# THE EFFECTS OF VIBRATION ON THE MECHANICAL PROPERTIES OF LOW-CARBON STEEL WELDED JOINTS

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## ABSTRACT

*In this study, the effects of mechanically induced vibrations on the mechanical properties of low carbon steel (0.18%C) was evaluated. Specimens were prepared for double V-butt welding on an electro-mechanical vibrating device that was designed and constructed specifically for the purpose of inducing vibration of frequencies 0Hz, 8.33Hz, 16.67Hz, 33.33Hz and 50Hz in the vertical direction on the welded joints. Tests for the percentage elongation, yield strength, impact strength and hardness tests were carried out. Metallographic analysis of the joints was also carried out. The yield strength increased with the frequencies of vibration up to a maximum value of 378N/mm$^2$ at about 47Hz, the percentage elongation had a generally increasing trend, and the impact strength was steadily declining while the hardness property initially increased with the frequencies of vibration up to a maximum value of 1.6kN/mm$^2$ at about 30Hz but thereafter started to drop. It is discernable from the photomicrographs that the grain sizes of the welded joints was decreasing steadily with the increase in vibration frequencies up to a minimum value of about 0.83μm at 32Hz, which is the point of the best grain refinement, but thereafter started rising.*

## INTRODUCTION

Welding operations carried out in the course of the maintenance of moving ships and submarines, on oil platforms on the high seas or in compressor rooms (while the compressor is still running) is definitely under the influence of induced vibrations (which is often multi – directional) due to the sea waves.

Mechanical vibrations can be used to improve the mechanical properties of castings and weldments by the way of grain refinement, but it is still necessary to determine the specific conditions under which this improvements can take place or the pattern of variation of this properties that can take place over a range of vibration frequency especially in the unique situations sited above which is the motivation for this work.

**Grain refinement and Strengthening of Steel**

The production of high strength structural materials is mainly based upon developing a product in which the grain size is as small as possible. The combination of good strength and toughness with low transition temperatures in steels is thus obtained by sophisticated treatments, which refine the grain size without hardening the grains [Easterling, 1993].

The following are the reasons why it is necessary to have refined grains in castings or any other metal fabrication process:

i. Twinned columnar grains have been noted to have poor fabricability, castability and mechanical properties when compared with the fine equiaxed grain casting. Products for structural applications are also noted with reduced mechanical properties, especially yield strength and tensile test to failure, when a uniform equiaxed grain is not achieved [Kashyap and Chandrashekar, 2001; Easton and StJohn, 1999; Radjai and Miwa, 2002].

ii. A coarse grained structure may result in a variety of surface defects in alloys used in rolled or extruded form, while the size of defects such as micro-porosity may reduce as a result of fine grain structures since the solidification of smaller, grains will allow the mould to fill more completely and avoid unfavourable micro and macro - porosity thereby producing a sound casting [Kashyap and Chandrashekar, 2001; Easton and StJohn, 1999; Binney et al, 2003].

iii. Hot cracking in the shell zone of the cast ingots have also been known to be more severe if the grain structure is not equiaxed. An equiaxed structure allows a higher casting rate to be achieved before hot cracking is produced [Kashyap and Chandrashekar, 2001]. Sadayappan M. et al (2004) also reports the improvement of fluidity and hot tearing resistance in permanent mould casted copper alloys due to grain refinement.

According to Smallman R. E and Bishop R. J. (2000), alloying, solute dislocation, grain size control and cold working can give rise to an increased yield stress. Of these methods, refinement of the grain size is of universal application for materials in which the yield strength has a significant dependence upon grain size.

Honeycombe R. W. K (1993) also reported that, an added bonus of fine grain size is that, the toughness of the steel increases with decreasing grain size. It is therefore a method for strengthening which at the same time leads to increased toughness. In the last two decades, emphasis has been placed more on the development of methods of processing and suitable steels to achieve very fine grain size. There is also of course, increasing emphasis on high quality steels which resist cracks initiation and propagation.

