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Hardness distribution and impact toughness of carburized steel welded by SMAW

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Abstract. Joining carburized steel by welding process becomes promising technique to substitute largely applied bolted connection on machine transmission elements which is often sustained from contact loading. The present study utilized microvickers and charpy impact tests to analyze the effects of welding current on hardness distribution and impact toughness of carburized steel joined by low-cost SMAW (shielded metal arc welding). The heat input played an important role to characterize the hardness distribution where the homogeneous distribution can be achieved by higher heat input controlled by higher welding current as a result of larger carbon-rich layer distribution within the fusion zone. The higher carbon enrichment at the center of fusion zone induced by higher welding current consequently reduced its ability to absorb impact energy after loading and thus degrade their impact toughness.

Keywords: Carburized steel, shielded metal arc welding, hardness distribution, impact toughness.

1. Introduction

Vast improvements of materials processing technology are consequently required to facilitate today's rapid development of materials, therefore, these new materials are possible to be fabricated as ready-to-apply products on various fields. A huge efforts have been extensively conducted to develop metallic materials due to their wide application, especially on automotive and construction field. Steel is favorable for load-bearing material due to its low cost, highly-available and desirable properties, such as high strength, relatively good ductility, highly-treatable, and superior formability. The properties of carbon steel is highly dependent to their carbon content, where lower carbon content indicates lower hardness and wear resistance [1], therefore, this material has less ability to sustain contact stresses mostly occurred on transmission element surface. In this case, surface hardening by introducing carbon diffusion through carburizing were largely proposed by several studies to overcome these limitations [2-4]. Joining by welding becomes one of the manufacturing processes mostly applied on metallic material to generate low-cost and lightweight joint which involves thermal cycle, namely melting and subsequent cooling, resulting, residual stress and the evolution on both microstructural and mechanical states of metal.

Recently, joining carburized steel by welding process becomes promising technique to substitute largely applied bolted connection on machine transmission elements, such as gear and sprocket, due to its absence of initial holes requirement, additional connection materials, excessive head bolt space and thus accumulated joint component weight itself. It is well-known that the presence high carbon



content on carburized steel degrades its weldability due to the increase susceptibility to induce hot cracking during subsequent cooling and solidification [5, 6]. However, the thicknesses of carbon-rich layer on several carburized steel were mostly less than 1000 μm [3, 4], therefore, it can be solved theoretically by selecting appropriate welding parameters in order to redistribute the carbon from the base metal surface to the entire weld pool region. Several studies had been conducted by proposing both friction welding and high-energy laser welding for establishing acceptable carburized steel welded joint [7, 8]. The results revealed that the welded connection performed equivalent joint quality, in case of torsional stiffness and fatigue life, compared with conventional bolted connection. On the other hand, hardness and noise problem on welded connection can be solved by modifying the welding prototype [8]. However, the low flexibility of friction welding and both high equipment and operational costs of laser welding makes these methods are less attractive to be used in large application.

Highly-available shielded metal arc welding (SMAW) becomes promising technique to join carburized steel due to its low operational and equipment cost. In this case, the heterogeneity of hardness distribution due to the presence of residual stresses on weld joint become the challenge of the welding application since it possibly rises the distortion on transmission element [9]. By controlling the heat input, the hardness distribution can be adjusted because the base metal was initially induced by residual stress after quenching process on carburizing. The other essential factor determining the hardness distribution is controlled by carbon movements from base metal surface to weld pool mainly stirred by Lorentz force where on arc welding and the magnitude of force is highly varied by selecting the welding current [5, 10, 11]. Hence, by introducing homogeneous carbon distribution in weld pool, the hardness level of welded joint remains at similar level, theoretically, so, the stress can be dispersed along the welded joint during joint loading. Additionally, the change of hardness distribution of joint induced by both heat input and carbon distribution will consequently alter its impact properties.

