The Effect of Ultrasound on the Microhardness and Nanohardness of Laser Welds in Mild Steel

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***Abstract*— Vibrations (both sonic and ultrasonic) has brought along various benefits when applied to a wide range conventional processes by modifying the properties, microstructure and yielding products of better quality in many cases. It has been shown that application of ultrasound can cause a decrease in power requirements, processing temperature and time.**

The objective of this research is to investigate the effects of ultrasound (US) on the hardness of the solidified weld bead which has been subjected to ultrasonic vibrations of 20 kHz frequency during laser welding. The hardness of the different specimens at equivalent positions will be measured using a micro hardness tester and a nanoindenter. The microhardness will not be compared directly to the nanohardness values but rather the effect of ultrasound on hardness in each case with welding speed will be considered.

Mild steel plates were subjected to ultrasound of low acoustical power during "bead on plate" laser welding at different speeds. The bead on plate weld is not a joining process but simply a "melting and solidification" process of the material. This is suitable in this particular case as only the effect of ultrasound on each of microhardness and nanohardness is being compared.

The results clearly show that there are many factors that affect the measurement of properties which are area or volume dependent. The changes in the microhardness and nanohardness for a specific welding condition are very irregular and do not follow the same trend.

***Index Terms*— Ultrasound, Laser Welding, Microhardness, Nanohardness, Steel.**

I. Introduction

Power ultrasound has been used successfully in the welding of similar and/or dissimilar metals or even metal to non metal combination **[1, 2, 3, 4]**. Ultrasound (US) has enhanced the properties of the components at the same time reducing the processing time, processing temperature and power requirements in most cases. It was also reported that a minimum power (threshold) **[5]** of ultrasound was necessary to have noticeable effects on the properties of the components and that there was also an upper limit (upper threshold) beyond which further increase in acoustical power did not bring any additional benefits in the properties under investigation. Given that ultrasonic waves are subjected to absorption, reflection, and diffraction when they are transmitted in any medium, the amplitude of the waves throughout the plate or component would be attenuated with distance traveled by the waves **[6, 7]** as well as the phases present.

Researches have always been directed towards the change in specific properties and microstructure of the components but not at the same property at different levels. The objective of this research is therefore to compare the effects of ultrasound on the hardness of the welds obtained using microhardness tester and nanoindentor. Bead on plate (no joining but only melting and solidification of the plate) weld was found to be suitable for this investigation as the objective is to determine the effects of ultrasound on the hardness measured at different levels with change in ultrasound power and welding speed.

The mild steel plate was held at one end by the ultrasonic horn through which ultrasound was injected. A bead on plate weld of length 80 mm was then performed along the center of the plate using a CO_2 laser (1 kW). At fixed laser power, the welding speed will affect the depth of the plate that would be melted (i.e. depth of penetration). After several trial tests, the following three different welding speeds; 400, 1200 and 2000 mm per minute were used. The ultrasonic powers selected were 3W and 6W respectively for each welding speed as higher acoustical power was causing ejection of molten metal from the pool during welding.

The same specimens were used for both measurements but the surface preparation was different for each case. In both cases, the specimens had to be bakelite mounted because of the size of the specimen (10 x 2 x 2 mm). The specimen (in bakelite) was polished mechanically to the desired finish and subjected to microhardness measurements. The specimens were then mechanically polished again before being electro polished. The bakelite mounts were drilled behind the specimen to allow electrical contact to be made to the specimens for electro polishing. The drilling process was very tedious and some mounts were damaged during the operation. The electropolished specimens were then lightly etched before being subjected to nanoindentation tests. This

Manuscript received February, 27th 2009.

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helped to clearly identify the region where the nanoindentation tests were to be performed.

The estimated size of the indentation is 25 μm and 650 nm with the microhardness and nanoindentation respectively. It was clear that the hardness at exactly the same location was not possible but the centre of the measurement was at the centre of the weld.

Depending on the heat intensity, the welding process can be classified as conduction welding or keyhole welding. In low energy process, the heat is conducted away from the heat source and it takes some time for the metal to reach melting temperature usually leading to a relatively large weld pool but with small penetration or a low depth (of penetration) to width ratio. Keyhole welding is obtained with high intensity heat source and results in vaporization of metal and formation of a very deep groove compared to the area of the surface melted. A large depth to width ratio is usually obtained in keyhole welding.

Miyahara *et al.* **[8]** proposed an equation for the conversion of nanohardness into Vicker's microhardness for steel and reported that the hardness measurements were dependent on the grain size of the microstructure. The equation is valid for depth of penetration $200<h<400$ nanometers which cannot be applied in this case as the depth of penetration is 100 nm. The hardness at nano scale and micro scale were found **[8]** to be almost the same in coarse grained structure but a sharp increase in hardness was observed when moving from nano scale to micro scale in fine grained structure. This was attributed to the grain boundary strengthening. The experimental values of moduli by nanoindentation were found **[9]** to be close to values stated in literature for materials with isotropic properties but the significance of the modulus obtained in the case of anisotropic materials were undetermined.

