A 100 kV/200 A Blumlein Pulser for High-Energy Plasma Implantation

José O. Rossi, *Member, IEEE*, and Mário Ueda

***Abstract*—A high-voltage pulsed power supply of 100 kV/200 A with output short pulses of the order of 1 μs (based on stacked coaxial Blumlein technology) was developed for use in surface treatment of materials by plasma implantation. The plasma implantation process requires pulse repetition and the authors' device is capable of operating at a frequency range of 10–150 Hz, depending on the level of the output voltage. Herein, the authors show that nitrogen–ion species were implanted into stainless steel surfaces (SS304) at high energies (> 30 keV) by using this pulser, inducing α phase as demonstrated by X-ray diffraction diagnostic. Moreover, microhardness tests of these treated samples have shown an improvement of about 13.0% for the surface hardness factor.**

***Index Terms*—Blumlein pulser, hardness factor, nitrogen, plasma implantation, stainless steel (SS), surface treatment.**

I. Introduction

PLASMA immersion ion implantation (PIII) is a technique developed during the 1980s that consists of applying a negative high-voltage pulse to a target immersed in a gaseous ionized medium called plasma [1]. In this way, ions are accelerated by the electric field formed between the plasma sheath and the target and implanted into the surface to be treated. To explore new operating regimes in surface treatment by plasma implantation, high-voltage pulses of about 100 kV are needed. High-energy ion implantation is essential to obtain great depth of penetration of ion species into surface of polymers and metals, which increases the hardness factor and wear resistance of several components used in industry. Recent studies [2] conducted by our group showed a great potential of plasma implantation treatment on the enhancement of mechanical properties of ultrahigh molecular weight polyethylene, a type of polymer widely used in prosthesis devices. The results so obtained demonstrated that implanted high-energy ions could lead to the formation of a more rigid structure on polymer surface identified as diamondlike carbon. Another application that requires high voltage is the implantation of N into Al alloys to form a layer of aluminum nitride (AlN) on Al surface for improvement of its hardness and corrosion resistance [3]. The reason for using such high energy in this case is due to the growth of an oxide layer (formed during or before the plasma implantation process) that hinders an effective penetration of the N ion when voltages less than 30/40 kV are applied. Another area to be explored is the nitrogen plasma implantation with high-energy ions (> 30 keV) in titanium and SS surfaces, although good tribological properties of N_2 implanted surfaces have been reported using much lower implantation voltages [4], [5] in the range of 3–10 kV. Therefore, for all the mentioned applications, we developed a high-pulse generator of 100 kV/200 A made from pieces of transmission lines. The pulser construction was based on stacked Blumlein technique [6], [7] rather than on conventional hard tube/pulse transformer technologies normally employed in PIII processes [8]. Since Blumlein pulser technology (as described in this paper) was mostly used in submicrosecond generation of high voltages in several areas such as X-ray generation, breakdown tests, etc. [9]–[11], the objective of this paper is to demonstrate the use of Blumlein pulsers mainly in nitrogen–ion implantation in the microsecond range with high-energy ions (> 30 keV). Extremely long cables are needed for these pulsers in microsecond pulse generation, so we decided to work with the minimum pulse duration required by PIII processes of $\sim$1.0 μs. In particular, we report that satisfactory nitrogen plasma implantation with 30-kV/1.0-μs pulses was obtained, as the measured hardness factor of stainless steel (SS) surfaces (SS304) increased by 13.0%, when compared with nontreated samples. Moreover, the presence of N_2 in the crystalline structure of the treated surfaces is evidenced using high-resolution X-ray diffraction (XRD) by the α-phase formation in the γ austenistic phase of the iron crystalline structure.