Grain refinement therefore remains a very important means of improving on the physical and mechanical properties of the welded joint. It is achieved through the addition of heterogeneous nuclei in a controlled manner during solidification. This result in an increase in the number of grains and grain boundaries formed.

Grain boundaries are remarkable effective barriers to dislocation motion because effective grain size strengthening can be obtained only when the grain boundary density is high (Courtney, 1999). The change in orientation at individual grain boundaries impedes the propagation of the cleavage crack by:

i. Creating cleavage steps
ii. Causing localized deformation, and
iii. Tearing near the grain boundary.

It is the extra work done in this process that apparently increases the surface energy. Therefore the smaller the distance a crack is able to propagate without being deviated by a change in orientation of the cleavage plane, the greater is the resistance to brittle fracture (Smallman and Bishop, 2000).

The techniques that could be used to grain refine industrial alloys were classified into the following three categories by Elliot R (1997):

i. Thermal techniques
ii. Mechanical techniques and
iii. Chemical techniques.

The chemical techniques basically refers to alloying of the materials, for example, it is fairly evident that an improved notch toughness steel, compared with that used for welded ships in World War II, is given by increasing the manganese content and decreasing the carbon content [Smallman and Bishop, 2000].

The main thermal technique employed for the purpose of achieving grain refinement is ensuring sufficient undercooling in order to facilitate the survival and growth of the nuclei. This may be established by either rapidly cooling thereby generating bulk undercooling and/or by partitioning of solute during solidification to generate constitutional undercooling [Binney et al, 2003]. The other thermal techniques include the heat treatment or thermo-mechanical treatment of the cast product.

The mechanical techniques include mould vibration, magnetic stirring of liquid metal, ultrasonic irradiation of the liquid metal, ultrasonic cavitations and so on. In relatively recent works, Vives C. (1998), and Radjai A. and Miwa K.(2002), have studied the effects of electromagnetic vibrations induced by the interactions of alternating electric and stationary magnetic fields during solidification of aluminum alloys and gray iron to achieve considerable structural refinement as a result of the cavitation phenomenon.

Although their results successfully present the advantage of acting uniformly without material contact with the melt, the process suffers a major drawback in the substantial energy consumption that is required to reach the cavitation threshold.

The methods highlighted above are however mainly used for high-energy input welds such as submerged arc and electro slag welding, where the grain structure is usually relatively coarse. Moreover, according to Easterling K. (1993), research is still in progress to develop mechanical techniques for refining welds and currently, there are still very few industrial applications of grain refinement in weld metals, except possibly in Russia.

This work is aimed at investigating the impact or effects that directly induced mechanical vibrations have on the welded joints of low carbon steel in the course of the welding. This is to be done by examining the mechanical properties and metallographic structures of the joints welded at different vibration frequencies of excitation.

## MATERIALS, EQUIPMENT, METHODS AND TESTING

### Material

A good length of rolled annealed low carbon steel rod with the following chemical composition was obtained:

**Table 1: The Chemical Composition of Elements in the Welded Material**

| Element | Chemical Composition, % |
|---|---|
| C | 0.18 |
| Si | 0.20 |
| Mn | 1.11 |
| S | 0.007 |
| P | 0.005 |
| Ni | 0.62 |
| Cr | 0.31 |
| Mo | 0.39 |
| Cu | 0.31 |
| Fe | Bal |

**Welding Procedure**

The steel rod was cut into pieces of 200mm lengths. Two pieces of the material were prepared for the double V-butt welding pattern. They were held firmly, end - to - end by clamps fixed to the vibrating surface of the vibrator to enable the pieces to be welded as the clamps vibrated. After welding, each welded piece was dressed to 12mm diameter (this was the original diameter of the pieces) by turning on the lathe machine with heavy supply of coolant.