In this study, the low-cost SMAW was utilized to join carburized steel plates and the different welding currents were applied to vary the heat input. The hardness distribution and impact toughness of the joint were evaluated by microvickers and Charpy impact method to provide general assessment on the capability of arc welding technique to join carburized steel as machine transmission element. The impact analysis is focused at weld region by providing fracture surface images of impact sample.

2. Experimental Details

The welding samples were prepared by cutting and carburizing the commercial St 37 plate with the thickness of 10 mm. The charcoal from coconut shell and barium carbonate (BaCO_3) were utilized as carbon additive and energizer on pack carburizing, respectively based on previous studies [4, 12]. SMAW method using E7016 electrode with different welding currents was applied to join the samples. The process was done for 3 passes and the welding speed was constantly controlled proportional to the selected current. To evidence the HAZ and weld area related with carbon distribution, macroscale image of cross-sectional surface was also performed by cutting, polishing, and 3% nital-etching the sample.

Microvickers was used for analyzing the hardness distribution conducted at the load of 300 g, dwell time of 10 s, and test interval of 4 mm across the weld cross section at the depth of 2.5 mm from weld top surface.

The V-notched Charpy impact samples having dimension of 10 mm x 10 mm x 55 mm were prepared from welded plate based on ASTM E23-16b [13]. The 45° notch was precisely made at the weld centerline of each sample and the test was conducted on room temperature utilizing 30 kg of pendulum weight to obtain impact energy absorbed by each sample. The fracture morphology of sample after impact test was also investigated to confirm the impact properties.

3. Results

3.1. Macroscale images of cross-sectional surface

From the figure 1, it is evident that the width of HAZ region was varied by the different welding currents, where the larger HAZ was generated by greater heat input controlled by higher welding current. This

phenomena is typical for any arc welding process. Additionally, the carbon layer of carburized steel is clearly shown on the base metal surface with the thickness approximately of 1 mm. At the weld region, the carbon initially located on base metal surface was distributed to the fusion zone with different amount depends on welding current applied during the process. For 80 A of current, the carbon rich layer is still embedded on weld-HAZ interface as shown on figure 1(a). By using higher current, the carbon distribution reaches larger region of fusion zone where the carbon-rich regions indicated by darker area remain less at upper zone as described on figure 1(b) dan (c).

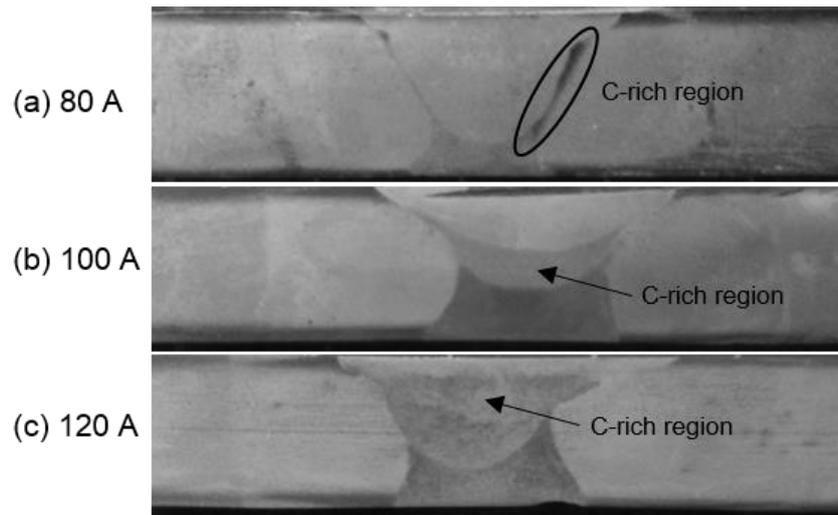


Figure 1. Macroscale images on cross-sectional surface of (a) 80, (b) 100, and (c) 120 A welded samples

3.2. Hardness

The hardness analysis was conducted using microvickers with 300 g of load at several locations across the weld cross-sectional surface as shown on figure 2. By using 10 s of dwell time, the hardness results across the weld cross section were listed and presented on table 1 and figure 3, respectively.