II. Single Switch Blumlein

A. Principle of Operation

Fig. 1 shows the circuit configuration of our Blumlein pulser that uses ten coaxial lines and only one switch. In the initial state, all lines are positively charged by a dc charging voltage V^+ via a current limiting resistor R, but the net output voltage is zero as shown by the initial opposed voltage vectors of the active (left) and passive (right) lines (see Fig. 1). The active lines are used to produce the vector inversion while the passive lines are only for the charging storage. As soon as the switch is closed, pulse voltages propagate along the active lines from the switch side to the right. After one propagation delay time, they convert the initial vector opposition to a series addition as shown in Fig. 1, persisting twice the line propagation time. Ideally, this would lead to an output voltage of NV for an open end or else $NV/2$ for the case of the load NZ_0 matched to the generator output, where N is the number of lines and Z_0

Manuscript received September 1, 2005; revised April 4, 2006. This work was supported by the State of Sao Paulo Research Foundation (FAPESP) SP, Brazil, under Grants Contracts 00/11114-7 and 01/12746-0, and also by the Brazilian funding agencies [Ministério da Ciência e Tecnologia (MCT) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)].

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Digital Object Identifier 10.1109/TPS.2006.881305

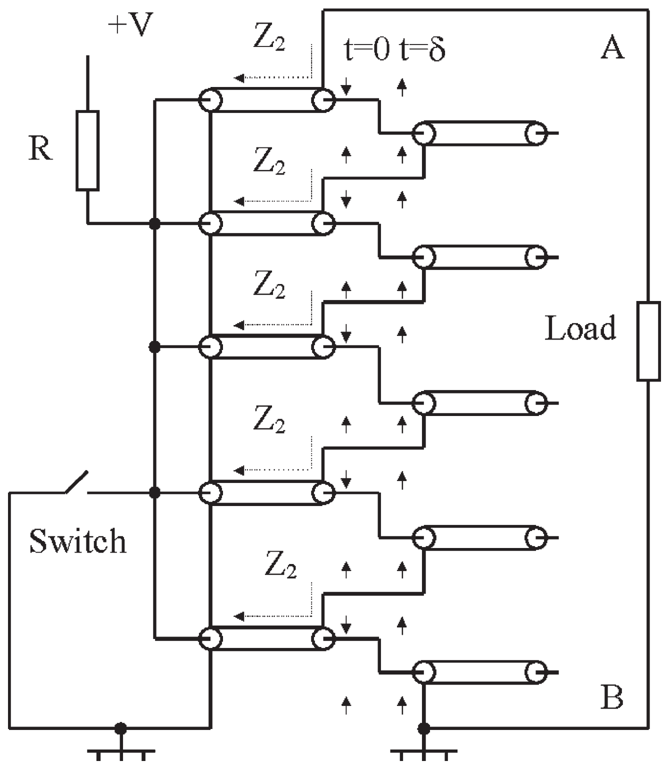

Fig. 1. Blumlein pulser made of ten coaxial lines.

is the line characteristic impedance. However, the shield cable impedance (represented by Z_2 in Fig. 1) has an adverse effect that reduces the output current by draining a fraction of it from the load, which causes the pulse droop. The potential difference between the shields of the top and bottom cables (points A and B) gives the output voltage and the potential along the cable shields floats. As soon as the voltage at each stage output is erected, the voltage potentials on passive lines shields are increased. For active lines, as they are grounded at the input, the shield-distributed inductance avoids short circuit between the input and output of the cable shields. The cables are also kept sufficiently apart to avoid isolation problems and mutual inductance between them. For a wound cable, the shield cable impedance of each active line can be considered as a lumped-impedance $Z_2 = sL$, where L is the cable inductance and s the Laplace operator. Therefore, increasing the shield inductance L so that $sL \gg Z_0$, by winding the cable on a coil former, reduces the drained current from the output and, consequently, minimizes the overall power loss of the device.