The current/voltage selector of the electric arc welding machine was adjusted to 110Amps and the vibrator activated by depressing the foot pedal connected to the electric motor for this purpose. Prior to this, the speed of the electric motor was adjusted by means of the potentiometer. Variation in the amplitude of vibration of the system was made possible by the adjustment of the potentiometer, which was connected to the switch of the electric motor to enable the speed of the motor to be regulated from 0 to about 4500 revolutions per minute, thereby altering the vibration frequency of the system.

For every speed selection, three pairs of the specimen pieces were welded in turn so that average values could be obtained for each test. Welding was first carried out on three pairs of specimen when there was no vibration.

**Mechanical Property Testing**

The test pieces were tested by tensile test to failure for yield strength and elongation (or ductility) according to British Standard and American Standard of Materials and Testing [BS 4A-1.2(1967), ASTM E8-04 (2004)] using the Makewa Universal Testing Machine.

The evaluation for the impact strength of the tested pieces was achieved through the Avery Universal Impact Testing Machine in accordance with the British Standard and American Standard for Testing and Materials [BS 131 part 1 (1989) and ASTM E23-05 (2005)]. The specimen was prepared with 2mm deep V-notch and struck with 163J impact energy from the pendulum swinging from a height of 0.61m with a velocity of about 3.5m/s.

Vickers diamond test was adopted for the hardness testing of the test pieces. This was carried out in accordance with stipulations and instructions in British Standard and American Standard for Testing and Materials [BS EN ISO 6507 (2005) and ASTM E92-82 (2003)] on the Avery's Universal Hardness Testing Machine. The indenter was forced into the surface of the test pieces under the action of a 785N static load for 15 seconds.

### Metallography

The metallographic examination test pieces were obtained by cutting through the welded joints, prepared by wet grinding, polished with 7μm diamond paste etched with 2% Nital as specified by the American Society of Metals [ASM Handbook, 2004; Smithells Metals Reference Book, 2003] and observed and photographed using a metallurgical microscope.

Vicker's M17 metallurgical microscope with inbuilt automatic exposure unit for 35mm photographic camera was used for the examinations. Photomicrographs were obtained for the various test pieces at x100 magnification. The microstructures gave the usual prominent light and dark microstructures necessitating the adoption of the Heyn's intercept method. The grains size was estimated by counting on the photomicrograph. Counts were made on three fields of view. The grains touched by the end of the line were counted as half grain.

## RESULTS

### Mechanical Property Testing

The results of the mechanical property testing for the welded specimens at different vibration frequencies are presented in Fig.1 to 5.

### Metallography

The results of the metallographic examination for the welded specimens at different vibration frequencies are as presented below in Figs 6 to 10.

## DISCUSSION OF RESULTS

### Mechanical Property Testing

Fig. 1 shows a steady decrease in the measured grain sizes as the excitation frequency of vibration increases up to about 32Hz where the best grain refinement was achieved, thereafter the grain sizes started to increase again. This observation is supported by the photomicrographs presented in Figs 6 to 10. Grain refinement could be clearly seen as the excitation frequency of vibration of the specimens increased from zero, but the best refinement could be seen in Fig. 9 where the specimen was vibrated at 33.33Hz excitation frequency.

As shown in Fig. 2, a steady increase in the yield strength of the welded joints can be seen as the excitation frequency of vibration increases from 0 to about 44Hz, beyond this the yield strength started to fall. This increase in strength may be linked with the process of cavitation which generates impulsive pressure within the molten liquid, which in turn fractures the primary crystals so that the resulting fragments could act as nuclei.

The percentage elongation or ductility of the welded joints increased steadily as the vibration frequency increased. This trend, which is shown in Fig. 3 may be attributed to enhancement of better of feeding and redistribution by accompaniment of the welding process with vibration.

Interestingly, the notch impact energy absorbed by the welded joints, as presented in Fig. 4, steadily decreased without fluctuations as the intensity of vibration increased from the unvibrated position. This is not unexpected because; the grain sizes are expected to be larger at lower vibration frequencies thereby being more capable of withstanding shock loads on impact.

