USE OF PULSE CURRENT MIG WELDING IMPROVES THE WELD CHARACTERISTICS OF Al-Zn-Mg ALLOY

By

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ABSTRACT

Extruded sections of commercial Al-Zn-Mg alloy have been welded by continuous and pulsed current MIG welding processes, using 1.6mm diameter Al-Mg filler wire. During welding the current and other pulse parameters such as its frequency and duration are varied and their influence on the weld bead geometry, chemical composition, hardness and porosity content are studied. The influence of various parameters on the recrystallization at HAZ adjacent to the fusion line has been examined. Finally the performance of the weldments under static and dynamic tensile loading are also investigated. The properties of the weldments prepared under pulsed MIG process are correlated to those of the weldments prepared by the conventional continuous current welding. It has been observed that a critical and selective use of pulse parameters improve the weldment properties as compared with those of the conventional weldments.

INTRODUCTION

The Al-Zn-Mg alloy is well known for a long time as a light structural material owing to its high strength to weight ratio. During application of this material for construction of light bridges and road or railway transport systems the metal inert gas (MIG) welding is largely being used for joining of structural members. However, it has been observed [1-5] that the weldments of Al-Zn-Mg alloy becomes prone to stress corrosion cracking and fatigue due to deterioration of its mechanical properties especially when the welding is carried out with large heat input Earlier investigations show that the presence of coarse dendritic structure [5] and porosity [3, 6] in weld deposit and the grain growth in heat affected zone (HAZ) adjacent to the fusion line [7, 8] are having significant adverse affect on these properties. The application of pulsed current, instead of conventional continuous current, during MIG welding of this alloy has been found beneficial to improve the mechanical properties of weld deposit [4, 6, 9-12] as well as that of HAZ [8]. This may have been primarily caused by high deposition rate at low heat input [1, 2] and interruption in metal deposition [9, 11-13], influencing the chemical composition [14], microstructure [9, 13], bead geometry [6, 12, 15] and porosity content [6, 13, 16] of the weld. It is also marked that the properties of weld and HAZ of a pulsed MIG welded Al-Zn-Mg alloy weldment are to a great extent sensitive to the pulse parameters, especially the mean current and pulse frequency. Thus, for effective utilization of pulsed MIG process it is essential to understand the influence of pulse parameters on various aspects of the weldment. In this paper an effort has been made to analyse critically some works carried out in the area of pulse current MIG welding of Al-Zn-Mg alloy, keeping in view the performances of the conventionally prepared MIG weldment of the alloy. This will be helpful in understanding the utility of pulse current MIG welding over the conventional one during welding of Al-Zn-Mg alloy.

Experimental Procedure

Welding

MIG welding of extruded section (50mm x 7mm) of Al-Zn-Mg alloy was carried out by using 1.6mm diameter 5183 filler wire and commercial argon (99.98%) as shielding gas at a flow rate of 15 l/min. The chemical composition of the base metal and the filler wire are given in Table 1. The welding was carried out by depositing weld metal by single pass in a properly cleaned groove (Fig. 1). During pulsed current welding the mean current was varied to three different levels such as 150, 180 and 210A. The pulsed frequency was varied in the range of 25-100 Hz, where the pulse duration was kept constant at about 6.58 ms. For a comparative study, the welds were also produced by conventional MIG welding process using the welding current of the same order as that of

Table 1 : Chemical composition of base metal and filler wire (Wt%)

Material	Al	Zn	Mg	Mn	Fe	Si	Cu	Cr	Ti
Base	Bal.	4.5	1.25	0.45	0.45	0.3	0.15	-	-
Filler	Bal.	-	4.9	0.7	-	-	-	0.15	0.15

the mean current of pulsed process mentioned above.

The welding speed was suitably adjusted to obtain full penetration by single pass. The welding parameters used in this work are shown in Table 2. The welding was performed on a copper backing plate and during welding the whole setting was rigidly held in a suitable fixture. During welding the pulse characteristics were monitored and recorded using a digital oscilloscope.

Estimation of Porosity

Transverse sections of the specimens, collected from central part of the weldment ensuring a true representation of the weld characteristics, were prepared by standard metallographic procedure. The porosity content of the weld, excluding its reinforced region, revealed on unetched matrix as dark spots of average size range of about 60-80 um, estimated under optical microscope by following the standard point counting method (17). The volume fraction of porosity of the weld was correlated with the pulse parameters and fatigue characteristics of the weldment.

Weld Geometry

The transverse section of the metallographic polished specimen was suitabley etched (Keller's reagent) to reveal clearly the geometry of the weld. The weld geometry, excluding its reinforced part, was estimated by measuring the widths at its top, A, and bottom, B, under optical microscope and reported as a ratio of B to A denoted as r. The value of r was correlated with the pulse parameters as well as with fatigue properties of the weldment.