B. Blumlein Device

Our Blumlein device was constructed with the following design parameters: 150 kV/300 A with pulse duration of 1.0 μs. The pulser load of 500 Ω required a design with ten pieces of a 50-Ω coaxial cable (or five stages). To ensure a high breakdown voltage, we chose the coaxial cable URM67/50 Ω with the maximum rating of 40 kV. Considering a pulser with ten lines (i.e., with an ideal gain of $N/2 = 5$) and output nominal voltage of 150 kV gives a maximum charging voltage of 30 kV, hence below the cable breakdown voltage. The length of each transmission line was 100 m, and as the selected cable URM67 has a

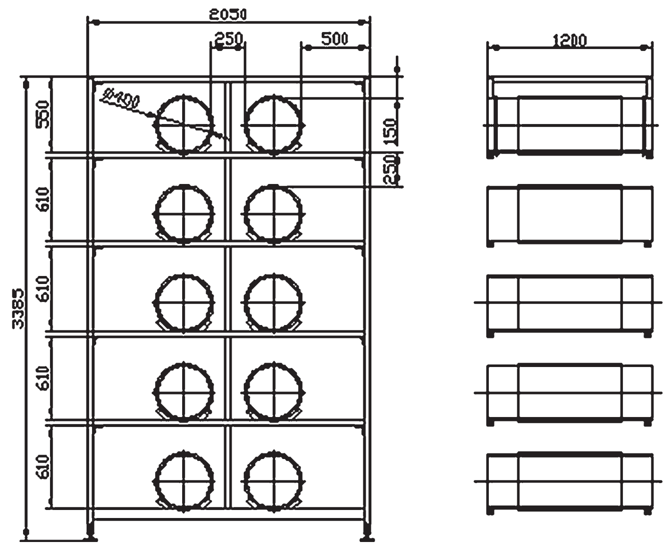

Fig. 2. Cross-sectional view of the pulser.

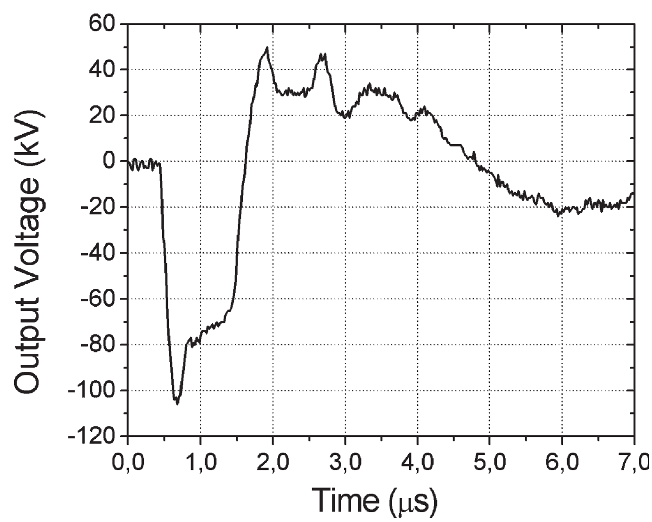

Fig. 3. Maximum peak voltage obtained of 100 kV.

double transit time of 10 ns/m, this implies a pulse duration of 1.0 μs. To increase the device gain efficiency, the coaxial lines were wound around PVC cylindrical tubes of 400-mm diameter in order to increase the shield cable inductance as shown in Fig. 2. By using an L-C bridge meter, we obtained a shield cable inductance of about 1.0 mH for each coaxial coil. To charge the coaxial cables, we used a compact switched mode power supply with negative polarity and maximum charge rate of 8.0 kJ/s. For the switching system, a thyratron tube with voltage/current ratings of 35 kV/5kA was used. Due to the operation with negative polarity, 60-kV isolation transformers were used for the driver/heating systems of the thyratron tube.

