# Wear Resistance of Plasma and Pulse Plasma Nitrided Gears

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**Summary**

In this study, wear behavior of plasma and pulse plasma nitrided gears, made from 42CrMo4 steel, was evaluated under a lubricated sliding and pitting wear regime. The nitrided samples were fully characterized before and after wear testing using metallographic, microhardness and surface examination techniques. Sliding wear tests were carried out on a pin-on-disc machine in which hardened ball-bearing steel discs were mated to nitrided pins. Pitting wear tests were performed using the standard FZG machine with C-type gears. (FZG refers to the Gear Research Centre, a part of the Institute for Machine Elements at the Technical University of Munich, Germany.)

Also, economic evaluation and comparison of hardening and plasma nitriding processes were carried out. The test results indicate that sliding wear resistance and, even more so, pitting wear resistance of 42CrMo4 steel gears can be greatly improved by means of plasma and pulse plasma nitriding.

**Introduction**

Traditionally, gear manufacturers employ techniques such as carburizing, flame hardening, induction hardening, and gas nitriding to increase the strength of gearing components. While carburizing is the most common and effective surface hardening method used to improve load-carrying capacity of gears, the technique has shown substantial difficulties in the production of large gears (Ref. 1). The quench hardening from a high austenitizing temperature often results in unpredictable levels of tooth deflection, helix angle change, and overall distortion (Ref. 2).

During conventional gas and bath nitriding, a multiphase compound layer is formed on the nitrided surface (Ref. 3). This layer contains high internal stresses in the transitional regions between the various lattice structures, which make the layer brittle and can cause it to spall off in service. Such layers are clearly undesirable and hence have to be removed from load-carrying surfaces before the gears can be used in service (Ref. 4).

One of a new generation of heat treatment processes that has been employed to improve the performance characteristics of gears is plasma nitriding (Refs. 5 and 6). Plasma nitriding, an environmentally clean method of nitriding, permits a fully automated and controlled nitrogen-diffusion process, which makes it possible to perform nitriding without a compound layer formation (Ref. 7). Furthermore, the low temperatures used in plasma nitriding and the absence of a quenching requirement assure

**Table 1—Details of the Heat Treatment Processes.**

| Process | Gas mixture | Temp. (°C) | Time (hrs.) | Pulse (sec.) |
|---|---|---|---|---|
| Through Hardening | oil quenched | 870/180 | 2/1 | — |
| Plasma Nitriding | 99.4% $H_2$, 0.6% $N_2$ | 540 | 17 | — |
| Pulse Plasma Nitriding | 99.4% $H_2$, 0.6% $N_2$ | 540 | 17 | 0.48/0.02 |

