

# Modification of Silicon Nitride Coated Steel Surface Hardness by Plasma-Flame Heat-Treatment

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## Abstract

In this work, the hardness of steel surface was introduced before and after coating with silicon nitride layer with heat treatment from 300 to 1000 °C. The silicon nitride was deposited on the steel surface by spray pyrolysis and heat treatment was carried out by high-energy plasma flame hitting the workpiece and scanning the surface. Maximum hardness of 1750 HV was achieved for the steel surface coated with silicon nitride and heat treated at 600 °C. An ideal balance between nanocoating hardness and enhanced adhesion in the interface region was observed as the steel substrate is kept safe from thermal or mechanical deformations.

**Keywords:** Steel surface; Silicon nitride; Vickers hardness; Plasma-flame heat treatment

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## 1. Introduction

Steel surfaces hardened by surface treatment, coated with chromium, or nitridized are intensively used in industrial and engineering applications due to their superior ability to provide optimum solutions for compensation between internal toughness, wear resistance, and surface friction [1-3]. In automobile industry, heat-induced nitridization are used to treat pistons, gearbox, hanging components in order to lengthen their lifetime under severe dynamic loading conditions and continuous friction [4-6].

In gas turbines and nuclear plant components, the hardened surfaces protect the rotating and sensitive parts from wear at high temperatures and pressures and hence guarantees safety and operational effectiveness [7-9]. They are also important in medical sector in orthopedic surgery instruments and artificial joints as they provide stainless, tough and biocompatible surfaces [10-12]. Accordingly, the hardened steel surfaces are not merely a technical modifications but a strategic investment to ensure machine reliability, reduce overall life costs by replacement, support innovation via much more complex and durable designs [13-15].

Practical hardening techniques are various and classified into three main categories: thermal, thermochemical, and mechanical. In typical thermal technique, the surface is rapidly heated and cooled to convert the microstructure into martensitic to limited depth while the internal structure of the metal is unchanged [16]. In typical chemical nitridation, the steel surface is subjected to activated nitrogen at

temperatures 500-550 °C to create a solid surface layer of ferrous nitrides without deformation [17]. Another technique for surface hardening is the deposition of ultra-high hard coating on the original surface. Coatings like nanostructured silicon nitride ( $\text{Si}_3\text{N}_4$ ) with several micrometers thickness made a revolutionary advancement in steel surface protection and hardening [18]. Vickers hardness up to 2500-3500 HV can be achieved, which is comparable to the hardness of some advanced ceramics, while such enhancement does not reduce the toughness of steel surfaces to keep their capability to absorb deformation energies without degradation [19]. Silicon nitride nanocoatings show excellent thermal and chemical stability as they maintain their properties and resist oxidation at temperatures up to 1200 °C in inert atmosphere. This reasonable reduce the wear and friction between surfaces and hence increase their functional lifetime [20-22]. Silicon nitride nanocoatings are seen as a new generation of smart solutions to support the performance of steels to limits not achieved before throughout the optimum compensation between extreme hardness, toughness, and stability under harsh conditions [23-25].

In this letter, the Vickers hardness of steel surface was introduced before and after coating with silicon nitride layer with heat treatment from 300 to 1000 °C.

## 2. Experimental Part

The plasma-flame heat treatment is a developed and promising technique to enhance the properties of thin coatings, such as  $\text{Si}_3\text{N}_4$  deposited on steel

surface. In this system, inert gas (mostly argon) is pumped through high-energy arc discharge to produce highly-activated thermal plasma, whose temperature is ranging within 8000-15000 °C. This plasma injected at high flow rate through a cooled nozzle towards the coated surface. As this energetic concentrated flame hits the surface, some complex physical and chemical reactions occur. Thermally, a very rapid heating localized within thin layer of coating can cause recrystallization, closing micropores, and redistribution of nanoparticles within the coating, and hence much denser and more cohesive structure is produced. Chemically, the reaction between activated plasma and silicon nitride coating can modify the Si/N ratio on the surface, support the atomic bonds, and may form a transition layer between steel surface and coating. This sufficiently enhances the adhesion of the coating on the surface, which is a critical drawback in many coating processes.

This technique shows several advantages over conventional treatment techniques. First, the high concentration of heat allows localized and ultra-fast processing, therefore, the bulk may not be affected and mechanical properties of steel are kept from degradation. Second, the dynamic pressure resulted from plasma injection contributes to merging the coating and increase its density. Third, flexibility to control processing parameters, such arc energy, scanning speed, nozzle distance, and gas composition, allow the highly-accurate adjustment of the final characteristics of the coating to satisfy the requirements of specific application.

As shown schematically in Fig. (1), the steel substrate (workpiece) is coated with a layer of silicon nitride by spray pyrolysis. The dc potential is applied between the steel substrate and tungsten electrode inside the nozzle assembly. The plasma gas (argon) is pumped into the inner channel surrounding the tungsten electrode, while the shielding gas (inert nitrogen) is pumped into the outer channel to isolate the treated region from the atmosphere.