According to our design, the output pulse should be able to reach an output voltage of 150 kV. Nevertheless, in practice, corona discharges (between metallic structure and connections) have limited the level of the output voltage up to 100 kV. Increasing the output voltage beyond this level requires improvements on the output connection isolation. Fig. 3 shows the output voltage with amplitude peak of about 100 kV across a noninductive resistive load of 500 Ω for a charging voltage

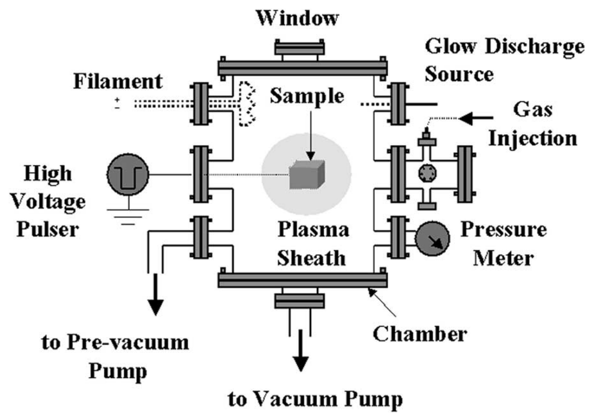

Fig. 4. Experimental setup used for the PIII system.

of the order of 20 kV. The pulse response is oscillatory with decreasing amplitude in time and droop rate in the middle part of 30% caused by the mismatch of the shield cable inductance. The overshoot in the rising/falling portions of the pulse are also explained taking into account the stray inductance and capacitance at the input switch connections as described elsewhere [12]. Another problem that worsens the corona effect is the device operation at a certain repetition rate. This is an important pulser characteristic to be evaluated since plasma implantation process requires at least frequencies of the order of 50/60 Hz. Beyond these frequencies, corona discharge has limited the pulser operation for voltages in excess of 60 kV. From this voltage up to 100 kV, the device was operated at a lower repetition rate, between 1 and 10 Hz.

III. High-Energy Implantation Experiment

The experimental setup used for the PIII treatment is depicted in Fig. 4. The sample to be treated was put inside a SS vacuum chamber (with a diameter of 58 cm and length of 68 cm) on an electrode support connected to the high-voltage pulser and immersed in nitrogen plasma. The vacuum base pressure for the plasma production (provided by one turbomolecular pump installed at the bottom of the vacuum chamber) was around 8.0×10^{-6} mbar with a typical working pressure of about 5.0×10^{-3} mbar. We produced the plasma by means of a dc glow discharge using an electric shower made of an ac heated tungsten filament and a dc power supply with maximum voltage/current capability of 1 kV/1 A. To start the glow discharge and reduce plasma potential, we adjusted the filament for an ac voltage of about 11 V under a dc power supply voltage of 350 V applied between a 0.5-cm diameter second electrode (made of SS) and a cylindrical flange neck with inner radius of 27 cm connected to the vacuum chamber. As soon as the discharge is produced, the plasma potential is lowered down to 100 V and the plasma current is limited up to 0.5 A by an external resistance of 500 Ω in series with dc power supply. In this way, surface sputtering was reduced using a low value of plasma potential and the implantation process was not compromised. A glass window at the top of the chamber was used to check the plasma production as indicated by a pink luminescence emitted from the nitrogen glow discharge.