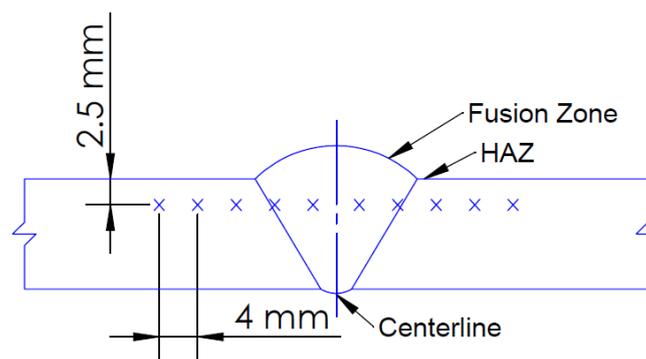
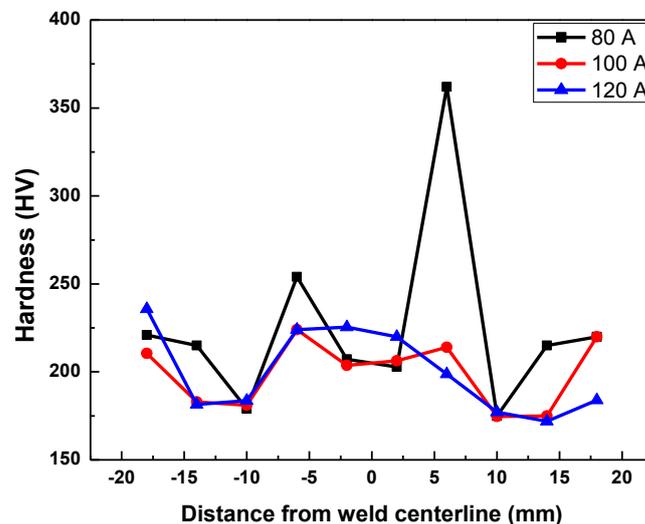


Figure 2. Schematic sketch of hardness indentation across the welded joint.

Table 1. Hardness of carburized steel welded joint using different welding currents at several regions from centerline

Distance from centerline (mm)	Hardness (HV)		
	80 A	100 A	120 A
-18	221	210.5	235.8
-14	215	182.9	181.5
-10	179	181.1	183.6
-6	254	224	224
-2	207.1	203.7	225.5
2	202.8	206.3	220
6	362	214	198.7
10	174.9	174.7	177.1
14	215	175	171.9
18	220	220	184

Figure 3 shows the hardness distribution of welded samples joined with different welding currents using test interval of 4 mm around the centerline and the results indicate different distribution trends among all currents. In general, the hardness distribution indicates similar trends among all welding currents, but the main variation is occurred at fusion zone. The tests conducted on base metal of 80, 100, and 120 A sample (at the both sides) are varied at range of 210.5 to 235.8 HV. At 80 A sample, the hardness shows decreasing trend at HAZ (-10 and 10 mm from centerline), afterwards, it is observed to be significantly increased at near-tip region of fusion zone (-6 and 6 mm from centerline) in both sides, that are 254 and 362 HV. The reduction is recognized near the weld centerline with 207.1 and 202.8 HV, representing inhomogeneous hardness distribution.

**Figure 3.** Hardness distribution on samples welded by different welding currents.

With the enhancement of welding current to be 100 A, the reduction occurs at the more distant region (-15 and 15 mm) from centerline indicating the generation of wider HAZ. The similar hardness improvement are then occurred at near-tip regions but the value are significantly lower than 80 A of welding current (224 and 214 HV at -6 and 6 mm from centerline, respectively). Afterwards, the similar reduction trends are observed near the centerline with relatively identical hardness level compared with the lower current. The hardness distribution of sample welded by the current of 120 A is nearly similar

with 100 A welded sample. The major hardness differences are noticed at a distance of 18 mm from centerline (showing lower value, that is 184 HV due to the wider HAZ generated by higher welding current) and at the fusion zone (from -6 to 6 mm) where the more homogeneous distribution is clearly detected in comparison with similar region of the other welded samples.

