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Investigation of the Impact of Vibrations on the Fatigue Behaviour of Al 5052 Alloy Weldments

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Abstract - Welded joints undergo severe heating and cooling cycles. Repeated heating and cooling cycles along the specimen reduces the service life of welded structure. Service life of welded joints is of prime of importance. In this, experimentation is conducted to analyse the microstructural behaviour and fatigue life of aluminium welded joints under the vibratory TIG welding process parameters. A comparison is made to analyse the behaviour of aluminium 5052 alloy under with vibration and non-vibration condition. Axial fatigue test conducted on the specimens fabricated with and without vibrations. Average fatigue life of the specimens is estimated at the predefined load conditions and S-N curve plotted for the both with and without vibrated specimens. Fatigue life of the specimen was improved with vibrations at 0.9, 0.7 and 0.5 UTS compared to without vibrations. Improvement is around 14% at stress level I that is 0.9UTS and there is 10% improvement in the fatigue life at maximum stress level 0.5UTS (level III).

Key words: *Fatigue life, Vibratory TIG welding process, Aluminium 5052-H32 alloy, Ultimate tensile strength, Vibrations*

1. INTRODUCTION

Aluminium alloys are generally used in the aircraft applications because of their high strength to density ratio. Over the years, extensive research has been conducted to better understand the fatigue behaviour of aluminium alloys. The fatigue process is made up of crack initiation and crack propagation until failure. Fatigue life expectancy is linked to stress and strain levels. Cracked specimens are utilized to investigate crack growth behaviour, and fracture mechanics techniques are commonly employed to characterize the propagation of crack. For the design and evaluation of a load-bearing structure, various approaches give emphasis to either the initiation of crack or growth of crack has been developed In the designs of Navy and Air Force, follows two basic approaches to fatigue design that are currently in use they are damage tolerance and safe-life [1]. The first method only considers fatigue crack nucleation, whereas the method forecasts crack growth. The "safe-life" method may be more appropriate for fatigue design of a structure, whereas the "damage tolerance" approach may be more appropriate for evaluating an existing component. Although there are disagreements about the appropriate definition of crack initiation, it is widely known that in the high cycle fatigue regime, the crack initiation phase consumes the majority of the life. Knowledge and predictions of crack initiation life are critical for assessing a structural component's fatigue life. Crack initiation behaviour serves as the foundation for crack growth predictions [2].

The majority of aluminium alloy experimental studies focused on uniaxial tension-compression loading with mean stress effects [3]. It is frequently discovered that the Coffin-Manson relationship for aluminium alloys does not obey the single slope behaviour in the minor plastic strain region. The standard linear log-log relationships between fatigue life and elastic and plastic strains did not adequately correlate the experimental consequences for 2024-T4 and 7075-T6 aluminium alloys. Plots of plastic strain amplitude versus fatigue life for aluminium alloys demonstrated the linearity of the Coffin-Manson relationship down to a critical level of plastic strain [4].

The relative inability of the microstructure to develop homogeneous slip during low plastic strain cycle was related to the deviation of the fatigue results of aluminium alloys from the single slope behaviour of a Coffin-Manson plot. The stress amplitude versus fatigue life curve of aluminium alloys, including 7075 aluminium alloy, is subjected to a bi-linear relationship. The bi-linear S-N model was shown to provide a better representation of the data than the commonly used single slope linear model [5].

Effect of harmonic vibrations on the size and distribution of intermetallic compounds in the gas metal arc welding of Aluminum 5083–H32 alloy were analysed. Interestingly grain size reduced from 200µm to 50µm with increasing the vibrations from no vibration condition. Intermetallic compounds such as Al_6Mn and Al_3Fe formed in the joints in discontinuous manner in the case of no vibration condition. Area fractions of intermetallic compounds were more in the samples prepared in the presence of harmonic vibrations [6].

Influence of vibratory stress relief on the residual stresses were analysed through simulation using Finite element method and Hole drilling method (strain gauge measuring method). More than 80% longitudinal residual stresses were decreased, when the magnitude of vibration frequency is 95% of the natural frequency of the specimen. Residual stresses decreased with the increasing of the vibration force [7].

Mechanical and microstructure characterization were carried out in the vibrated and non-vibrated steel specimens. Authors observed that there is no considerable difference in the hardness and tensile strength of S235 steels with vibration. All the samples failed at far from the HAZ [8]. Thermal and mechanical analysis was carried out on Inconel 625. A multi pass model developed and tested for the residual stress distribution and is compared with simulations in the ANSYS [9].

