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SURFACE HARDENING OF TOOL STEEL BY PLASMA ARC WITH MULTIPLE PASSES

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ABSTRACT
Plasma arc surface hardening is an alternative selective surface hardening method that is effective, economical and a promising technology in heat treatment industries. In the present work, an investigation was carried out to study the hardness distributions of multiple passes in surface hardening of tool steel by plasma arc. The effects of multiple passes with overlapping and non-overlapping scans were investigated. The results show that the hardness is higher at centre of the plasma arc hardening tracks, and then decreasing in the region adjacent to each plasma arc track. It was found that the formation of hardened zone hardness in multiple passes non-overlapping scan is more uniform on the each scan when compared to the overlapping scan. However, hardness distribution of overlapping scan in width direction shows that it was more uniform compared with non-overlapping scan.

Keywords: Hardness; Multiple passes; Plasma arc; Surface hardening

1. INTRODUCTION
The method of surface hardening is a modification of the surface structure of steel containing sufficient carbon to allow the transformation from austenite to martensite after the appropriate amount of heat is applied to the surface, followed by a rapid cooling of the heated layer by heat sink. The surface hardening process has been typically carried out by laser beam (Ruiz et al., 1996; Selvan et al., 1999) and electron beam (Hwang & Fung, 1996; Song et al., 2003). However, there is very little independent published information available on the use of plasma arc source for surface hardening (Bourithis et al., 2002). Plasma arc is a concentrated heat source and widely used in the welding (Luo, 2003), cutting (Wang et al., 2001), and forming (Pan et al., 2002), as well as in surface treatment of biomedical materials (Chu et al., 2002). As a heat source, a plasma arc possesses advantages over electron beams or lasers. Plasma arc does not require vacuum chamber as in the case of electron beam, or a complex and expensive optical-mechanical system for laser. Therefore, the plasma arc surface hardening is one of the most attractive and effective methods in achieving higher surface hardness without any additional quenching mediums, so that the wear and corrosion resistance of the materials can be improved.

Research efforts on surface hardening by plasma arc began in 1980s (Linnik et al., 1983; Kraposhin et al., 1989).

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Most of the studies have been concentrated on the single pass of plasma arc (Bourithis et al., 2002; Linnik et al., 1983; Kraposhin et al., 1989; Nitkiewicz & Jeiorski, 1991; Samotugin, 1998; Yang, 2001). The plasma arc surface hardening with multiple passes to achieve a large hardened area has been reported (Pan et al., 2005). Multiple passes in selective hardening are made continuously from one end of the surface to the other without intermittent stops. After making a pass, the hardened zone will cool down rapidly. At the same time, the heat is also conducted away raising the temperature of the substrate adjacent to it, including part of the area covered by the previous pass, i.e. the overlapped zone and the new area to be hardened.

The rapidity of heat conduction depends on the thermal diffusivity of the material (Carslaw & Jaeger, 1959). The temperatures of the hardened zone of the previous pass and the new area to be hardened, depend on this factor as well as the size of the area to be hardened and the arc scanning velocity (Yang, 1993). For a small area, with a short length of travel, and high scanning velocity, the turn around time, i.e. the time taken between the first and the second passes, is shorter. The temperature on the hardened zone of the previous pass may remain high while the new area to be hardened may remain at a lower temperature. On the other hand, for a larger area with a longer length of travel and a lower scanning velocity, the turn around time is long. The temperatures on the hardened zone of the previous pass may be lower while the temperature on the new area to be hardened may be higher. Hence, different results would be expected from different processing conditions.

In this study, the experimental study is carried to investigate the effects of multiple passes with overlapping scans on the hardness of the hardened zones in the plasma arc surface hardening process. In addition, multiple passes without overlapping scans were also conducted for comparison.

2. EXPERIMENTAL

The experimental studies were performed on a plasma arc machine with torch diameter of 1.6 mm, which integrated with a six degree-of-freedom articulated robot. The negative terminal of the power supply is connected to tungsten electrode and the workpiece is connected to the positive terminal of the power source as shown in Figure 1. Argon gas was used at 6 bar as shielding gas to minimize oxidation. The nozzle-workpiece standoff distance was kept constant at 13 mm. The selected currents of plasma arc were 30 A and 60 A. The scanning velocities of plasma arc were 0.1, 0.3 and 0.5 m/s. The ASSAB DF3 steels were used in this study and the chemical compositions of is shown in Table 1.

