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A study on the effect of varying pressure and distance on material hardening in INTI Plasma Focus Machine

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Abstract

Material hardening is a topic of much interest. In this paper, material hardening on AISI 1020 low carbon steel was done using INTI plasma focus (INTI PF) machine. It was found that the best distance for optimum hardening was to place the sample material 4 cm from the anode at a pressure of 1 Torr when the plasma machine is operating at 12 kV as it improves the hardening by 97.8%. Computation with the Lee codes produce plots of ion beam energy versus pressure and number of ions versus pressure. Thus we are able to correlate the optimum hardness of the treated sample surface to the interaction of optimum beam energy and number of ions.

Keywords

AISI 1020, INTI PF, Nitriding, Material Hardness, Beam Energy

Introduction

Surface modification of materials has been an ongoing process since early history as can be observed in the process of making swords. Today the methods of material hardening has become much more varied and include nitriding, carburizing, boriding and various forms of heat treatment. This paper explores nitriding on low carbon steel (AISI 1020) using the dense plasma focus machine.

Nitriding is a process in which nitrogen ions are diffused into the surface of a metal to induce surface hardening. The surface hardening is very important because it is directly proportional to the stress at the location of an imposed strain to avoid any deformation on the surface. Nitriding can be done via gas nitriding, salt bath nitriding and plasma nitriding (Menthe et al., 2000). In a research article exploring nitriding on low carbon steel material by using the dense plasma focus machine, the researcher (Teh et al., 2019) observed that the distance of the sample from the anode has an inverse relationship with the hardness and the further the distance

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of the sample from the anode, the less was the hardness obtained. Another researcher, (Al-Hawat et al., 2010) obtained results that showed that the surface hardness increased with increasing shot number and decreased with increasing distance from the anode. Since surface hardness is a topic of much interest, this paper will present the percentage improvement of the material hardness measured at different heights from the anode tip at various pressure range when surface modification is done using INTI plasma focus machine.

Methodology Used

In this study, the following methodology was used. First the sample was prepared. It was then nitrided by exposing to the plasma focus radiation. The results were analyzed.

The steel bar (AISI 1020 alloy) was cut into samples of size 70 mm × 25 mm × T 7 mm that fitted within the sample holder (placed 40 mm, 60 mm and 80 mm respectively from the anode tip [2]). The samples were milled to remove the oxide layer. They were gradually heated to 910^0C over a period of 1 hour. This temperature was kept constant for 1 hour. The samples were allowed to cool down over a period of 16 hours (Tukur et al., 2014). The treated samples were polished and grinded to remove any residue oxide on its surface (Sonmez & Demir, 2007). The hardness of the steel samples was measured.

A processed sample was placed into the Plasma focus machine at a distance from the anode (40 mm, 60 mm or 80 mm). The chamber was filled to the desired pressure (0.5, 1, 1.5 or 2 Torr). The capacitor bank was charged to 12 kV, and discharged into the nitrogen gas. After 30 shots, the hardness of the irradiated steel sample was measured again.

During each shot, a Digital Phosphor Oscilloscope [Tektronix-TDS3034C] was used to observe the current derivative waveform obtained using a Rogowski coil. This waveform was numerically integrated to obtain the waveform of the discharge current. This current waveform was then input into Lee 6 phase code (Lee et al., 2010).

To use the Lee code, the bank, tube and operational parameters were input into the codes. The bank parameters consist of the values for the capacitance, inductance and unavoidable stray resistance. The length and radius of the anode as well as the radius of the cathode were also input into the code.

For the operational parameters, the voltage of 12 kV, nitrogen gas and pressure of operation (0.5, 1, 1.5 or 2 Torr) respectively were keyed in the input.

Finally, the model parameters (mass and current factor in both axial and radial phase) were obtained by fitting the computed current waveform to the measured current waveform. The flow chart for this is shown in Figure 1. The current fitting is shown in Figure 2.

Once the current waveform had been fitted, the plasma dynamics and properties of the focus for that particular shot were computed within the code and also printed in the code output.