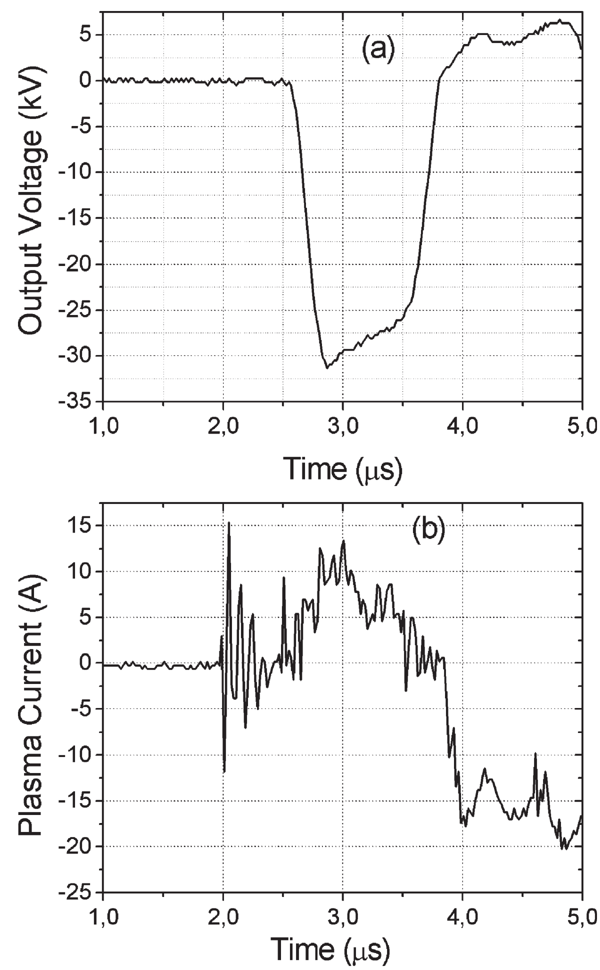

Fig. 5. Output voltage obtained at the (a) sample holder and (b) plasma current.

IV. Results

For the PIII treatments with plasma loads, we started the pulser operation with the lower voltage limit of the order of 30 kV. Moreover, we kept the high-voltage resistive load of 500 Ω (used in the initial tests) to limit the output current since severe arcs are very frequent inside the plasma chamber during the implantation process. In this stage, we used in the treatment only samples made of stainless steel (SS304) with an exposure time of approximately 1 h. Fig. 5(a) and (b) shows the first pulser waveforms obtained during the PIII processing at a repetition rate of 100 Hz. The top curve represents the output voltage obtained at the electrode of the sample holder with pulse duration of the order of 1.0 μs (as expected) and pulse rise/fall time measured of 300 ns. As mentioned in the last section, the pulse rise time limitation can be explained taking into account the stray inductance and capacitance [12] at the switch connections estimated to be of the order of, respectively, 700 nH and 5 nF. Moreover, we notice that the overshoot and droop rate (approximately 20% in this case) were reduced when compared with the 100-kV full voltage shown in Fig. 3. This is so because the plasma behaves nonlinearly, stabilizing the total load (plasma resistance plus 500-Ω load) at a higher value of the order of 2 kΩ. By modeling the nonlinear plasma nature as an electrical circuit composed of capacitors and resistances,

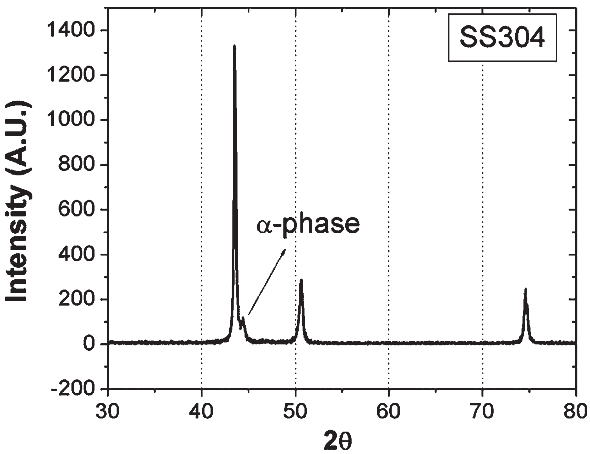

Fig. 6. XRD pattern of an SS304 surface nitrided in pure N_2, showing the induced α phase shifted to the right of the γ peak (intensity given in arbitrary units and 2θ angle in degrees).

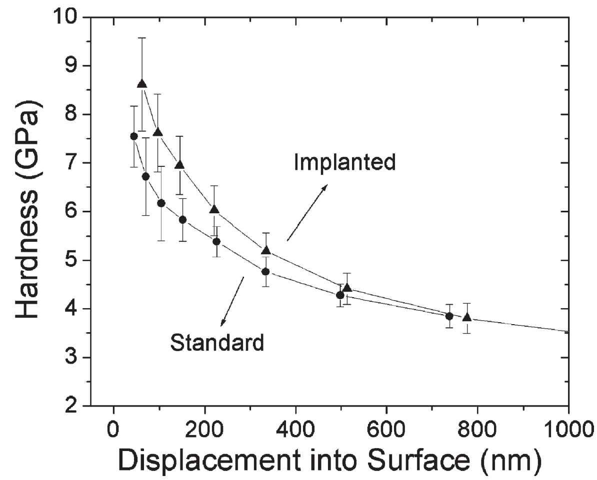

Fig. 7. Hardness profiles obtained for the implanted SS304 and standard (nontreated) samples.