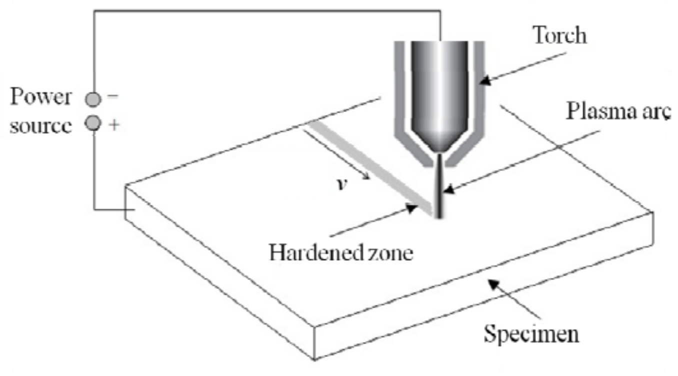

Figure 1 Schematic diagram of experimental setup

Table 1 Chemical composition of ASSAB DF3 steel (Unit: wt.%)

C	Mn	Cr	W	Fe
0.90	1.20	0.85	0.55	Bal.

Specimens of size 60×40×10 mm^3 were cut, grounded and polished with silicon carbide paper in order to remove oxides and obtain a smooth surface. After scanning the steel surface with different conditions, the hardened specimens were cut perpendicular to the scanning direction, grounded, polished and etched in 2% Nital for hardened depth measurements using an optical microscope. After completing all the runs, specimen preparations were carried out for hardness measurement and microstructure observations. Hardness distribution of the hardened zones was performed using a load of 200 g and a keeping time of 15 s. Microstructure of the hardened zones cross section was also performed with the aid of an optical microscope.

All the experimental runs were conducted along the direction of the length. As shown schematically in Figure 2, the specimens were hardened in two ways.

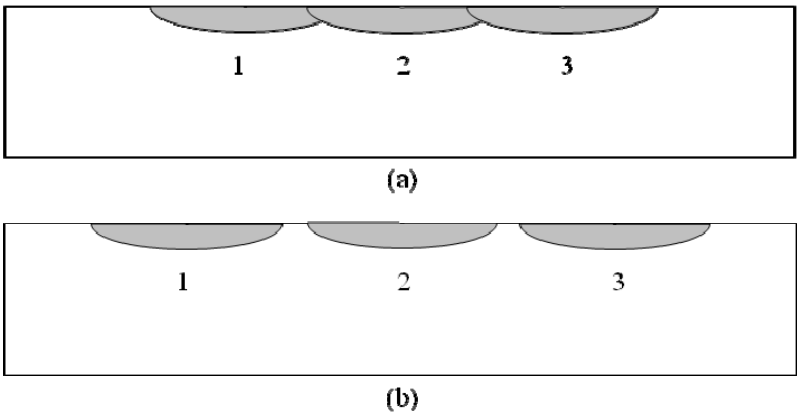

Figure 2 Schematic diagram of multiple passes in cross-sectional view (a) with overlapping scan of 20% and (b) without overlapping scan

First way was hardening the specimen in multiple runs with an overlapping pass, and the second way was multiple runs without overlapping pass. The percentage of overlapping pass was 20%. The multiple scans for each setting were completed with a single programme which contained instructions for performing three passes.

3. RESULTS AND DISCUSSION

Figure 3 shows the optical micrograph of a cross-section for the plasma arc hardened specimen using overlapping ratio 20% and the hardness measurements perpendicular to the plasma arc passes direction at a constant depth of 30 μm from the surface. It can be seen that the hardness is higher at centre of the plasma arc hardening tracks (zone P), and then decreasing in the region adjacent to each plasma arc track (zone OV). The decreasing hardness in the rehardened zone is mainly due to the tempering of martensite. It can also be seen that the size of hardened width for the final pass is largest compared to the first pass. However, Figure 4 shows that the 0.5mm wide spacing between non-overlapping passes has the same hardness as the substrate, and tempering effect was not observed in this region. It can be seen that the second pass has the same hardness with the first pass, while the final pass has increased hardness as a result of pre-heating effect from the previous passes.