The hardness of the welded joints, as shown in Fig. 5 increased steadily from $1.31kN/mm^2$ at the unvibrated position to the peak value of about $1.60kN/mm^2$ at about 29Hz excitation frequency before beginning to descend in this same manner. It is however noteworthy that the entire variation of the hardness values (that is, $1.31kN/mm^2$ to $1.60kN/mm^2$) was marginal, this is mainly because there was very little change in the composition of the welded joint.

The trend of variation of the hardness property could be explained as being caused by the fact that, at lower frequencies the grains were larger not well packed thereby tending to be softer when subjected to indentation or abrasion.

**Metallography**

The photomicrographs reveal the presence of two phases – ferrite and cementite – arranged as two micro-constituents – primary ferrite ($\alpha$ - ferrite) and pearlite. The structures generally consist of islands of pearlite structures surrounded by the primary ferrite. According to Askeland D. R. and Phule P. P. (2005) this permits the welded joint to be strong, due to the dispersion – strengthened pearlite, yet ductile due to the continuous primary ferrite.

The unvibrated position was characterized by the presence of relatively bigger grains and porosity defects. However at lower excitation frequencies the porosity defects were highly reduced and there were rearrangement of the grains but grain refinement was not prominently noticed until the excitation frequency was in the region of 33.33Hz. As the excitation frequency increased, the grain sizes reduced considerably until there was almost absence of voids.

At 55Hz, there was further refinement of the grains but they had so reduced in sizes that they began to fuse together forming cluster of grains, this is similar to the phenomenon described by Gray T.

G. F. and Spence J. (1982): when a steel is held in the upper austenite range for a long time, the grains tend to increase in size due to grain boundary migration and coalescence.

## CONCLUSION

The study revealed that at some specific excitation frequencies of the vibration, the mechanical properties and metallographic structures of the welded joints was clearly influenced, this showed that not all levels of vibration frequencies are tolerable when welding low carbon steel. The best grain refinement was achieved when the frequency was in the region of 33Hz. This grain refinement situation affected most of the mechanical properties of the material as the material had extreme values at points in the region of 33Hz.

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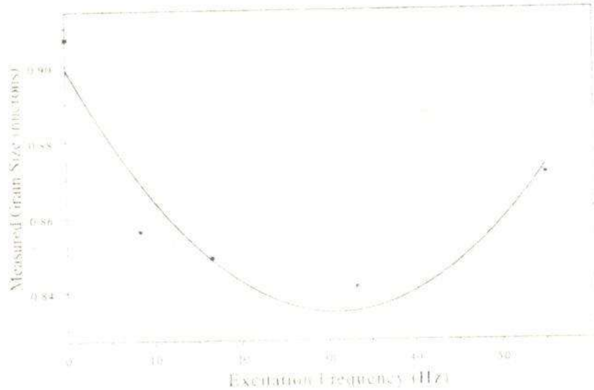