and the Blumlein pulser made of ideal transmission lines, it is possible to check the droop rate and overshoot reduction of the output voltage in personal computer simulation program with integrated circuit emphasis [12]. The plasma current measured has a peak of nearby 15 A, as given by the bottom curve of Fig. 5(b). For this measurement, we used a current transformer installed at the pulser output with a current sensitivity of 10 mV/A. Unfortunately, the response is very noisy as shown by the high peaks of very short duration on the current curve beginning 500 ns before the appearing of the output pulse. This can be explained considering the electromagnetic interference (EMI) generated during the tube switching and the coaxial line delay of 500 ns for output pulse generation after switch triggering. A possible solution to avoid EMI would be the installation of the current meter in a screened metallic box.

To certify that implantation was successful by applying 1.0-μs pulses, XRD measurements of the nitrogen implanted SS304 samples were carried out, as shown in Fig. 6. For this, we used a Philips 3410 diffractometer in the Seeman–Bohlin 2θ mode. As indicated in Fig. 6, the PIII treatment has induced α-phase formation as indicated in the XRD by the small α-peak shifted by $\Delta\theta = 1.0^\circ$ approximately to the right from the ordinary $\gamma(111)$ peak at $\theta = 43.5^\circ$. Besides that, using a nanoindenter (with load varying between 20–200 gf) obtains an increase for the hardness factor of 13% when compared with that of nontreated samples as shown in Fig. 7. To confirm both results, Auger electron microscopy (AES) was performed to provide information on the concentration of the implanted atoms on the treated surface. This diagnostic indicated an atomic concentration peak of nitrogen–ions near 10% and a depth penetration less than 30 nm.

V. Conclusion

In this paper, we have demonstrated that high-energy implantation process works well by using Blumlein pulsers with short pulses of the order of 1.0 μs for implant voltages in excess of 30 kV. This is demonstrated by analyzing the nitrogen implantation effect on the XRD patterns and hardness profiles of several implanted SS304 samples.

In a near future, by applying higher voltages (from 50 up to 80 kV), we also expect to identify the presence of AlN compounds in Al5052 samples, which are essential for hardening the Al surface and improving its resistance against corrosion attacks. In this case, an interesting application would be the treatment components of jet aircrafts operating in marine environments [13]. Other important properties to be checked for the treated Al 5052 samples are the wear and the coefficient of friction. If wear of the implanted surface improves and its friction decreases after PIII treatment, we can envision a possible application of nitrogen implantation in Al pistons of bike/car suspensions, which are normally anodized to obtain lower friction coefficient and better wear factor.

Although the presence of α phase in the austenistic steel samples is already appropriate in some applications, we expect to obtain the harder γ_N modified austenistic phase by increasing the temperature sample, which enhances the ion depth penetration into the surface. Here, the idea is to use an extra ac heating filament in the sample holder to increase the temperature, since the present pulse repetition rate of the order of 100 Hz is limited by the 8.0-kJ/s maximum charge rate of the pulser charger. The hardening effect on surface must be evidenced by other type of XRD pattern showing the γ_N peak shifted to the left on the standard γ austenistic phase of the SS304 bulk and or by a higher concentration of nitrogen on the surface given by the AES spectroscopy (e.g., of 30% for ion atomic concentration peak and penetration depths < 600 mn). If the ac filament technique proves to be successful, this will open an excellent prospect for nitrogen plasma implantation in Ti alloys used in the fabrication of prosthesis of femoral knee articulation. In this case, the main goal is to obtain a harder surface with a lower coefficient friction to avoid a fast wear when the prosthesis is put in a biological medium [14], [15].