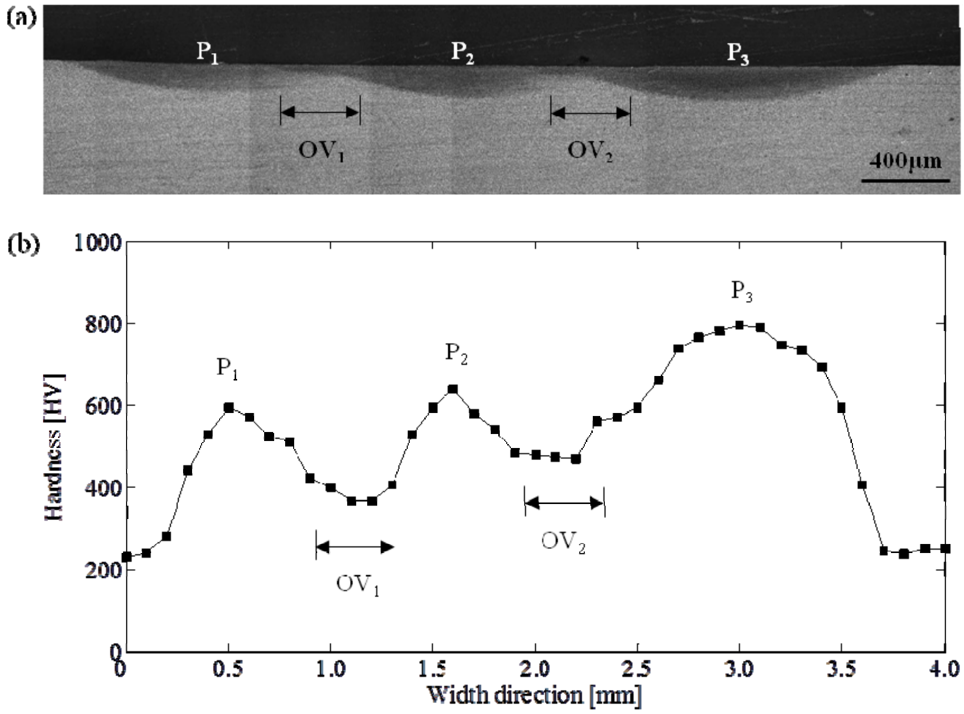

Figure 3 (a) Optical micrograph of the cross-section of the hardened specimen with overlapping scans; (b) microhardness measurements along the subsurface at a constant depth of 30 µm and perpendicular to the plasma arc passes direction

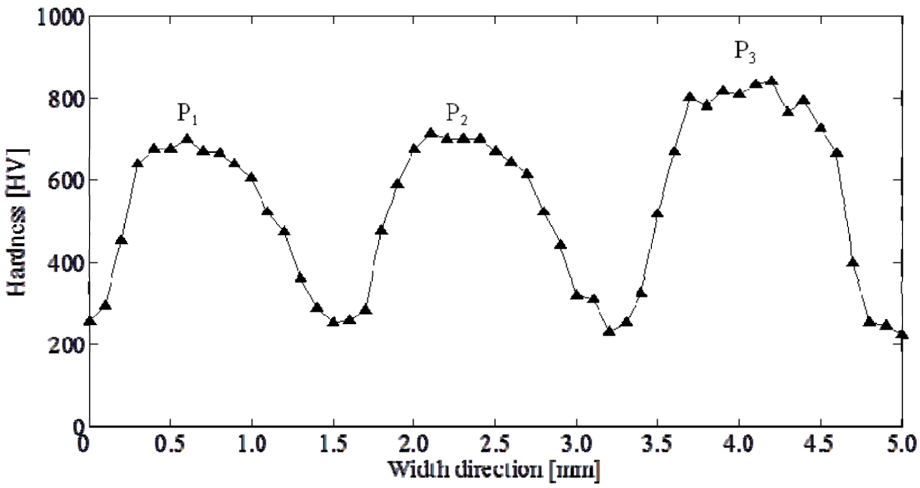

Figure 4 Hardness profile of non-overlapping scans

Figure 5 shows the hardness measurement of the hardened specimen with three passes, 20% overlapping, an arc current of 30 A, and scanning velocity of 0.3 m/s in direction of thickness. It can be seen that the hardness of the overlapped areas is generally lower. This is due to the temperature of the overlapped zone having reached a temperature near the room temperature, with the formation of martensite as a result of hardening in the previous run, then temperature rise of above martensite start temperature (M_s) caused by the additional heat in the next run caused tempering of the already hardened zone. The end result is reduced final hardness. However, the hardness of the non-overlapped areas has increased from a lower value in the first pass to a higher value in the final pass. This would be due to the increased austenitizing temperature as a result of the pre-heating effect from the earlier passes. It can also be noted that the size of the hardened depth for the final pass is largest compared to the first pass.