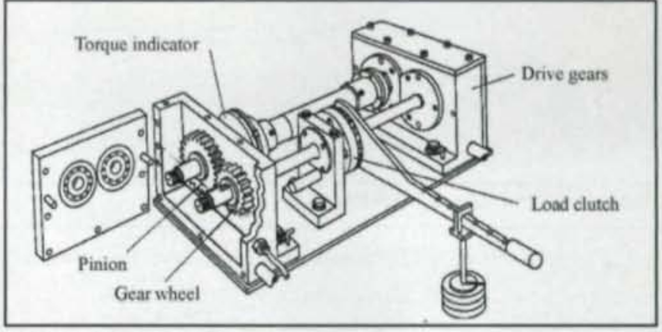


**Figure 1—FZG gear test rig.**

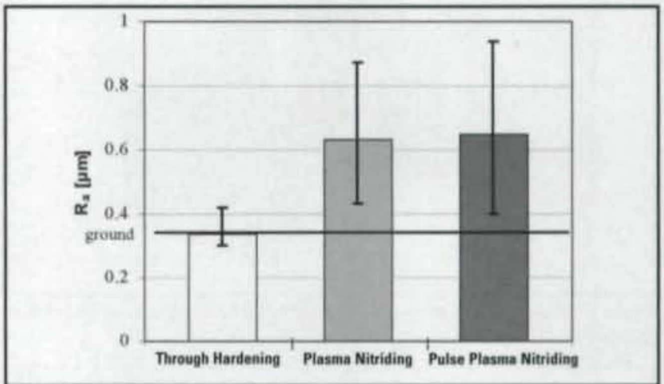


**Figure 2—Surface roughness.**

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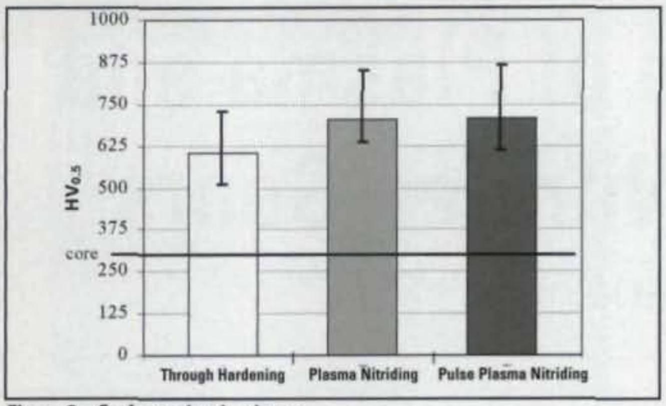


**Figure 3—Surface microhardness.**

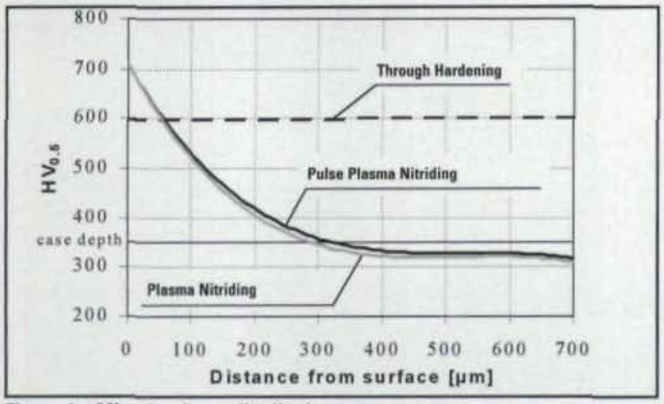


**Figure 4—Microhardness distribution.**

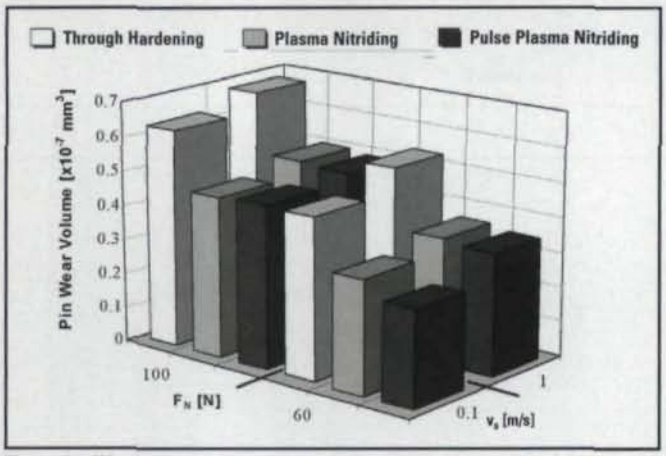


**Figure 5—Wear volume of heat treated pins as a function of load and sliding speed.**

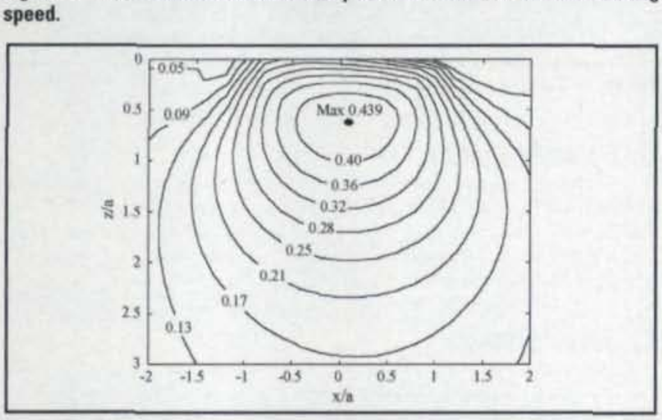


**Figure 6—Principal shear stress distribution ($\tau/p$) of tested gears ($\mu = 0.1$, T = 239.3 N-m, contact radius a = 0.20 mm, contact pressure p = 1,125 N/mm²).**

minimal distortion and dimensional variations (Ref. 8).

Therefore, by using plasma nitriding, the need for a subsequent grinding operation can be reduced or even eliminated. More advanced pulse plasma technology, employing pulse duration and duty cycle control, allows the use of the smallest amount of plasma power for the process to prevent overheating and to ensure uniform temperature distribution. Furthermore, almost every type of steel can be nitrided using a pulsed plasma technology (Ref. 9).