**Fig. 1: Variation in Measured Grain Sizes with Excitation Frequency**

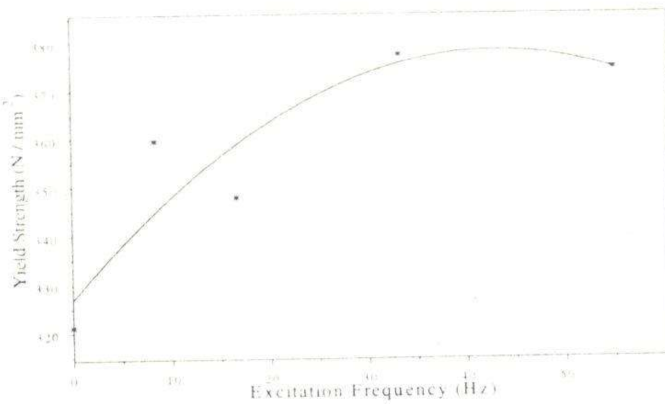


**Fig. 2: Variation in Yield Strength with Excitation Frequency**

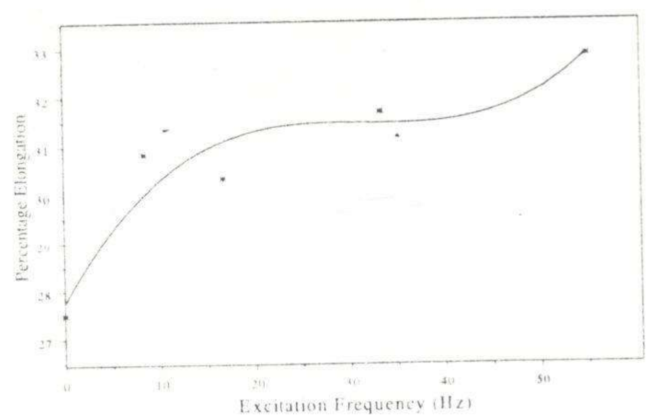


**Fig. 3: Variation of Elongation (at the point of breaking) with Excitation Frequency**

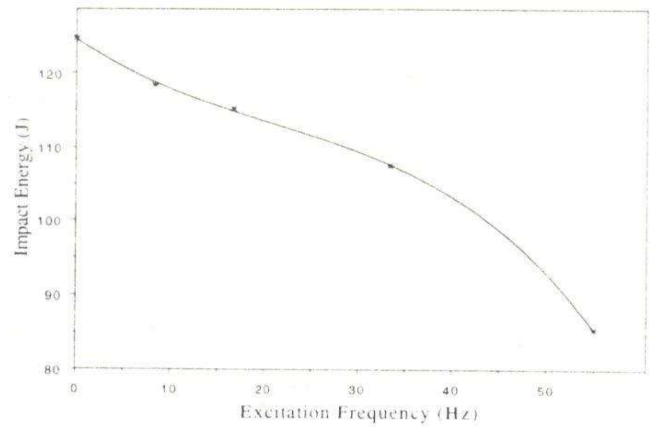


**Fig. 4: Variation of Impact Energy with Excitation Frequency**

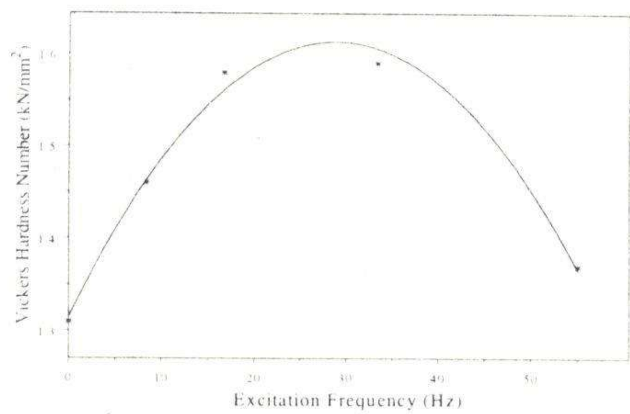


**Fig. 5: Variation of Vickers Hardness Number with Excitation Frequency**

**Fig. 6: Welded Specimen without Vibration (Magnification x100)**

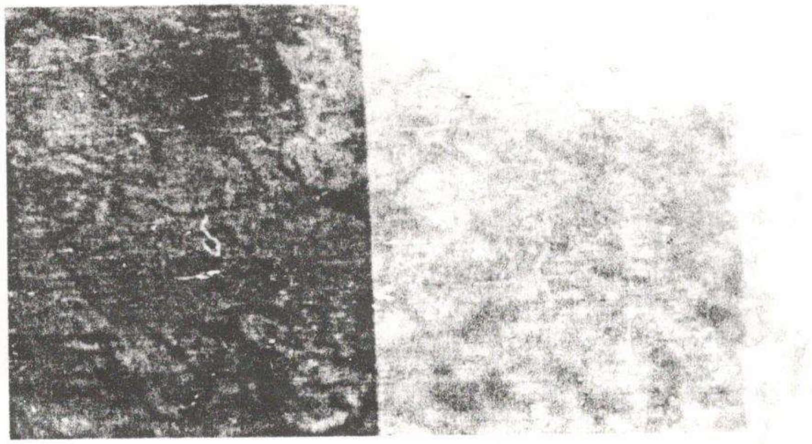

Fig. 7: Welded Specimen Vibrated at 8.33Hz Excitation Frequency (Magnification x100)