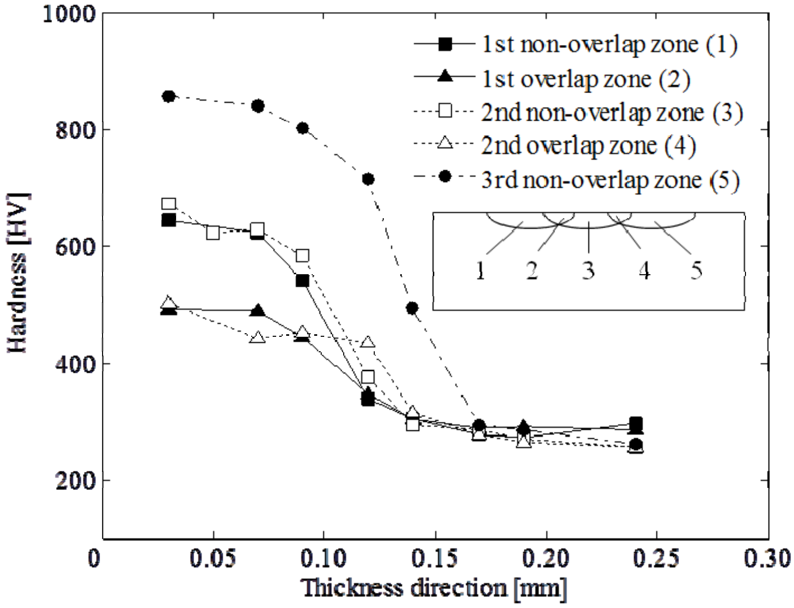

Figure 5 Hardness profile of plasma arc hardened in multiple passes

Figure 6 shows the result of hardness measurement with three passes, 20% overlapping, and an arc current of 60 A, scanning velocity of 0.1 and 0.5 m /s.

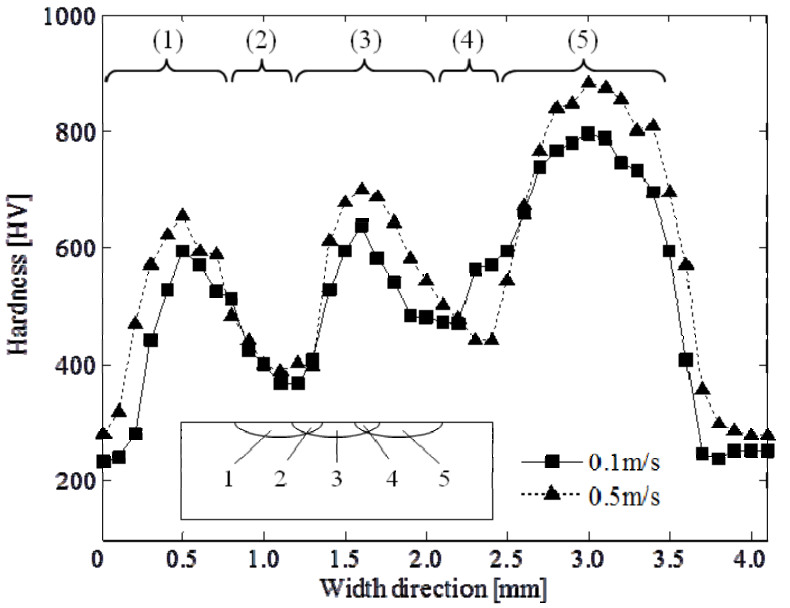

Figure 6 Hardness distribution of multiple passes with different scanning velocities

It can be seen that, with a low scanning velocity, the hardness of both overlapped zones and non-overlapped zones is low compared with the high scanning velocity. With a higher scanning velocity, the heat input per unit area is reduced and as a result, the quenching rate is increased. Presumably because the turn around time is shorter and the temperature on the hardened zone of the previous pass was remaining high and has been increased by the next pass, and this has increased the hardness. It can also be seen that the hardness at the overlapping zones is lower than that of the non-overlapping zones. Same as stated previously, that there is a tempering effect at the overlapping zones as a result of excessive heat input and heat built-up into the zones.