3.3. Charpy impact

The Charpy impact test was conducted at room temperature based on ASTM E23 to investigate the relation of heat input controlled by welding current on impact energy absorbed by V-notched sample. By locating the notch at the weld centerline, the impact energy absorbed at fusion zone is clearly decreased when the higher welding current applied to join the sample. The impact energies of 80, 100, and 120 A sample are determined to be 43; 16.06; and 13.7 J, respectively, as depicted on Figure 4. To further analyze this phenomena, the fracture surface of impact samples were also carried out and the results indicate the enlargement of brittle-fracture region noticed on the surface sample joined by higher welding current. This region is presented by shiny area of cone-side fracture surface (surrounded by spline) on figure 5.

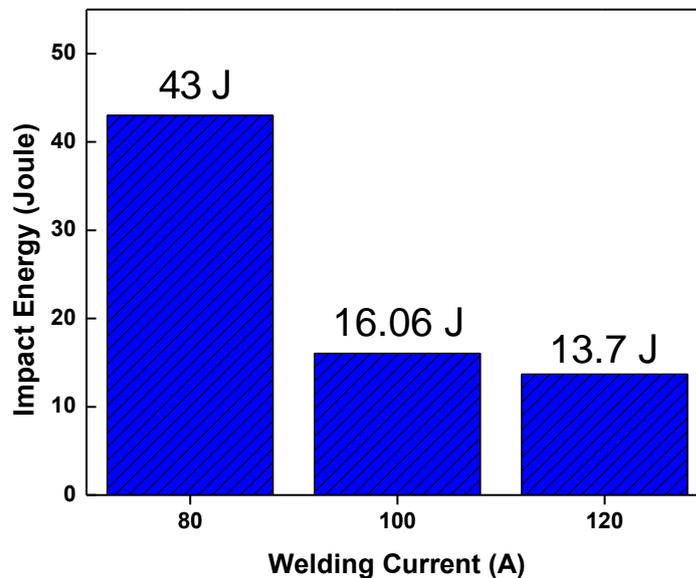


Figure 4. Room temperature V-notched impact toughness of samples welded by different welding currents.

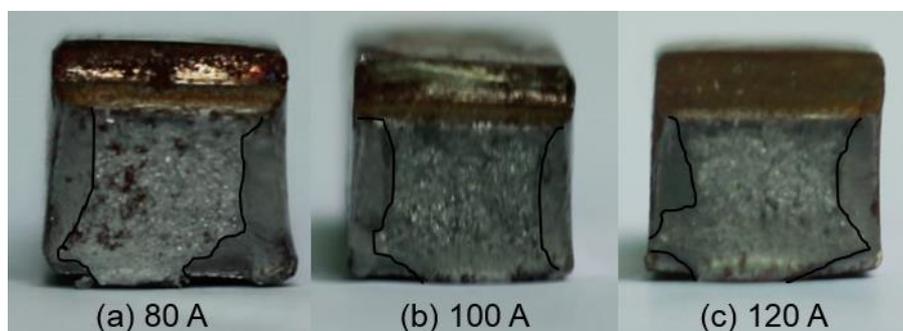


Figure 5. Fracture surface of impact samples welded by different welding currents.

