

Investigation of the Grain Structure of the Fusion Zone of Single Pass Arc Welding of Structural Steel (NST 34 L-C).

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ABSTRACT

Some welded structures show poor mechanical properties at the weld and the adjacent zones. This has led to the collapse of structures when subjected to various torques. This research investigates the grain structure of the fusion zone of a single pass arc welding of structural steel to identify the mode of growth and grain transition of the zone and adjacent weld.

Two parameters – temperature gradient in the direction of solidification and rate of advance of solidification were studied vis-à-vis welding speed, arc current, and plate thickness. The results showed that changes in the welding variables affected the mechanical properties of the welded structure.

(Keywords: structural steel, fusion welding, solidification, temperature gradient)

INTRODUCTION

The intense heat of the arc (temperatures as high as 5000 C) when concentrated on the edges of pieces to be joined, melts the pieces and the electrode. The crystals that form during solidification of the weld pool are nucleated by the solid crystals located at the solid/liquid interface. This type of crystal growth is known as epitaxial.

Each grain forms initially as a continuation of the grain that lies along that path of the fusion boundary where the weld width is greatest. In this process, grain growth is initiated by arranging atoms from the liquid phase on the existing crystalline substrate, thereby extending it without altering the crystallographic orientation.

The continuity of crystallographic orientation across the fusion boundary was first confirmed by Savage and Aronson (Savage, 1980) using the Laue X-ray back reflection technique. As the

fusion boundary moves forward grains continue to grow in a columnar fashion.

Welders use various speeds in the welding of structural steel. Some failures have been unexplained by regular investigation. Many structures have failed when subjected to moderate torque or bending. The objective of this study therefore is to investigate the relationship of the speed of welding to the resultant structure of welded structures.

THEORY

A fusion weld has a primary grain structure and individual grains have a substructure which results from micro segregation. The type of substructure that appears in weld metal depends on the form of the solidification front. This, in turn, is influenced by the solute content of the liquid weld metal and by a solidification parameter equal to the temperature gradient in the direction of solidification G divided by the rate of advance of the solidification front R .

For any given solute content the microstructure tends to become more dendritic as the ratio G/R decreases. G/R is a significant parameter with respect to both the mode of growth and to final grain structure in solid solution alloys.

Progressive change in the ratio from a high to a low value is accompanied by successive transition in the mode of crystallization.[Kou, 1987]. The successive stages are illustrated in Figure 1.

Diminishing values of G/R brings about the cell→ dendritic transition with columnar growth now occurring on probes of solid some distance ahead of the main interface.

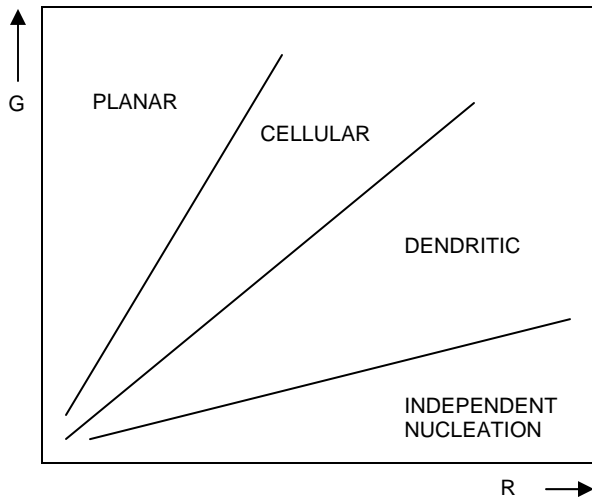


Figure 1: Influence of Temperature Gradient (G) and Freezing Rate (R) on Solidification Morphology of a Given Alloy.

For the weld pool solidification the freezing rate is equal to the welding speed V multiplied by the sine of the angle ϕ between the tangent of the weld pool boundary and the welding direction.

$$R = V \sin \phi \quad (1)$$

The temperature gradient $\frac{dT}{dx}$ is equal to:

$$\frac{dT}{dt} \cdot \frac{dx}{dt} = \frac{1}{V} \left[\frac{dT}{dt} \right] \quad (2)$$

For three dimensional heat flow, the gradient at the rear of the weld pool is numerically:

$$G = \frac{1}{V} \left(\frac{dT}{dt} \right) = \frac{T_m}{X_1} \quad (3)$$

where

- T_m = the melting temperature (C)
- X_1 = the distance between the heat source and the rear of the weld pool.
- G = temperature gradient in the direction of solidification
- R = rate of advance of solidification (freezing rate)

- V = welding speed
- ϕ = angle between the tangent of the weld-pool boundary and the welding direction.

At this point,

$$\sin \phi = 1 \text{ and } \frac{G}{R} = \frac{T_m}{VX_1} \quad (4)$$

X_1 increases with welding speed and therefore the parameter G/R falls as the welding speed increases. Also at the boundary of the fused zone, $\sin \phi = 0$ and G/R is theoretically infinite.

MELTING RATE CONTROLLING PARAMETERS

Heat is generated by electrical reactions at the anode and cathode regions and within the plasma. Part of this heat will melt the electrodes unless they are adequately cooled.