II. MICROHARDNESS TEST

A. Specimen Preparation

The mild steel specimens were sectioned using a band saw and mounted in bakelite. Metallographic samples were then prepared by polishing and etching in 2 % Nital to reveal the microstructure. The specimens were successively ground with 240, 600 and 1200 grit SiC grinding pads and then polished with 6μm and finally 1 μm diamond paste until a satisfactory surface was obtained.

B. Measurements

Microhardness measurements were performed on the specimens using the Vicker's microhardness tester. The first measurement was at the centre of the weld in the same region used for the nanoindentations tests. A few more microhardness tests were performed around the first indentation and the average was then determined.

Trial tests were performed to determine the best load for the microhardness test to give an accurate hardness value. The general rule **[10]** is that the load should be such that the Vicker's diagonal is not smaller than 10 μm. According to German Standard DIN 51 225, $V.d \leq 14$ mm where V is the total magnification and d is the diagonal in μm. The magnification used on the microhardness tester was 400; therefore the diameter must be smaller than 35 μm. The size of the indentations was in the range 25 to 30 μm with a load of 100 gf. The selected test load for the mild steel was, therefore, set to 100 gf with a dwell time of 15 s. The microhardness of the specimens is given in terms of the Vicker's pyramid number or VPN.

A distance of not less than 2.5 times the diagonal of the indentation is required from the free surface and between the disturbed area i.e. indentations. The hardness would be affected by material flow at the free surface of the specimen and also by the work hardening at the disturbed area surrounding the previous indentation. The distance between successive indentations was 100 μm.

III. NANOINDENTATION TEST

A. Specimen Preparation

The specimens must be electropolished **[11]** for the nanoindentation tests to remove the dislocations and effects of mechanical grinding. The nanoindentation tests require that the specimens be in mount of about 30mm diameter, therefore, the specimens used for the microhardness had to be mechanically polished again and then electro polished.

It is recommended **[12]** to mechanically grind the specimens to grit 600 before electropolishing but the time required to electropolish a specimen decreases with finer mechanical polishing. It is also stated that more time may be required to establish polishing conditions when starting with a fine mechanically polished surface. The surface in this case was ground using grit size 600 followed by 1200 and finally polished using 3 μm diamond. This was done after trial tests and also to reduce the electropolishing time as large electropolishing time may adversely affect the surface.

B. Parameters for Electro Polishing

The chemical composition **[12]** of the electrolyte was 25g CrO_3, 133 mL acetic acid and 7mL water and the voltage used was 20 V with a recommended current density of 0.09-0.22 A/cm^2. The temperature of the electrolyte during the electropolishing process was maintained in the range 17-19^{0}C by a water bath.

The set up during the electropolishing process is shown in Fig 1. The specimen is held in the electrolyte by the anode and the "L" shaped copper cathode is on the side of the beaker. Thermometers are used to monitor the temperature of the electrolyte and the water bath. The bakelite mount is hanging inside the beaker from the anode. The surface of the mild steel specimens is almost parallel to the lower horizontal part of the copper cathode (inside electrolyte).

The specimens were lightly etched prior to the nanoindentation testing using 2% Nital as Yao et al. **[11]** reported that the formation of the oxide layer has some effect on the nanoindentation burst in 316 stainless steel. This also helped in identification of the area to be tested.

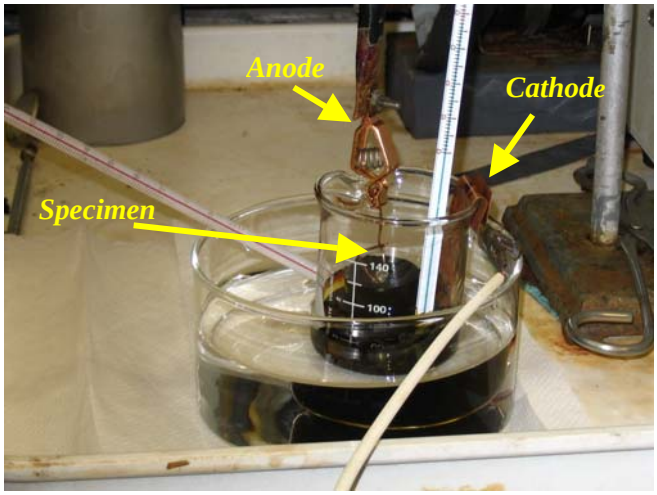

Fig 1: Set up during electropolishing

C. Measurements

The properties of materials can be measured by measuring the penetration depth of indenter using displacement transducers and the typical load used is in the range 10^{-5} to 10^{-2} N **[13]**. At this load the volume of material involved during indentation is much smaller than at microhardness level, hence allowing a better control over the local features.