### Experimental

The material used in the present investigation was commercial structural steel for hardening and nitriding, 42CrMo4 (0.5%C, 1.0%Cr, 0.2%Mo). After the specimens (pins and gears) were machined from hardened and tempered bars (300 $HV_{0.5}$), they were ground ($R_a \approx 0.4$ μm) and degreased before plasma nitriding.

The specimens were nitrided in a commercial, sensor-controlled plasma nitriding furnace. Plasma nitriding was carried out with precise control of all process parameters, under plasma and pulse plasma mode, to form a nitrided case with a nitriding depth of ≈0.3 mm and surface structure without a compound layer (Table 1), which was realized using low nitrogen content in the plasma (Ref. 10). For comparison purposes, one group of specimens was also hardened (oil quenched and tempered at 180°C), ground to a surface roughness of ≈0.35 μm.

Stylus profilometry was used to analyze surface roughness and topography of thermochemically treated specimens. Surface hardness and subsurface hardness distribution were measured using a Vickers microhardness tester at a 50 g indentation load.

Sliding wear resistance of heat treated flat-ended pins (ϕ 2 mm) was determined on a pin-on-disc machine. The pin was loaded against a rotating ball-bearing steel disc, hardened to 700 $HV_{0.5}$ and ground to an average roughness value of ≈0.4 μm. Lubricated sliding wear tests (non-aditivated ISI VG68 oil) were carried out at room temperature (≈20°C) and relative humidity of about 50%, sliding speeds of 0.1 m/s and 1 m/s and normal loads of 60 N and 100 N. Wear tests were stopped after 2,000 m of sliding.

Pitting wear tests were performed using the standard FZG machine (Fig. 1) with the C-type gears. A detailed description of the test rig is given by Winter and Michaelis (Ref. 11). The same heat treatment process was used for the pinion and the gear wheel. Heat treated gears were lubricated by formulated gear oil ISI VG68. Pitting wear tests were carried out as a two-step process at an oil temperature of 90°C. After a running-in sequence (2 hrs. at 94.1 N-m—stage 5), the test was run at 239.3 N-m torque (stage 8) until pitting failure occurred. The failure criterion was the occurrence of a pitted area on one pinion tooth greater than 4% of the tooth's area.

### Results—Surface Properties

After nitriding, both the average roughness value $R_a$ and the maximum peak-to-valley height $R_{max}$ increased when compared with the original ground surface. The average roughness of the original surface changed from 0.35 µm to approximately 0.65 µm, measured for plasma and pulse plasma nitrided specimens. Pulse plasma nitriding, however, was found to cause larger scattering of the results, as shown in Figure 2.

Characteristic surface microhardness of heat treated 42CrMo4 steel is shown in Figure 3. Compared to hardening with the highest obtainable surface hardness of ≈600 $HV_{0.5}$ and a constant hardness over hardened zone (≈1 mm), plasma nitriding increased the surface hardness of investigated steel to approximately 700 $HV_{0.5}$. For both plasma nitriding techniques, the hardness decreased gradually with increasing distance from the surface (Fig. 4). Comparison of plasma and pulse plasma nitrided 42CrMo4 steel showed larger scattering of the surface hardness values in the case of pulse plasma nitrided specimens (Fig. 3). Furthermore, pulse plasma nitriding was found to produce almost the same nitriding depth (0.3 mm) compared with plasma nitriding, as shown in Figure 4.

**Wear Properties—Pin-on-Disc Test**

From the pin-on-disc tests, it was found that, under all testing conditions, the coefficient of friction was largely independent of differences among heat treatments used in this study. In all cases, the coefficient of friction was in the range of 0.15. Figure 5 shows wear volume of heat treated pins as a function of heat treatment, test load and sliding speed after 2,000 m of lubricated sliding. Depending on the testing conditions, plasma and pulse plasma nitriding were found to improve sliding wear resistance of 42CrMo4 steel by 30–40% as compared to hardening (Fig. 5), which is in agreement with earlier results (Refs. 12–14). However, comparison of plasma and pulse plasma nitriding showed no noticeable difference in wear of plasma and pulse plasma nitrided pins, as shown in Figure 5.