When the electrode is the cathode terminal, considerable control of the energy released is possible. Since heating is caused by the resistance of the electrode to the flow of current, it is expected to be dependent upon Ohm's law and be greater with small diameter electrodes, long extensions, and high electrical resistivity (Quigley, 1977). The relationship can be written as follows:

$$MR = aI + bL \left(\frac{I}{A} \right) \quad (5)$$

where:

- MR = the electrode melting rate,
- a = the constant of proportionality for the anode or cathode heating
- b = the constant of proportionality for electrical resistance heating and includes electrode resistivity.
- L = the electrode extension or stickout.
- A = the cross-sectional area of the electrode. This may be modified with some exponent to account for the presence of a flux etc.
- I = the welding current.

STRUCTURAL CHANGE IN THE HEAT AFFECTED ZONE (HAZ)

Welding is often described as being a small casting in a metal mould. The properties of the casting and the adjacent metal are directly related to the thermal condition and alloying element (Lindberg and Braton, 1976). It will be realized that there is a zone adjacent to the weld where the material is affected structurally by the heating and cooling associated with the welding cycle. This is termed the Heat Affected Zone (HAZ).

The fact that the material is heated to its melting point means that there is a temperature gradient in the material that is not melted and this clearly extends from its melting point down to the temperature of the material well away from the weld. The whole area of the weld will cool down as soon as the source of heat has been removed or has moved away from the point being considered, and the hottest material will cool most rapidly from the higher temperatures (Oyawale and Ibadode, 2004)

FACTORS AFFECTING WELD METAL COOLING RATES

Many factors affect the rate at which the weld deposit and the HAZ cool. Among these are the energy input, plate thickness, geometry, and thermal characteristics of the base metal (Kou, 1987). The term energy input is used to describe the amount of heat or energy used for each inch of weld and is determined as follows:

$$H = \frac{60EI}{S} \quad (6)$$

where, H = energy in joules/in.
E = voltage used
I = current in amps.
S = speed in inch/min.

The time a plate will remain at an elevated temperature tends to decrease with an increase in thickness and the thermal characteristics of a material and this is referred to as its diffusivity or thermal conductivity (Quigley, 1977). The lower the thermal diffusivity of the material, the steeper the distribution of peak temperature; the higher the thermal diffusivity, the shorter the time at elevated temperature for a thermal cycle with a given peak temperature.

Part of the heat affected zone becomes heated to the austenitic condition and transforms to martensite on being cooled rapidly. Cooling is by conduction into the surrounding metal and it is very rapid in welds which have not been preheated, particularly where heavy sections are involved. The extent of the change in the grain structure depends upon the maximum temperature to which the metal is subjected, the length of time this temperature exists, the composition of the steel, and the rate of cooling (Savage, 1980).

The cooling rate will not only affect grain size but it will also affect physical properties. As a rule, faster cooling rates produce slightly harder, less ductile, and stronger steel. For low carbon steels, the relatively small differences found in practice make insignificant changes in these values. However, with higher carbon content in appreciable amounts of alloying material, the effect may become significant. In their work, Glickstein and Friedman (Glickstein et al., 1981) demonstrated the time dependence of the shape of the isotherm representative of the heat-affected zone boundaries. From the table of thermal diffusivity of some at room temperature it will be noted that aluminum has a diffusivity of 0.912 while that of iron is 0.208. The peak temperature for aluminum is 660 C and that of iron is 1540 C. By comparison, the HAZ of a fusion weld in iron would have a higher peak temperature but the distance from the edge of the weld to where the metal remains at room temperature would be much less (about 23%) than that of aluminum (Kou, 1987).

MATERIALS AND METHODS

Mild steel (NST 34-L-C) was collected from the Osogbo rolling company in South Western Nigeria. These were cut into plates 110mm x 60mm and in thickness of 2mm, 4mm, 6mm, and 12mm. Welding electrode (E6013) gauge 12 was used for the welding of test pieces using an ESAB 175 ampere oil cooled welding machine set at 90 amps. A hacksaw was used to cut specimens which were filed, ground, polished and etched for examination on the metallurgical microscope.

Specimen Preparation

All weld tensile test pieces were prepared using the mild steel electrodes. A stop watch was used

to time the welding process for each pass and efforts were made to maintain the time for each specimen run.

Traveling/welding speed was then obtained from:

Length of weldment

Time taken

This was carried out for the various thicknesses of plates. The weld was then cut out and prepared for tensile impact and hardness tests. In addition, specimens were cut for microscopic examination. These were hot mounted in a thermoplastic material using a mounting press. The thermoplastic material was molded at a temperature under 200 C, which was low enough to avoid any structural damage to the specimen.

The specimen was then ground on a grinding machine mounted with successively finer grades of abrasive and lubricated by a stream of water. The gauges of emery papers used ranged from 320 to 1000 to create a very smooth surface.

Polishing was then carried out on a rotating cloth pad impregnated with aluminum oxide powder. Light pressure was applied in a circular motion until the surface of the specimen was free from scratches and shone like a mirror. It was then washed in warm water, swabbed with methylated spirit and dried in air.