4. Discussion

4.1. Hardness distribution

Due to the previous carburizing process involving quenching, the initial hardness of weld metal was sufficiently high by the presence the large amount of residual stresses. The hardness reduction is clearly observed when the test is taken from base metal region to HAZ indicating softening phenomena on the welded metal by reheating process on HAZ during welding. This HAZ softening is a typical feature of the welding processes and welding consumables used on high strength and high hardness steel [14]. The level of softening occurred in the HAZ are determined by weld thermal cycle controlled by welding parameter, the nature of base material used, and the phase transformation of material [15, 16]. In this study, the joint using 80 A of current has a lower level of softening compared with the other joints and the variation of these softening phenomenon is likely caused by heat input given during welding. The presence of this soft zone in a welded structure may reduce the weld design strength into the lower level, and subsequently degrade its torsional stiffness and wear resistance. From the results, the larger width of HAZ is obtained on higher heat input indicating the characteristic of arc welding. The greater HAZ softening effect is occurred on sample welded using highest heat input induced by 120 A of current resulting relatively lower hardness of HAZ compared with other heat input samples with the lowest hardness value of 171.9 HV.

The other main difference of hardness distribution induced by varied heat input is observed at fusion zone where the more homogeneity distribution is achieved by applying higher welding currents. The homogeneous hardness and strength distribution is often required for welded joint to distribute the stresses equally to the entire body [5], therefore the joint can sustain the higher level of loading before failure. At a lower current of 80 A, the heterogeneous fusion zone hardness distribution is noticed. This condition is evidenced by the presence of carbon-rich layer at the fusion zone-HAZ interface having relatively high hardness of 362 HV. By increasing welding current to 100 A, the hardness difference between near-tip and near-centerline regions remains lower indicating more homogeneous distribution. The most homogeneous distribution appears at welding currents of 120 A, correspond to the larger distribution area of carbon-rich element as shown by dark region at fusion zone (figure 1).

It is clear that the hardness evolution on fusion zone is determined by the carbon content on the respective test region. This carbon distribution is expected to be controlled by both weld pool convection and temperature during welding. The weld pool convection is reportedly driven by several stirring forces, where the dominant force is lorentz force determined by the magnitude of welding current [5, 10]. At low welding current of 80 A, the weld convection rate stirred by lorentz force and the welding temperature were insufficient to degrade the carbon layer, proven by the carbon-rich layer embedded at fusion zone-HAZ interface on figure 1 (a). By using higher welding current, the former carbon-rich layer on carburized steel base metal surface was completely eliminated and distributed within the weld pool by sufficient convection rate and temperature, where the largest carbon-rich distribution area is obtained by utilizing highest welding current of 120 A.

4.2. Impact toughness

The hardness of the fusion zone center is enhanced by higher welding current conducting carbon-rich hard zone at the near-centerline region. Consequently, it can reduce the ability of fusion zone to withstand the impact loading due to the reduced energy absorbability [17]. It is obvious from the result performed on figure 4 indicating the degradation of impact toughness by the increase of applied welding current. This hard weld structure has less ability to absorb the crack initiation and propagation energies after impact loading [10]. This phenomena is also caused by the greater amount of hard pearlite phases formed caused by high carbon content at higher welding current sample which induces the larger brittle fracture region as shown on figure 5 (c) in comparison with the other fracture surfaces of lower welding current samples. This larger brittle surface implies that the hard carbon-rich weld structure has less ability to retard the spontaneous crack propagation after loading.

5. Conclusion

In this study, carburized steel was successfully welded by SMAW without significant major defect. The effect of welding current on the hardness distribution and impact toughness were carried out using microvickers and Charpy impact. The main information derived from the analyses can be concluded as follows:

1. The heat input controlled by welding current played an important role to determine the hardness distribution, especially at fusion zone, where the homogeneous distribution can be achieved by higher heat input.
2. The macroscale images of cross-sectional weld surface revealed that the evolution of hardness distribution was characterized by carbon-rich zone distribution within the fusion zone.
3. The impact energy absorbed by the center of fusion zone was consequently lowered by carbon enrichment using higher welding current.
4. The larger brittle fracture region was obtained at sample surface welded with higher welding current.

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