Aluminium alloys have many more advantages, including corrosion resistance, acceptable formability and weldability. Because of these advantages, Aluminium has been universally used in the marine, automotive and construction industries. Welding is a common method to join a wide variety of materials. During the welding process, a portion of the specimen is subjected to heating. Because of the localized heating specimen is subjected to thermal expansion. In general, with the change in temperature, materials tend to shrink or expand. When the material at the weld bead solidifies, it pulls the adjacent material to maintain the bond. So that it causes to develop welding residual stresses. Residual stresses may be of either tensile or compressive. Compressive residual stresses increase the service life of structures. Tensile residual stresses cause the service life to decrease. Tensile residual stresses need to be reduced or relieved from the structure.

There are several ways to decrease tensile residual stresses i.e., design considerations, preheating, shot peening, natural ageing, sequence of welding and post welding heat treatment. Most of these methods are time consuming and costlier. There is another alternative way to decrease residual stresses that is vibratory stress relief. Most of the researchers concluded that stress relief through vibrations has a positive influence on reducing the residual stresses and increasing the mechanical properties of materials treatment [11]. To increase the hardness and tensile strength of 1018 mild steel materials a noval approach of mechanical vibrations is introduced [12-13].

Little, R (1975) [14] mentioned the techniques to analyze the facts associated with fatigue, techniques to design the fatigue experiments, planning strategies for test, methodology for determining the sample size, stress stage selection and determination of average fatigue life.

2. MATERIALS AND METHODS

In this a novel vibratory welding system is developed. It mainly contains of a platform on which the specimen is clamped and then welded. Eccentric rotating mass vibration motor (ERMVM) is fitted to the platform of the vibration setup. Specimen is vibrated by changing the voltage given to the ERMVM through dimmerstat. Amplitude by which the sample is pulsated can be regulated by this dimmerstat. In order to analyze the fatigue life, Aluminium 5052-H32 specimens are taken into consideration. It consists of 2.2 to 2.8% Mg. double V-butt joints of 150 mm length and 100 mm width and 5 mm thick plates are taken into consideration for the experimentation. Specimens are welded at a voltage input of 160V. Specimens are also welded without giving any vibrations.

3. RESULTS AND DISCUSSIONS

The welded specimens prepared with and without vibrations are subjected to axial fatigue testing. Following are the Steps to determine the fatigue life and to establish the S-N curve.

Conducting static tests to determine the UTS.

Stress level selection based on the results of static tests.

Sample size determination.

Conduction of fatigue tests.

Analysis and presentation of fatigue test data.

Specimens were set for tesnsile test as per ASTM E8 and these specimens were tested on universal testing machine. Average value of ultimate tensile strength was considered as the final tensile strength of the material. The ultimate tensile strength of without vibrated and specimen prepared at 160V vibration as 198MPa and 227MPa respectively.

Achutha et al., (2008) [15] mentioned a standard procedure to conduct fatigue tests at 3 or 5 levels. In this experimentation 3 stress levels are considered, i.e., level-1 (90% UTS), level-II (70% UTS) and level-III (50% UTS). At each level of stress, the sample size was obtained at confidence level of 90% based on the following assumptions. i) Fatigue lives are not uniform (Scatter) at all the stress levels ii) Tolerable error percent is 10%. iii) At stress level one the assumed coefficient of variation percentage is 4, for stress level two assumed coefficient of variation percentage is 5, and for stress level three assumed coefficient of variation is 7.

In case at a given stress level, if the %COV of fatigue life is more than the assumed one, in order to maintain some percent error additional specimen has to be tested. Sample size required for 90% confidence and 10% error for specimens prepared with and without vibration is shown in Table 1.

Table 1: Sample size required for 90% confidence and 10% error for Specimens prepared at 0 vibrations and 160 volts vibration

	Stress (Mpa)	Assumed Coefficient of variation (%)	% Error / Assumed Coefficient of variation	Sample size required
Without Vibration (0V)	178 (0.9 UTS)	4	2.5	3
	138 (0.7 UTS)	5	2	3
	99 (0.5 UTS)	7	1.43	4
With Vibration (160V)	204 (0.9 UTS)	4	2.5	3
	158 (0.7 UTS)	5	2	3
	113 (0.5 UTS)	7	1.43	4

3.1 Determination of average fatigue life

The number of test specimens required for fatigue testing at different stress levels was determined to be 4, 5 and 7 [16-17]. Instron fatigue testing machine was used for axial fatigue testing. Fatigue life of a specimen was considered as failure of the specimen for number of tension compression cycles. Number of tension and compression cycles that a specimen withstands up to failure is considered as fatigue life of the specimen. Fatigue test was conducted at an input frequency of 5 Hz. Fatigue life test results of specimens prepared at without vibration i.e., 0V and with vibration i.e., 160V are shown in Table 2 and 3 respectively. Actual COV percentage is less than the allowable limit. So, those three samples are sufficient. So, a total of 10 specimens were tested for each condition that is with vibration and without vibrations. Number of cycles that the specimen withstands at different stress level is shown in figure 1 and 2 for without and with vibration condition.