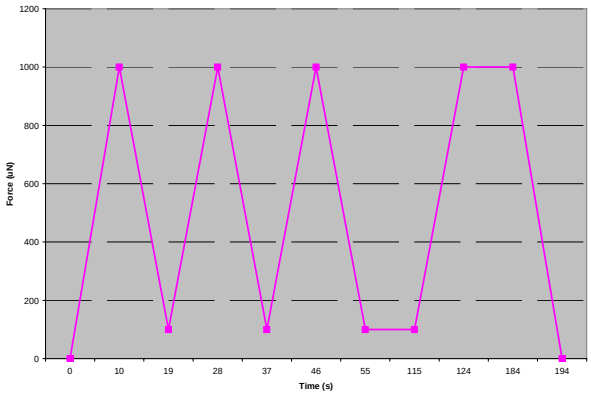

Fig 1: Loading sequence for nanoindentation tests

The specimens were subjected to a similar load-time sequence (Fig 2) as that used by Oliver et al **[9]** using a Berkovich indenter. The maximum load and the loading/unloading rate used in this experiment were 1000 μN and 100 μN/s respectively. The indenter was loaded to the maximum load and unloaded by 90% of the peak load three times in succession. The load was then held at the 10% of the peak load for 60 seconds during which the drift rate was monitored. The specimen was then loaded to the peak load followed by a 60 seconds hold and finally unloaded completely.

The total number of segments, including the approach segment, in this case is 11 and the maximum that can be used with the Nanoindenter II is 13. A drift rate of 0.2 was selected as lower values can affect the measurements and stop the whole process.

16 indentations were made in a square matrix of 4*4 at the centre of each of the weld bead. The first row was close (approximately 100 μm) and aligned with the surface of the weld bead. The distance between the indents was 100 μm for the 400 mm/min welds and 50 μm for the other two welds. Different distances were used to cater for the change in the weld bead size and to allow a sufficient number of indents to be made in the top centre of the weld. The average depth of penetration observed was 100 nm which would give an indent of approximately 650 nm in size as compared to an average of 25-30 μm with microhardness testing.

IV. Results

A. Hardness of reference Welds

The results obtained for the last unloading only has been considered and the Poisson's ratio was taken as 0.3. The average microhardness and nanohardness of the parent plate is 104 VPN and 3.0 GPa respectively.

The changes in the average Vicker's hardness for the respective region under consideration have been computed and compared with changes in the hardness obtained from the nanoindentation tests.

The nanohardness for each of the unloading segment (segments 3, 5, 7 and 11) were determined by the nanoindentor. The nanohardness was found to decrease almost linearly with the unloading segment in each case. A larger drop was observed from unloading segment 7 to unloading segment 11, and this is due to the holding segments. The hardness from the last unloading segment is the required one as it caters for elastic deformation and the drift rate.

The hardness in GPa obtained from the nanoindentation shows an increase at all laser welding speeds as compared to the hardness of the parent plate, the increase varying almost linearly with speed. The increase in hardness is 46%, 73% and 86.7% at 400, 1200 and 2000 mm/min respectively. The magnitude of the increase is much less than that obtained with microhardness at all three speeds.

The trend in the change in hardness at the nano and micro scale for the reference welds are seen to agree. The microhardness values have been divided by 100 to be included in the same axes as the nanohardness in Fig 3. The gradient of the two trendlines are not the same which means that there is no direct relationship between the hardness at the two levels (i.e. nanohardness and microhardness). Conversion of the microhardness into nanohardness will have to take the welding speed into consideration.

Table 1: Hardness of Reference Welds Compared to Parent Plate

	Parent plate	weld 400	weld 1200	weld 2000
Av Nanohardness (GPa)	3.0	4.42	5.2	5.6
St. Dev	*0.4*	*0.66*	*2.2*	*1.9*
Av. Micro Hardness (VPN)	104.0	175.5	247.8	308.5
St Dev.	*4.1*	*8.2*	*11.3*	*22.6*

Table 2: Percentage Increase in Hardness of Reference Welds

Hardness Test	Percentage increase in hardness in reference welds		
	400 mm/min	1200 mm/min	2000 mm/min
Nano Hardness	46	73	86.7
Vicker's Hardness	67	135.8	193.5