**FZG Test**

Contact stresses of tested gears (pitch point C) were calculated using Hertzian equations (Ref. 15), taking into account coefficient of friction, measured on pin-on-disc machine ($v_s$ = 1 m/s, $F_N$ = 60 N), and load conditions and geometry of testing gears. As shown in Figure 6, maximum principal shear stresses of tested gears are located ≈0.12 mm below the surface, which for nitrided gears is inside the nitrided zone. However, in the case of highly loaded gears, longer nitriding times should be used in order to obtain larger nitriding depths and adequate strength of the material (Refs. 5 and 16).

The results of the pitting wear tests are shown in Figure 7. Plasma nitrided and pulse plasma nitrided 42CrMo4 steel gears showed greatly improved pitting wear resistance as compared to hardened steel gears. In the case of hardened gears, pitting failure occurred after ≈2 million cycles. Nitriding increased pitting wear resistance of 42CrMo4 steel by a factor of 5. The increase can be attributed to the combination of a high surface hardness, a fine surface microstructure and a tough core obtained by nitriding. As in the case of sliding wear tests, plasma and pulse



plasma nitriding give very similar pitting wear resistance to the investigated steel, as shown in Figure 7.

## Economic Evaluation

In order to complete the comparison of hardened and plasma nitrided gears, calculation of production and replacement costs was carried out on a medium-sized gearbox (gear outer diameter of ≈100 mm and tooth width of ≈20 mm), as an example. This calculation was carried out with the assumption that, due to pitting failure, hardened gears have to be replaced at least once during use of an industrial gearbox. Furthermore, analysis of maintenance in Slovenian companies revealed that, in the case of medium-sized gearboxes, replacement of a gear takes approximately six hours.

Figure 8 shows treatment costs per unit for induction hardened, through hardened and plasma nitrided gears as a function of number of treated gears. In all cases, treatment costs decrease with increasing numbers of gears to be treated, as expected. However, by increasing the number of gears (> 100), plasma nitriding became more profitable compared with hardening (Fig. 8). Another very important cost-saving advantage of plasma nitriding is the fact that gears of different sizes and shapes can be nitrided at the same time.

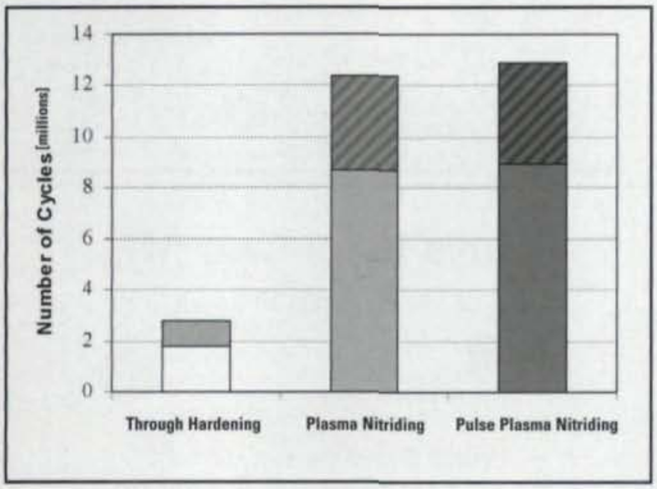


**Figure 7—Pitting wear resistance of heat treated gears. (The top segments of the bars represent scattering of the results.)**

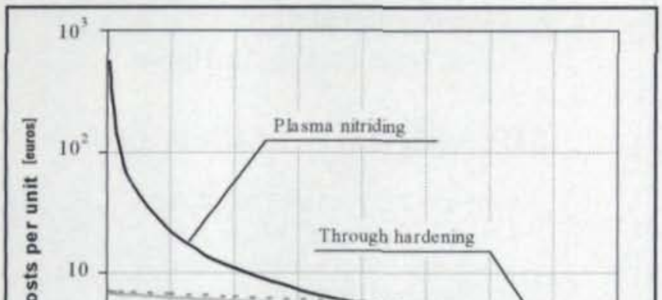


**Figure 8—Heat treatment costs per unit as a function of number of treated gears.**

By taking into account the results of pin-on-disc and FZG tests, as well as production and replacement costs, the following evaluations can be made:

1.) In the case of special, small-volume gears (< 10), changing from hardened to plasma nitrided gears may not be profitable. However, in the case of specialized gears, production of gears represents the main part of overall costs. Therefore, prevention against gear failure represents the main criterion for heat treatment selection.