References

[1] J. R. Conrad, J. L. Radke, R. A. Dood, F. J. Worzala, and N. C. Tran, "Plasma source ion-implantation technique for surface modification of materials," *J. Appl. Phys.*, vol. 62, no. 11, pp. 4591–4596, Dec. 1987.

[2] K. G. Kostov, M. Ueda, I. H. Tan, N. F. Leite, A. F. Beloto, and G. F. Gomes, "Structural effect of nitrogen plasma-based ion implantation on

ultra-high molecular weight polyethylene," *Surf. Coat. Technol.*, vol. 186, no. 1/2, pp. 287–290, Aug. 2004.

[3] K. C. Walter, R. A. Dodd, and J. R. Conrad, "Corrosion behavior of nitrogen implanted aluminum," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 106, no. 1–4, pp. 522–526, Dec. 1995.

[4] M. Ueda, G. F. Gomes, E. Abramof, and H. Reuter, "In-line nitrogen PIII/ion nitriding processing of metallic materials," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 206, pp. 749–753, May 2003.

[5] M. Ueda, G. F. Gomes, L. A. Berni, J. O. Rossi, J. J. Barroso, A. F. Beloto, E. Abramof, and H. Reuter, "Plasma immersion ion implantation using a glow discharge source with controlled plasma potential," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 161–163, pp. 1064–1068, Mar. 2000.

[6] J. O. Rossi, M. Ueda, and J. J. Barroso, "Design of a 150-kV 300-A 100-Hz Blumlein pulser for long-pulse operation," *IEEE Trans. Plasma Sci.*, vol. 30, no. 5, pp. 1622–1626, Oct. 2002.

[7] ——, "Pulsed power modulators for surface treatment by plasma immersion íon implantation," *Braz. J. Phys.*, vol. 34, no. 4B, pp. 1565–1571, Dec. 2004.

[8] ——, "A hard-tube pulser of 60 kV, 10 A for experiment and modeling in plasma immersion ion implantation," *IEEE Trans. Plasma Sci.*, vol. 28, no. 5, pp. 1392–1396, Oct. 2000.

[9] F. Davanloo, C. B. Collins, and F. J. Agee, "High power repetitive stacked Blumlein pulsers commutated by a single switch element," *IEEE Trans. Plasma Sci.*, vol. 26, no. 5, pp. 1463–1475, Oct. 1998.

[10] I. C. Somerville, S. J. MacGregor, and O. Farish, "An efficient stacked-Blumlein HV pulse generator," *Meas. Sci. Technol.*, vol. 1, no. 9, pp. 865–868, Sep. 1990.

[11] P. N. Graneau, J. O. Rossi, M. P. Brown, and P. W. Smith, "A high voltage transmission line transformer with very low droop," *Rev. Sci. Instrum.*, vol. 67, no. 7, pp. 2630–2635, Jul. 1996.

[12] J. O. Rossi, I. H. Tan, and M. Ueda, "Plasma implantation using high-energy ions and short high voltage pulses," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 242, no. 1/2, pp. 328–331, Jan. 2006.

[13] M. Ueda, H. Reuther, and C. M. Lepienski, "Comparison of nitrogen–ion beam and plasma implantation in Al5052 alloy," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 240, no. 1/2, pp. 199–203, Oct. 2005.

[14] M. Ueda, M. M. Silva, C. Otani, H. Reuther, M. Yatsuzuka, C. M. Lepienski, and L. A. Berni, "Improvement of tribological properties of Ti6Al4V by nitrogen plasma immersion ion implantation," *Surf. Coat. Technol.*, vol. 169–170, pp. 408–410, 2003.

[15] M. Ueda, L. A. Berni, and R. M. Castro, "Application of plasma immersion ion implantation for improved performance of tools and industrial components," *Surf. Coat. Technol.*, vol. 200, no. 1–4, pp. 517–520, Oct. 2005.

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