Table 2 : Welding parameters and specimen designation

Specimen designation	Mean welding current (A)	Base current (A)	Pulse frequency (Hz)	Pulse duration (ms)	Arc voltage (V)	Travel speed (cm.min^{-1})
1	150	-	0	-	26	27.0
2	150	120	25	6.58	26	27.0
3	150	110	33	6.58	26	27.0
4	150	90	50	6.58	26	27.0
5	150	30	100	6.58	26	27.0
6	180	-	0	-	26	35.0
7	180	150	25	6.58	26	35.0
8	180	130	33	6.58	26	35.0
9	180	110	50	6.58	26	35.0
10	180	40	100	6.58	26	35.0
11	210	-	0	-	26	40.0
12	210	180	25	6.58	26	40.0
13	210	150	33	6.58	26	40.0
14	210	130	50	6.58	26	40.0
15	210	60	100	6.58	26	40.0

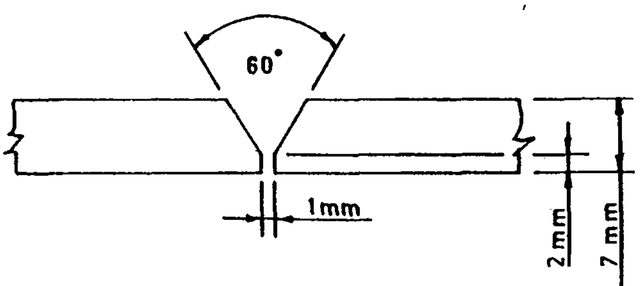

Fig. 1 : Schematic diagram of the weld groove.

Chemical Analysis

The powders collected by drilling from the base material and the central part of the weld were analysed under Atomic Absorption Spectrometer and X-ray Diffractometer to analyse primarily the magnesium and zinc content and the presence of any precipitate in the weld respectively. The X-ray diffraction study was carried out by using cuke radiation and nickel filter.

Hardness

The Vicker's hardness, along the centre line of the weld, was determined on the polished and etched transverse section of each specimen at a load of 50N. The hardness of the weld was correlated with the pulse parameters.

Recrystallization at HAZ

The width of recrystallized region at HAZ adjacent to the fusion line, revealed in the etched transverse section of the weld, was measured under optical microscope. The measurement was carried out by positioning a micro-scale, inserted inside he eyepiece of the microscope, perpendicular to the fusion line and the mean value was correlated with the pulse parameters.

Tensile Test of Weldments

The tensile properties of the weldments were studied using standard (DIN 50215) tensile specimens (Fig.2) collected from the central part of the weld run excluding the run-on and run-off portions. The specimens were fabricated after removing the material up to a depth of about 0.3mm from both the top (excluding reinforced bead) and bottom surfaces of the weldment. Before fabrication of the specimens the weldments were stored at room temperature (295K) for about 30 days so that they get a sufficient amount of natural ageing. The tensile tests were carried out at a cross head speed of 1 mm/min. The elongation was estimated over a guage length of 40mm.

Fatigue Test of Weldments

Specimens (Fig.3) for fatigue testing were also collected from the central part of the weld run. Before fabrication of test specimens the weldments were also given a natural ageing, and a part of the material from its top and bottom surfaces was machined out as stated earlier. Fatigue testing was carried out under uniaxial tensile loading, where the mean stress and stress ratio, R, defined as the ratio of minimum to maximum stress, were kept constant at 127.5 N mm^{-2} and 0.5 respectively.

RESULTS AND DISCUSSION

Geometry of Weld Bead

It is observed that during pulsed current welding the variation in mean current and pulse frequency influences considerably the geometry of the weld (r) as depicted in Table 3.

Table 3 : Influence of pulse parameters on the weld geometry.

Specimen designation	Bead top A (mm)	Bead root B (mm)	Ratio r (B/A)
2	10.75	5.16	0.48
3	12.02	6.60	0.55
4	11.39	6.45	0.56
5	12.25	7.19	0.58
7	12.04	7.74	0.64
8	12.47	7.095	0.57
9	12.47	6.45	0.52
10	12.47	8.60	0.69
12	10.965	7.525	0.68
13	13.115	3.225	0.24
14	12.47	0.873	0.07
15	13.25	5.3	0.40