2.) In the case of larger volumes (> 100), changing from hardened to plasma nitrided gears represents a cost reduction of up to 50%. For highly loaded gears, this reduction can be even higher, since plasma nitriding gives up to five times better pitting wear resistance compared with through-hardened gears (Fig. 7).

## Conclusions

The combination of a high surface hardness, a fine surface microstructure and a tough core, obtained with plasma nitriding, leads to favorable tribological properties in nitrided steel. Pin-on-disc and FZG wear test results show that, compared with hardening, plasma and pulse plasma nitriding can greatly improve sliding wear resistance and—even more so—pitting wear resistance of 42CrMo4 steel gears.

Depending on the production quantity, both types of plasma nitriding can be rather expensive. However, changing from hardened to plasma nitrided gears reduces the probability of gear failure, and therefore leads to a reduction of overall costs connected with the gear replacement and cessation of production. ○

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### References

1. Albertin, L., R.L. Frohlich, H. Winter, B.-R. Höhn and K. Michaelis. "Load carrying capacity of nitrided steel gears" (94FTM4), American Gear Manufacturers Association Fall Technical Meeting, St. Louis, MO, October 1994.

2. Fronius, S. *Maschinenelemente*, VEB Verlag Technik, Berlin, 1971.

3. Karamis, M.B. "Tribological behaviour of plasma nitrided 722M24 material under dry sliding conditions," *Wear*, Vol. 147, No. 2, 1991, pp. 385–399.

4. Arques, J.L., and J.M. Prado. "The dry wear resistance of a carbonitrided steel," *Wear*, Vol. 100, 1985, pp. 321–332.

5. Roelandt, A., J. Elwart and W. Rembges. "Plasma nitriding of gear wheels in mass production," *Surface Engineering*, Vol. 1, No. 3, 1985, pp. 187–191.

6. Bell, T. "Towards designer surfaces," *Industrial Lubrication and Tribology*, Vol. 44, No. 1, 1992, pp. 3–11.

7. Lampe, T., S. Eisenberg and G. Lauden. "Compound layer formation during plasma nitriding and plasma nitrocarburising," *Surface Engineering*, Vol. 9, No. 1, 1993, pp. 69–76.

8. Karamis, M.B. "Friction and wear behaviour of plasma-nitrided layers on 3% Cr-Mo steel," *Thin Solid Films*, Vol. 203, No. 1, 1991, pp. 49–60.

9. Huchel, U., J. Crummenauer, S. Stramke and S. Dressler. "Pulsed plasma nitriding and combined processes," *Proceedings of the 5th World Seminar on Heat Treatment and Surface Engineering* (IFHT'95), Isfahan, Iran, 1995, pp. 329–335.

10. Sun, Y., and T. Bell. "Modeling of the plasma nitriding of low alloy steels," Developments in the nitriding of iron and titanium based alloys, Royal Society London, London, U.K., 1995.

11. Winter, H., and K. Michaelis. "FZG Gear Test Rig—Description and test possibilities," CEC 2nd International Symposium of Performance Evaluation of Automotive Fuels and Lubricants, Wolfsburg, Germany, June 1985.

12. Podgornik, B., J. Vizintin and V. Leskovsek. "Dry sliding wear characteristics of induction hardened, conventional plasma nitrided and pulse plasma nitrided AISI 4140 steel," *Proceedings of the COST 516 Tribology Symposium*, Espoo, Finland, May 1998, pp. 369–379.

13. Podgornik, B., J. Vizintin and V. Leskovsek. "Wear properties of induction hardened, conventional plasma nitrided and pulse plasma nitrided AISI 4140 steel in dry sliding conditions," *Wear*, Vol. 232, No. 2, 1999, pp. 231–242.

14. Podgornik, B., J. Vizintin and V. Leskovsek. "Sliding wear characteristics of induction hardened, conventional plasma nitrided and pulse plasma nitrided structural steels," *Proceedings of the 2nd COST 516 Tribology Symposium*, Antwerp, Belgium, May 1999, pp. 171–179.

15. Johnson, K.L. *Contact Mechanics*, Cambridge University Press, Cambridge, U.K., 1985.

16. Karamis, M.B. "Experimental study of the abrasive wear behaviour of plasma nitrided gearing steel," *Wear*, Vol. 161, 1993, pp. 199–206.