Table 2: Average fatigue life determination within 10%error and 90% confideence according to initial estimate for without vibration

	Without Vibration (0V)					
	178 MPa		138 MPa		99 MPa	
Sample Number	**Life (Cycles)**	**Log (Life)**	**Life (Cycles)**	**Log (Life)**	**Life (Cycles)**	**Log (Life)**
1	21022	4.3226	67489	4.8292	122175	5.0869
2	25495	4.4064	79974	4.9029	101237	5.0053
3	38115	4.5810	94572	4.9757	98378	4.9928
					135298	5.1312
Average	28211	4.4504	80768	4.9072	114272	5.0579
Standard Deviation		0.1318		0.0732		0.0511
% COV		2.9625		1.4930		1.0104
Permissible %COV		4		5		7

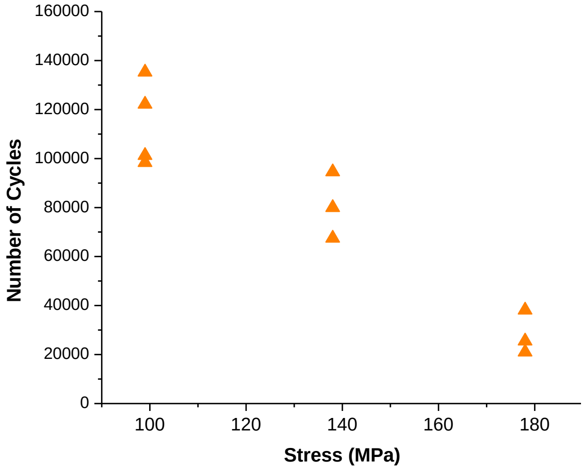

Fig.1. Number of Cycles vs. Stress (Without vibrations)

Table 3: Average fatigue life determination within 10% error and 90% confidence according to initial estimate for with vibration (160V)

	With Vibration (160V)					
	204 MPa		158 MPa		113 MPa	
Sample Number	**Life (Cycles)**	**Log (Life)**	**Life (Cycles)**	**Log (Life)**	**Life (Cycles)**	**Log (Life)**
1	40185	4.6040	118345	5.0731	190575	5.280
2	23257	4.3665	85346	4.9311	125754	5.099
3	33245	4.5217	98743	4.9945	137972	5.139
4					181365	5.258
Average	32229	4.5082	100811	5.0035	158916	5.201
Standard Deviation		0.1206		0.0711		0.094
% COV		2.6751		1.4214		1.822
Permissible %COV		4		5		4

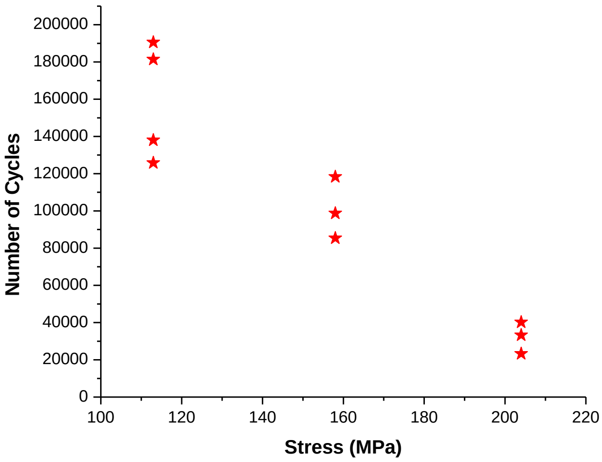

Fig.2. Number of Cycles vs. Stress (at 160V vibrations)

4 WELD JOINT MICRO-STRUCTURES EVALUATION

Microstructure of the different zones of the welded specimen was observed through the metallurgical study. In this two welded specimens were considered for the analysis i.e., with and without vibrated specimen (0V and 160V vibrated specimen). As per the standard procedure these specimens were polished after sectioning, mounting, and grinding. The samples were etched with Keller's reagent after polishing thoroughly. Leica optical microscope was used for taking photomicrographs. Image-J analyzer software was used for obtaining the average grain size. Line intersection and rectangular method is used for calculating the average grain size.