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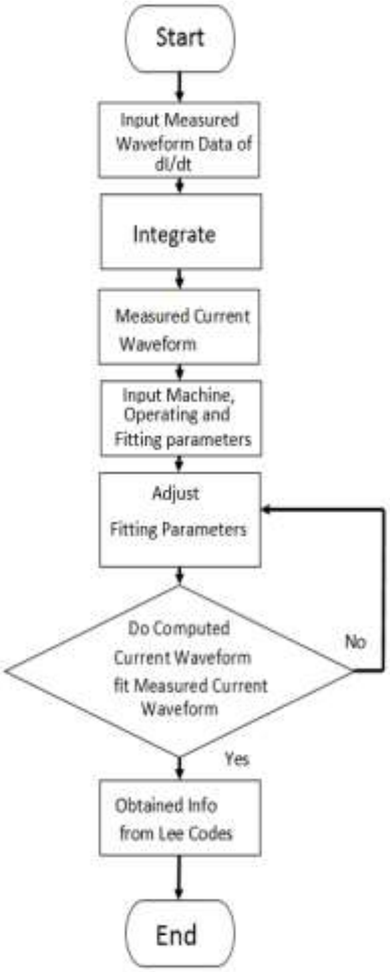

Figure 1. The steps in using the Lee Codes

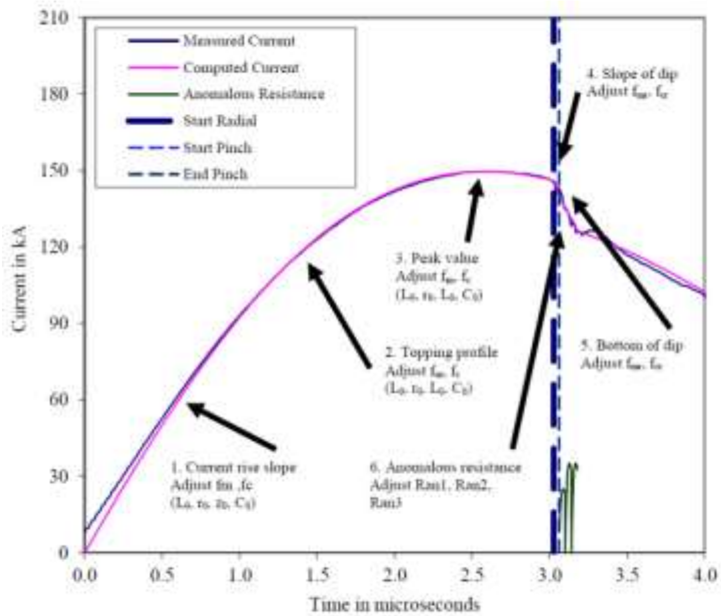

Figure 2. The 6 –point fitting of computed current trace obtained from shot number 11 of INTI International University Plasma focus machine operated at 12 kV, 0.5 Torr in nitrogen gas. The fitting uses Lee Model 6-phase code (Singh et al., 2018)

Results and Discussion

The current fittings were carried out for all 360 shots for pressures from 0.5 to 2 Torr. Using the fitting parameters (not displayed here) which were later input into Lee code model version: RADPFV5.15FIB (Lee at al., 2012; 2013; 2014; 2020), the beam energy and number of ions produced by each shot were obtained.

Figure 3 shows the plot of beam energy of the 360 shots against the variation of pressure obtained from the Lee codes. The figure shows that the maximum beam energy produced by the plasma was when the pressure was at 1 Torr.

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When the number of ions of each of the 360 shots obtained from the Lee codes were plotted against the variation of the gas pressure as shown in Figure 4, it shows that the most ions were produced at 1.5 Torr.