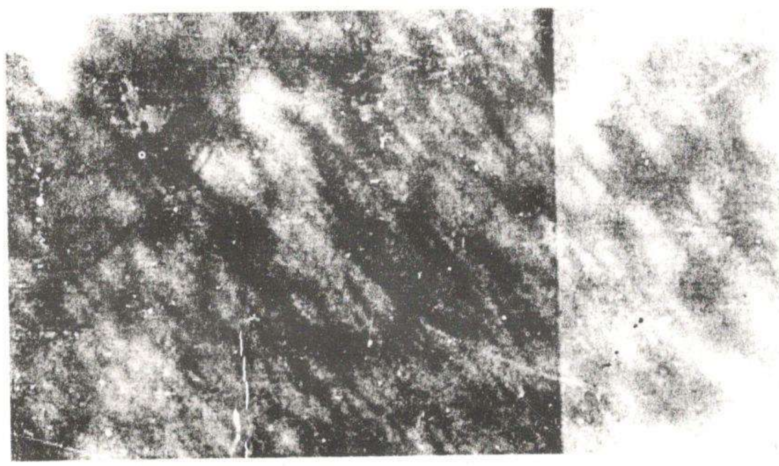

Fig. 8: Welded Specimen vibrated at 16.67Hz Excitation Frequency (Magnification x100)

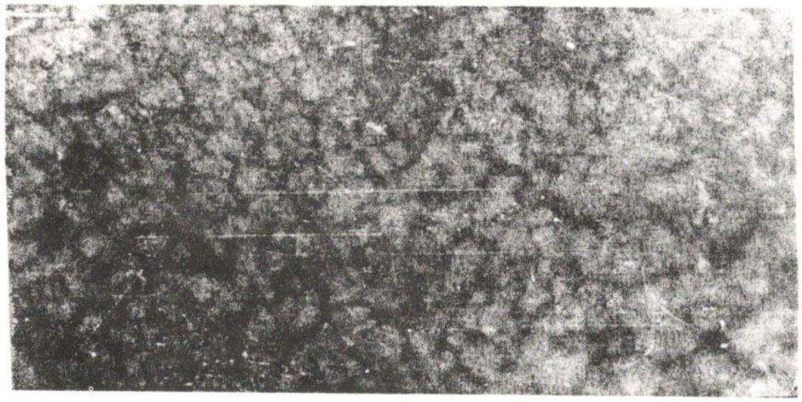

Fig. 9: Welded Specimen vibrated at 33.33Hz Excitation Frequency (Magnification x100)

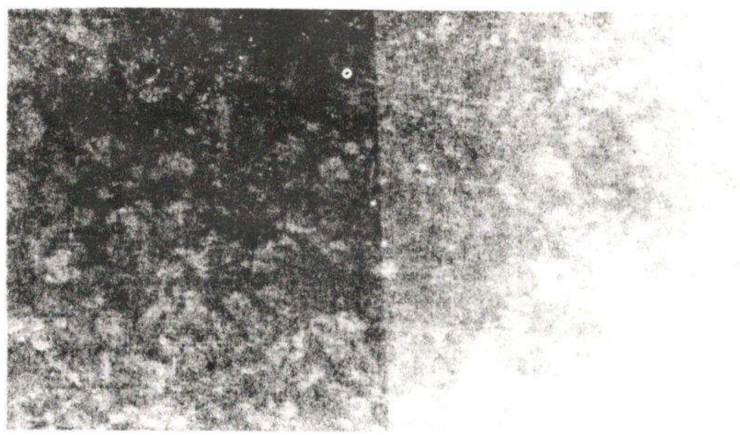

Fig. 10: Welded Specimen Vibrated at 55.00Hz Excitation Frequency (Magnification x100)