The scattering of filler metal in the weld zone in the absence of vibrations is shown in Fig.4. That is, in the absence of vibrations during welding. Micro-structure shows the elongated dendrites throughout the weld. The metal was fused because of high welding temperatures. Large dendrites have developed at the weld zone as a result of this fusion process and the lack of vibrations.

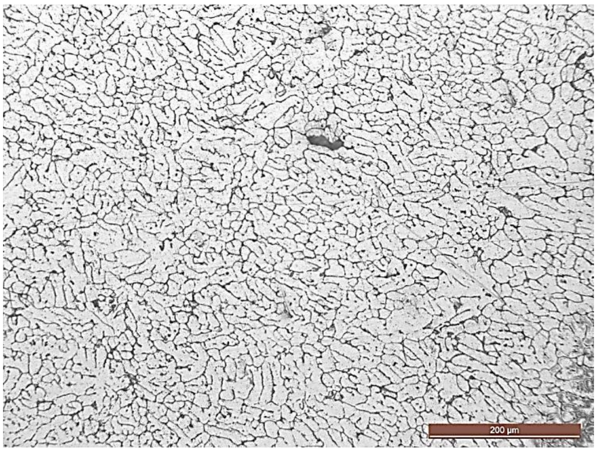

Fig.4. Micro-structure of specimens prepared in the absence of vibrations (200X)

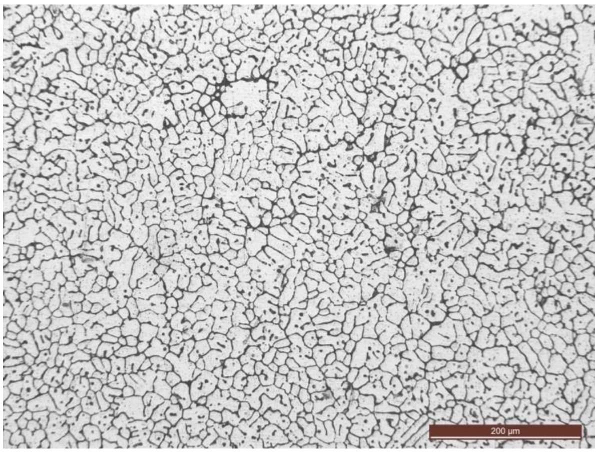

Fig.5. Microstructure of specimens prepared at with 160V vibration condition (200X)

Fig.5 shows the microstructure of specimens welded at 160V vibromotor voltages. Weld zone clearly indicates fine filler metal distribution; dendrites were broken into smaller sized grains. Smaller grains form as a result of vibration energy applied to the specimen during welding. Vibration energy during welding helps in solidifying metal at a faster rate results in finer grain size. Hence, inducing mechanical vibrations to the weld pool lead to dynamic solidification, which resulted in finer grain size as compared to without vibrations.

When, the orientation of a grain boundary changes, the slip plane does not carry on in the same way beyond the barrier. As a result, dislocations gliding on a slip plane are unable to cross the border and instead pile up against it and occur in fine-grained materials only. According to the Hall-Petch relation, the yield strength of a polycrystalline material is a function of grain size [18].

$$\sigma = \sigma_o + Kd^{-1/2} \quad \ldots (1)$$

Where, the applied stress is σ, the back stress is σ_o and the average size of grain of the material is d.

Typically, grain boundaries are seen as impediments to dislocation motion. A greater number of grain boundaries increases the amount of impediments encountered during dislocation motion. Grain boundaries are also mismatch zones. Inside the grains, dislocation movement is easier than at the edges. As a result, the dislocation takes some more stress to migrate from one grain to another. The dislocation movement of coarse grains is greater than that of smaller grains. As a result, considerable amounts of stresses are required for plastic deformation in the case of fine-grained structures.

CONCLUSIONS

After analyzing the fatigue life of welded joints with and without vibration and microstructure following conclusions were made

i) The fatigue life of the specimen was improved with vibration. This improvement is around 14% at stress level 1 that is 0.9 UTS. Interestingly the fatigue life improvement is around 10% in the specimens vibrated at 160 volts even at stress level III that is 0.5 UTS.

ii) Transverse vibrations are transferred to weld pool during solidification. Dendrites are shattered into little grains by transverse vibration before they develop into large grains. This mechanism is solely responsible for increased fatigue life

iii) According to ASTM E 112-96 the average size of the grain is 20.707, 16.56μm for the specimens prepared in the absence of vibration and with 160V vibration respectively.

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