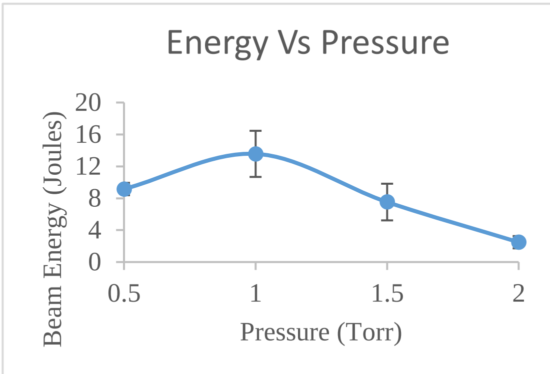

Figure 3. The beam energy of 360 shots taken versus the gas pressure

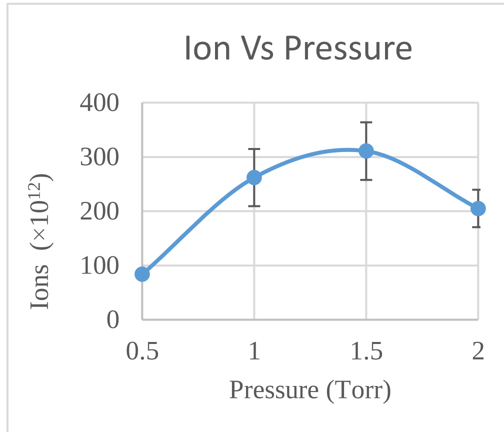

Figure 4. The number of ions of 360 shots taken versus the gas pressure

Figures 3 and 4 show that the ion beam energy peaks at 1 Torr whilst the number of ions in the beam peaks at 1.5 Torr. We note that the ion beam energy is a product of the number of ions in the beam and the energy of each beam ion. Data in the computations (not displayed here) shows that the energy of beam ions are higher at lower pressures due to the higher plasma speeds at lower pressures which therefore induce greater inductive effects resulting in faster beam ions with greater ion energy. On the other hand, the number of beam ions is greater at higher pressure until the pressures are so high that the plasma speeds are too low to generate beam ions efficiently. Hence the ion beam energy peaks at a lower pressure than the number of beam ions. The peaks of Figures 3 and 4 are consistent with the above explanation.

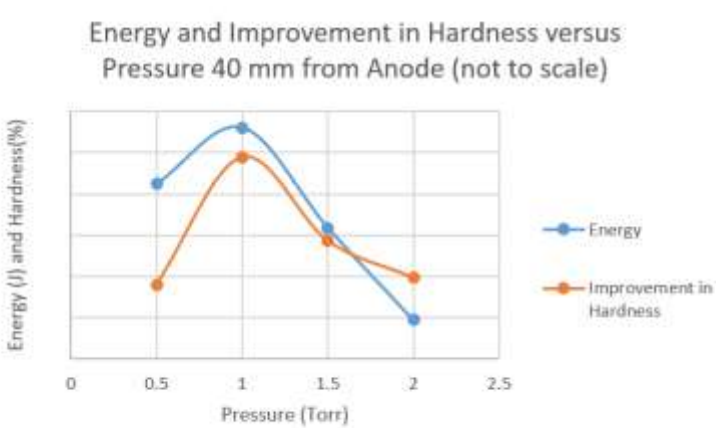

Figure 5. Ion beam energy and % hardness (not to scale) versus the gas pressure

Figure 5 shows the improvement in surface hardness and the beam energy produced by the plasma at different pressure when the sample was placed 40 mm from the anode. It can be observed that the maximum hardness occurs at 1 Torr when the beam energy produced is at its peak.

Closer analysis of Figure 5 shows that the hardness correlates well with the ion beam energy from 0.5 to 1 Torr, but beyond 1 Torr and extending to 2 Torr, the hardness appears not to drop as fast as would be suggested by the dropping slope of the ion beam energy curve.

For the second part of the research study, the average hardness reading was obtained from 15 positions taken for each sample, from the position -7 mm to +7 mm at 1 mm intervals before and after nitriding. This range was chosen to take into account the angle of divergence of the Focus ion beam energy (Pimenov et al., 2013) and also because the shock wave effect on the surface of the sample (Teh et al., 2019).

The average reading of the 15 samples before and after nitriding was measured and its improvement in hardness is shown in Table 1

Table 1. Percentage improvement in hardness at various pressure and distance of sample from the anode tip using Vickers Hardness test (HV 0.3 kgf)

Pressure (Torr)	Average Ion Bean Energy (Joules)	Distance from Anode tip		
		40mm	60mm	80mm
		Percentage improvement		
0.5	8.5	36.1	24.9	20.2
1	11.2	97.8	29.2	21.2
1.5	6.37	57.3	26.7	9.0
2	1.89	39.4	6.3	1.8

Observing the results obtained from Table 2. It shows that when the sample is placed further and further away from the anode, the percentage (%) improvement of hardness reduces due to the divergence of the ion beam. Another observation made is that both the energy and production of ions starts to reduce as the pressure increases.

Conclusion

Nitriding improves the hardness of the steel due to the diffusion of nitrogen ions into the surface of steel. The ions are discharged in a narrow beam along the axis of the device. This narrow beam strikes the central region of the interaction pattern. The high density of energy deposited by the ion beam in this central region causes high temperature and localized melting. The results of Lee model computation show that the beam energy (which is the product of the ion energy and number of ions) correlates with the hardness of the irradiated sample. This is consistent with the theory of increase of hardness due to diffusion and number of nitrogen ions into the surface. Because the ion beam diverges, as the sample is placed further away from the anode, the hardness gets less.

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