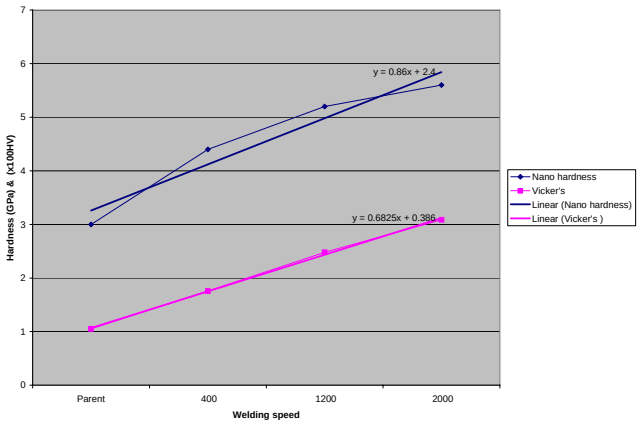

Fig 3: Hardness of Reference Welds Compared to Parent Plate

B. Hardness of US assisted Welds

The hardness in two different welds at two acoustical power, namely 3 and 6W, were considered for the welding speed of 400 and 2000 mm/min. The hardness in second specimen at 1200 mm/min could not be measured as it was damaged during specimen preparation for electropolishing. Two specimens were prepared from each ultrasonic welding condition.

The Vicker's hardness graphs for the three different speeds are completely separated at both ultrasound powers. This is due to the different cooling rate which is affecting the microstructure and phases formed. The hardness at each speed is varying within a relatively narrow range.

The nanohardness can be grouped into two categories namely the low speed (400 mm/min) and the high speed (1200 & 2000 mm/min). At 400 mm/min, the variations in hardness are similar to those of the microhardness at the same speed. The hardness at each ultrasound power is varying about a mean line. The nanohardness in the specimens for the two high speeds are within the same ranges but very irregular.

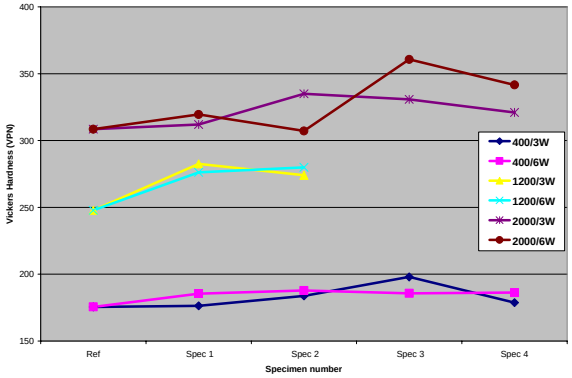

Fig 4: Micro Hardness of US Assisted Welds

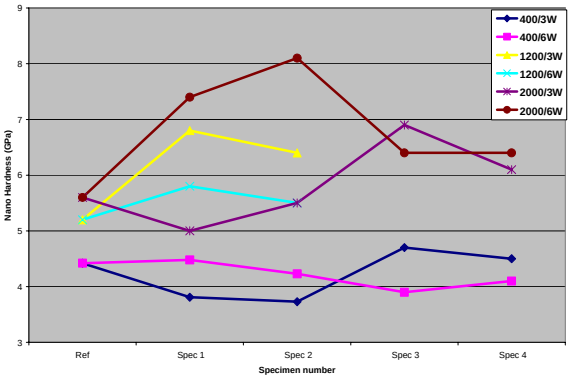

Fig 5: Nanohardness of US Assisted Welds

V. Discussion

The difference in the hardness values as well as the percentage change may be explained by the fact that the nanoindenter is measuring the hardness at a nano scale where the depth of penetration is only 100 nm whereas the depth of penetration with the microhardness tests is calculated as 3.57 μm for an indent diameter of 25 μm. The properties will depend on the phases present and its distribution in the microstructure. At 400 mm/min, the grain structure is relatively large with mostly coarse ferrite and pearlite. The high cooling rate and small size of the weld bead at 1200 & 2000mm/min is causing the formation of fine grained structure.

The microhardness is affecting a much wider volume hence measuring the hardness of different phases at the same time. The nanoindenter measurement is very localized disturbing a small volume of material and represents the hardness of a particular phase.

At the low speed, the hardness of the matrix of ferrite is being measured due to the large distances between the cementites needles in the structure. Ultrasound is causing a breakdown of the needles with little or no grain refinement.

The fine grain structure at the higher speeds gives a more compact distribution of the cementites in the microstructure. Ultrasound is causing a breakdown of the needles and a more regular distribution in the microstructure. The microhardness indenter is measuring the hardness over the same phases which results in a small change in hardness. The nanoindentor may in this case come into contact with the fine and closely distributed cementites particles in the structure.

VI. Conclusion

The effect of ultrasound on the properties depends on the level of the measurements and some changes may not be visible at some specific level. The lower the level the more distorted the results will be as the measurements become very localized.

The changes in the hardness at both levels are irregular. This confirms that the ultrasonic power does affect the hardness of the weld bead but there are also other factors which are involved. Some of these factors may be dependent on the ultrasound and its transmission in the plates.

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