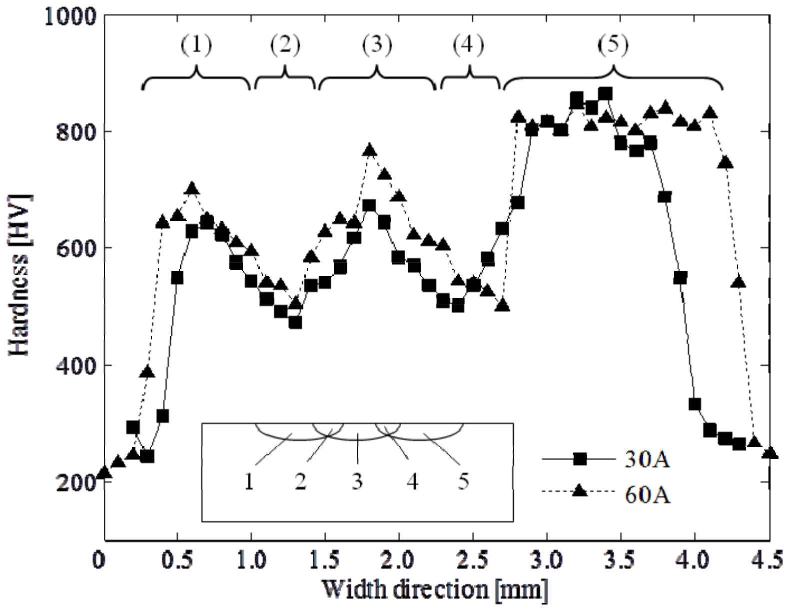

Figure 7 Hardness distribution of multiple passes with different arc currents

Figure 7 shows the result of hardness measurement of hardness measurement with 20% overlapping pass, a scanning velocity of 0.3 m/s and arc currents of 30 A and 60 A. It can be seen that the increase of arc current has increased the hardness both of the overlapping zones and the non-overlapping zones. The increasing arc current has presumably provided a higher austenitizing temperature to increase the hardness of both the overlapping and the non-overlapping zones. However, the higher hardness of final pass for both conditions was similar. It can be noted that the pre-heating effect by previous passes is able to increase the austenitizing temperature to an optimum condition in the new hardened zone. It can also be seen that the hardened width increased from a lower size in the first pass to a higher size in the final pass. This also happens when arc current is increased.

In the present investigation, as noted above that with high arc current, a higher hardness was obtained in the overlapping zones. However, the maximum hardness could not be obtained near the surface. It seems that the maximum hardness is achieved at 0.12 mm from the surface, as shown in Figure 8. The maximum hardness was found at the boundary between the non-overlapping and overlapping zone. This is due to a lower temperature not reaching the hardening temperature during previous pass, and the additional heat from next pass has increased the austenitizing temperature to induce further hardening. The additional heat may be able to increase the interaction time to allow more carbide dissolution into the austenite to get more complete transformation into martensite upon hardening. On the other hand, the overlapping zone near the surface was affected by tempering effect, since the martensite is converted into tempered martensite, and the cooling rate was reduced by the additional heat from the next pass.