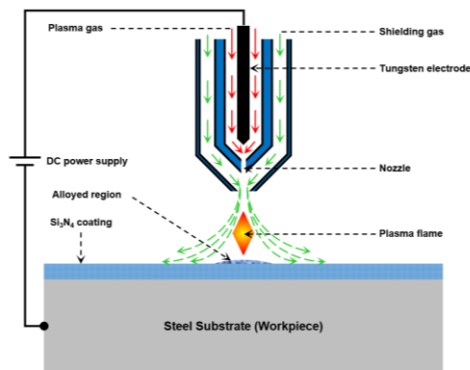


Fig. (1) Schematic diagram of the experimental setup

The scanning electron microscopy (SEM) image in Fig. (2) shows apparently the modified microstructure of the coating after heat treatment. An alloyed layer of 1 μm thickness is formed directly below the silicon nitride coating throughout diffusion and thermal reaction between coating components and steel surface to support the adhesion reasonably. Finally, a heat-affected zone (HAZ) of about 1.4 μm thickness is observed in the fundamental steel surface as the microstructure is modified without melting to keep the surface toughness. These integrated regions explain the overall enhanced mechanical performance of the surface.

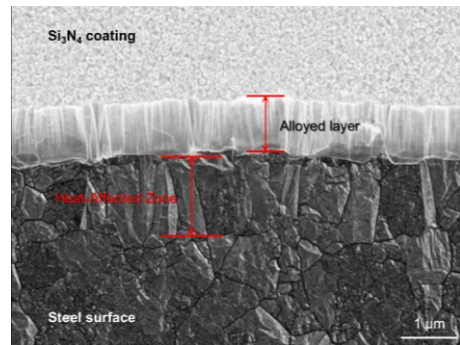


Fig. (2) A microscopic image of the photonic crystal cavities based on multimode nanobeams fabricated in this work

### 3. Results and Discussion

Figure (3) shows the Vickers hardness (HV) of the steel workpiece before and after coating with Si<sub>3</sub>N<sub>4</sub> layer and heat-treated with plasma flame. Reasonable enhancement in the mechanical properties of the surface can be achieved as an ideal relationship between temperature and performance is shown. At 300 °C, the hardness increases from 180 HV for uncoated surface to 780 HV for coated surface. This reveals the relative effectiveness of coating and treatment at low temperatures. With increasing treatment temperature, the hardness is continuously enhanced to reach its peak of 1750 HV at 600 °C, i.e., 10 times higher than the initial value. This means that the temperature of 600 °C is the optimum for the steel-coating-plasma system as it results in complete recrystallization and ideal diffusion. As well, a tough, homogeneous, transition alloyed layer may be formed with a limited and brittle-resistant heat-affected zone (HAZ).

Beyond 600 °C, a gradual but sharp decrease in hardness is observed with increasing treatment temperature, from 1350 HV at 700 °C through 950 HV at 800 °C to 650 HV at 1000 °C. The silicon nitride coating may start to dissociate or oxidize and hence lose its cohesive and density. On the other hand, the excess diffusion of elements at the coating-substrate interface may lead to form brittle or bubble phases those weakens the adhesion and cause micro-

cracks. Also, the HAZ region reasonably extends in the fundamental steel substrate, which may cause the grain growth and weaken the microstructure. The plasma-flame heat treatment at 600 °C shows an ideal balance between nanocoating hardness and enhanced adhesion in the interface region as the steel substrate is kept safe. Any deviation from this optimum point – either lower or higher – leads to retract the performance of the integrated surface system. This confirms the significance of fine control of heat treatment parameters to achieve the maximum technological advantages of this advanced technique.

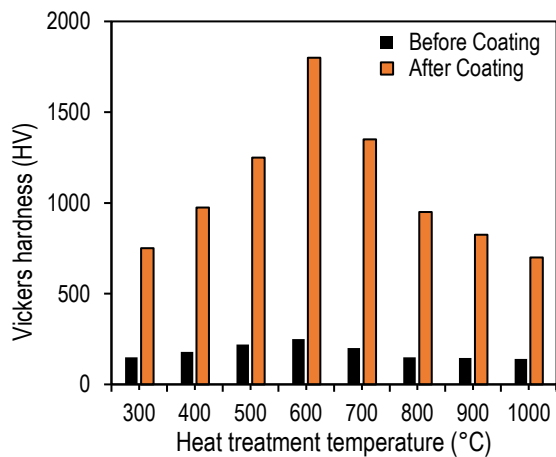


Fig. (2) Spatial distributions of transverse-electric (TE) modes of multimode nanobeam waveguide (750nm width and 400nm thickness) at 940nm wavelength

#### 4. Conclusion

In concluding remarks, this work showed that the heat treatment with plasma flame at 600 °C can enhance the hardness of steel surface coated with silicon nitride layer to reach a maximum of 1750 HV, which is an order of magnitude higher than that of untreated surface. At this temperature, an ideal balance between nanocoating hardness and adhesion to the substrate at the interface region while the thermal and mechanical deformations in the steel substrate were avoided. Lower and higher treatment temperatures showed lower values of hardness due to coating degradation or brittle phase formation within the interface region. Consequently, the accurate control of heat treatment parameters is significant to achieve the maximum advantages of this hardening technique.

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