Etching was carried out by immersing the specimen in natal agitating vigorously for a few seconds. It was quickly transferred into running water to wash away excess reagent. On completion of the etching the specimen was washed and dried.

Tests

Test pieces were prepared for the tensile test which was carried out on the universal testing machine. For the hardness tests, the specimens were mounted on the Brinell hardness tester using a 10 mm indenter under a load of 750 kg for 15 seconds. The hardness values were read using a microscope.

For the impact test, a specimen 110 mm long was machined into 10 mm square section with a notch 2 mm deep and radius $\frac{1}{4}$ mm with sides sloping at 45°. The piece was clamped in the izod tester

and tested. The energy possessed by the falling weight was recorded. A metallurgical microscope was used to observe the specimen earlier prepared after which the microstructure was snapped on a black and white film using an attached camera (see plates 1 – 10).

RESULTS AND DISCUSSIONS

The impact test results were different for the different welding speeds and plate thickness. For the 4mm plate, the highest mean impact value was recorded at the speed of 1.83 mm/sec. For the 6 mm plate, the highest value was recorded at a speed of 2.5 mm/sec and the lowest was at 4 mm/s. With the 12 mm plate, the highest value was recorded at 5 mm/sec and the lowest value was recorded at 2mm/sec (see Tables 1 - 3).

The microstructure revealed that the grain growth region was immediately adjacent to the weld metal zone. In this zone, parent metal has been heated to a temperature well above the upper critical A_3 temperature. This resulted in grain growth, or coarsening, of the structure. The grain refined region is the region adjacent to the grain growth region.

The parent metal has been heated to just above the A_3 temperature where grain refinement was completed and the finest grain structure existed. In the transition zone, a temperature range existed between the A_1 and A_3 transformation temperatures where partial allotropic re-crystallization took place. The parent metal outside the heat affected zone remained unaffected. The rate of growth relative to the rate of nucleation was greatest at or just under the freezing point. In a case where the molten metal was in contact with a cool boundary, a temperature gradient would exist in the liquid.

The outside was at a lower temperature than the centre and therefore started to solidify first. Thus many nuclei were formed at the interface and began to grow in all directions. Since the heat source moved rapidly away, the direction of grain growth was in the direction of movement of the heat source. In general, fine-grained materials exhibited better toughness or resistance to shock. They are harder and stronger than coarse-grained material.

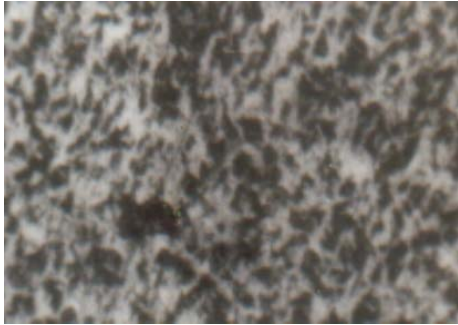


Plate 1: 2mm thick at 1.83mm/sec.



Plate 6: 6mm thick at 1.2mm/sec.



Plate 2: 2mm thick at 3.14mm/sec.



Plate 7: 12mm thick at 5.5mm/sec.



Plate 3: 4mm thick at 4mm/sec.



Plate 8: 12mm thick at 1.3mm/sec.



Plate 4: 4mm thick at 7.5mm/sec.



Plate 9: 12mm thick at 6.2mm/sec.



Plate 5: 6mm thick at 2.83mm/sec.



Plate 10: 12mm thick at 1.3mm/sec.

Table 1: Impact Strength and Hardness for 4 mm Plates Welded at Various Speeds.

Speed (mm/s)	Impact Strength	Hardness
1.83	52.8	228.0
3.14	22.7	226.7
5.5	38.5	173.3

Table 2: Impact Strength and Hardness for 6 mm Plates Welded at Various Speeds.

Speed (mm/s)	Impact strength	Hardness
1.3	33.5	212.0
2	41.4	237.3
2.5	48.8	182.0
4	25.9	145.3

Table 3: Impact Strength and Hardness for 12 mm Plates Welded at Various Speeds.

Speed (mm/s)	Impact strength	Hardness
2	47.8	160.3
3.5	47.6	181.7
5	49.8	160.7

CONCLUSION

1. At the region immediately adjacent to the weld metal zone, the microstructure showed that the structure was coarsening and large regions of pearlite and smaller ferrite could be seen.
2. At the transition zone, the microstructure showed that the ferrite grains had not been altered but the pearlite region had been made much finer.
3. The microstructure of the parent metal that was not heated sufficiently to change its microstructure showed the typical grain structure of the parent metal (ferrite (white), pearlite (dark)).
4. The mechanical properties of the structural steel were different with welding speed, plate thickness and arc current.
5. The heat-affected zone was weakest at the weld. Most welding failure originated in this zone.

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SUGGESTED CITATION

Oyawale, F.A. and K.O. Sanusi. 2008. "Investigation of the Grain Structure of the Fusion Zone of Single Pass Arc Welding of Structural Steel (NST 34 L-C)". *Pacific Journal of Science and Technology*. 9(1):173-178.