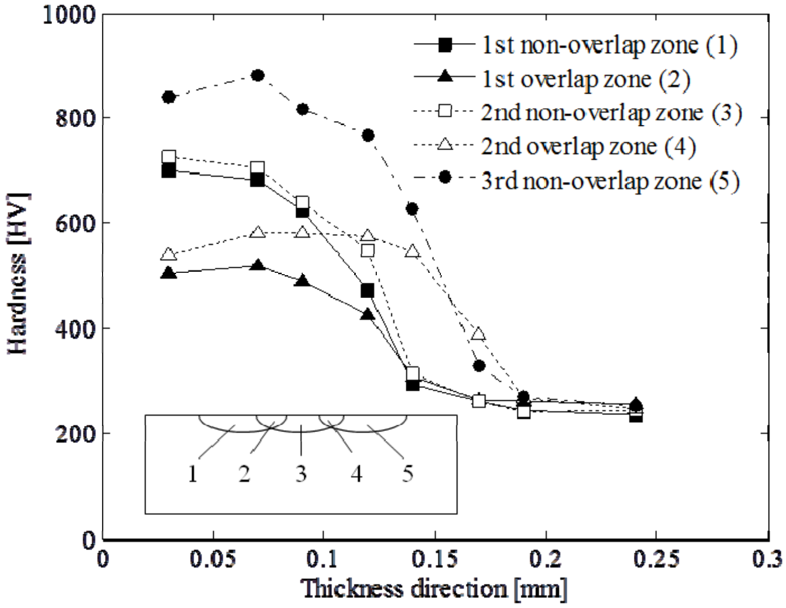

Figure 8 Hardness profile of plasma arc hardened with high 60 A arc currents

The advantage of multiple runs without overlapping pass is the formation of a hardened zone with more uniform hardness on each pass when compared to multiple runs with overlapping pass as shown in Figure 9.

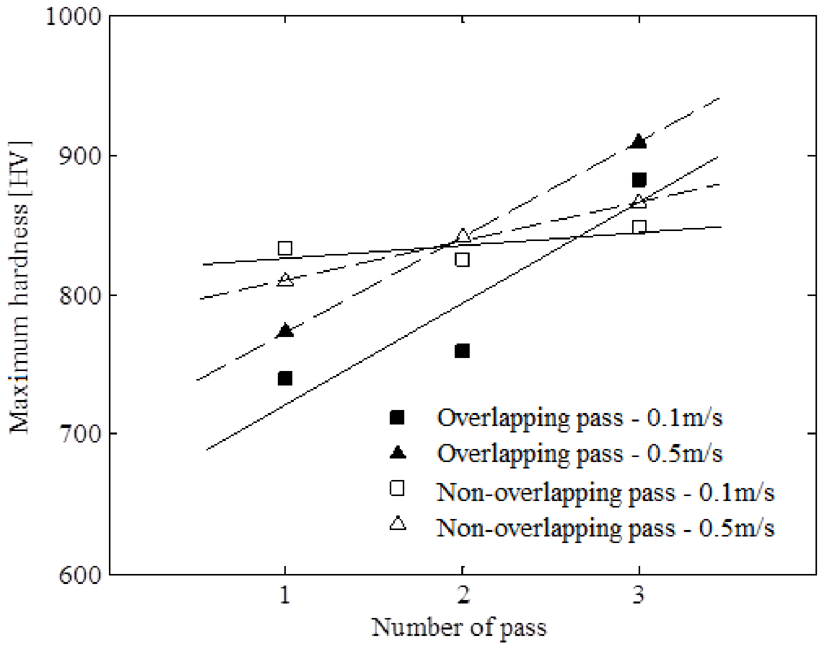

Figure 9 Maximum hardness of multiple passes versus number of plasma arc scan

The maximum hardness of final pass is not so affected by the previous passes for non-overlapping pass, and the value of maximum hardness for all passes are similar to the maximum hardness of single run, whilst maximum hardness of the final pass for overlapping passes was greatly increased due to pre-heating effect from the previous passes. At the same time, the hardness of the first pass in overlapping runs is obviously reduced and different from the hardness of a single run. Presumably because the temperature of the hardened zone of the first pass has already reached a temperature near the room temperature, while the final pass induced temperature rise and cause tempering effect on that zone, and this has increased the hardness.

4. CONCLUSION

In this study, an attempt has been made to determine the hardness distribution of both overlapping and non-overlapping hardened zones in the plasma arc surface hardening process.

It has been found that multiple passes may either decrease or increase the hardness of the overlapped and non-overlapped areas. It is proposed that the decrease in hardness at the overlapped areas is due to tempering. On the other hand, the increase in hardness in the overlapping area is due to the increased interaction time and the austenitizing temperature as a result of pre-heating caused by earlier passes. In addition, depending on the selection of parameters, the multiple passes may either decrease or increase the hardness.

The hardness of the steel specimens increases considerably after plasma arc surface hardened. The overlapped plasma arc hardened surfaces exhibited higher hardness at the centre of the plasma arc hardening tracks followed by decreased values in the region adjacent to each plasma arc track i.e. overlapped zone.

The formation of hardened zone hardness in multiple passes without overlapping scan is more uniform on each scan when compared to the overlapping scan. However, hardness distribution of overlapping scan in width direction shows that it was more uniform compared with non-overlapping scan. Therefore, the optimum combination between the overlapping and the non-overlapping scans can be performed to obtain more consistent hardness distribution in the hardened zone.

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