntable 300 mm diameter) CFUBMSIP system with an argon and nitrogen mixed atmosphere at a pressure of 0.4 Pa (3.0mTorr) on the as-prepared and ASPN samples. 3) The as-prepared samples were nitrided by the use of high power (2.5 W/cm^2) medium frequency (350 kHz) pulsed Ar + N_2 plasma nitriding (HPMFPPN) for 3 h during which the pressure was 1.33 Pa (10mTorr) with a N_2:Ar gas flow ratio of 3:1, followed by the deposition of a 6.0 μm CrAlN coating as described in step 2) but carried out consecutively in a single, sequential batch process. A cross sectional schematic illustrating the results of a batch duplex treated steel substrate is presented in Fig. 1 and describes the surface structure resulting from the single batch duplex treatment.

Hardness was measured by the use of microhardness test equipment. Metallurgical phases and microstructures were analyzed using XRD and SEM. The resistance to surface plastic deformation was estimated using a constant load of 20 N on a 200 μm radius diamond tip producing a scratch at a sliding speed of 10 mm/min and indentations from a 60 kgf load on a 1.6 mm diameter WC-Co hard-metal ball. The wear resistance of the as-treated discs was investigated using a pin-on-disc tribometer under conditions of dry sliding against a 5.0 mm diameter WC-8%Co hardmetal ball, at a linear speed of 200 mm/s, with loads increased in increments up to 20 N and with a constant test duration of 60 min. The wear tracks were then metallographically sectioned and the resulting cross-sectional structures were studied by means of SEM.

3. Results

Constant 20 N load diamond tip scratches and indentations of 1.6 mm diameter WC-Co hard-metal ball with a load of 60 kg on the steel and nitrided steel surfaces were used to estimate the

Table 1
Composition and hardness of AISI316 and ACS steels.

Element, wt%	C	Cr	Ni	Mo	Si	Mn	Fe	HV0.05
AISI316	0.06	17.20	11.70	2.20	0.60	1.30	Bal.	230
ACS	0.77	1.2	–	–	0.45	0.78	Bal	310

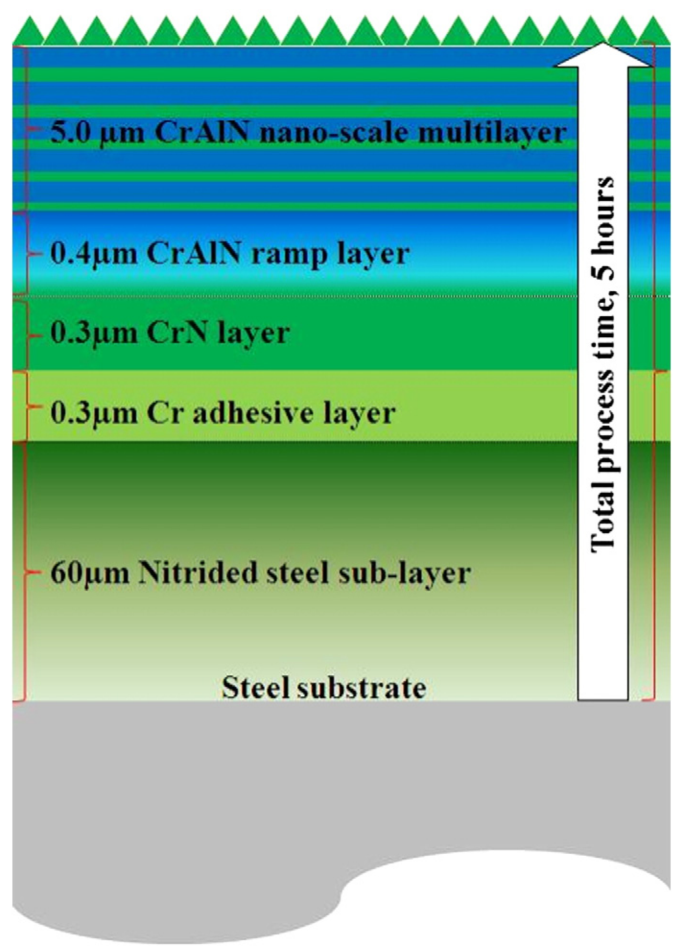

Fig. 1. Schematic diagram of a single batch duplex treatment.