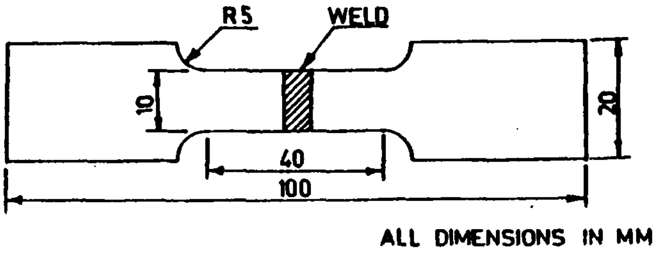

Fig. 2 : Schematic diagram of sile specimen

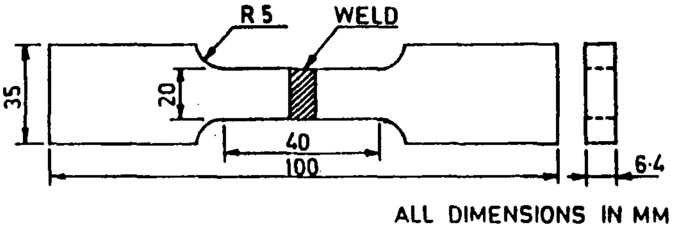

Fig. 3 : *Schematic diagram of fatigue test specimen*

In general, it is marked that the r-value of pulse current weld is comparatively lower than that observed in case of conventional continuous current weld. It is found that at a mean current of > 180A the r-value decreases with the increase in pulse frequency upto 50 Hz, followed by an increase in it with a further increase in pulse frequency to 100 Hz, and is more pronounced at the mean current of 210A. However, at the low mean current of 150A, the r has been found to marginally increase with increase in pulse frequency from 25 to 100 Hz.

The above behaviour of variation in weld geometry (Table 3) with a change in pulse frequency infers that the increase in pulse frequency up to 50 Hz reduces the net heat input [9,18,19], (defined as difference of actual heat input and heat loss due to interruption in solidification), and thereby reduces the melting of base material which narrows down the weld root. But at higher pulse frequency of 100Hz the weld deposit starts behaving again like a conventional (0 Hz) welding due to reduction of interruption in weld pool solidification as observed earlier [9, 11-14]. This may have resulted in the enhancement of net heat input, thereby causing execessive melting of base metal which broadens the weld root and consequently enhances the r-value.

Table - 4 : X-ray differaction analysis of the weld bead

Sin θ	d	(hkl)
0.631	1.22	(311)Al
0.532	1.431	(220)Al
0.381	2.02	(200) Al
0.359	2.142	(710, 550) (Al,Zn) 49Mg32
0.333	2.307	(532, 611) (Al,Zn) 49Mg32
0.329	2.34	(111)Al
0.315	2.44	(530,433) (Al,Zn) 49Mg32
0.076	10.1	(110) (Al,Zn) 49Mg32

Chemical Composition of the Weld

During MIG welding chemical composition of the weld becomes affected by the following factors [14] : (1) magnesium loss during metal transfer primarily occurs due to contamination in inert jacket; (2) zinc loss due to its vaporisation controlled by heat input; and (3) amount of dilution depending upon weld geometry, Table 3. It is understood that during pulsed current MIG welding all the three factors are significantly governed by the pulse parameters, especially the mean current and pulse frequency [14] as they are affected by the energy level of the process. At different mean currents of 150 and 210A, the influnce of pulse frequency on the magnesium and zinc content of the weld has been shown in Fig.4. The figure shows that, in general, the use of pulse current reduces and enhances the magnesium and zinc content of weld, respectively, in comparison to those observed in case of continuous current welding. At a given pulse frequency the increase in mean cur-

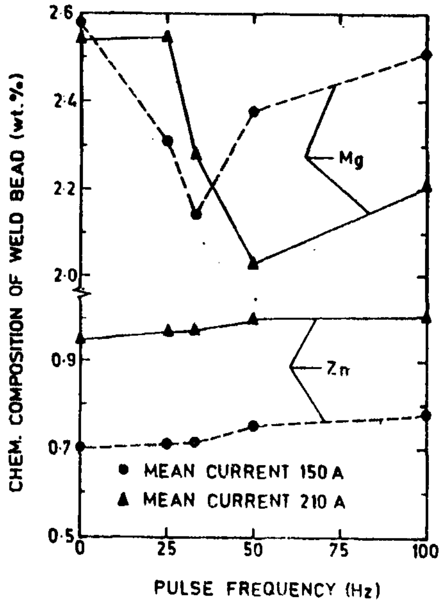

Fig. 4 : At different mean currents the influence of pulse frequency on the chemistry of weld bead.

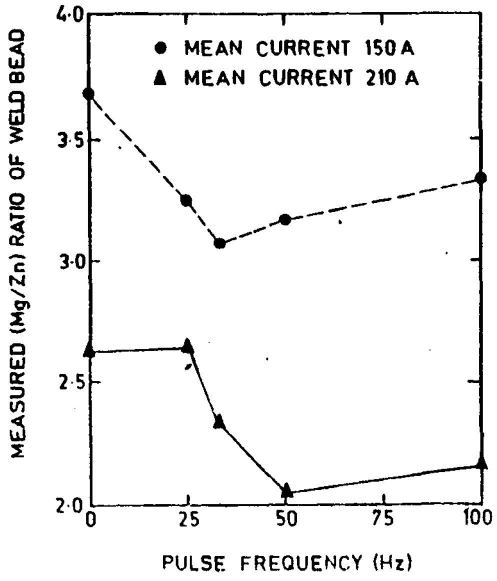

Fig. 5 : At different mean currents the influence of pulse frequency on the Mg/Zn ratio of weld bead.

rent has been found to enhance the zinc content of the weld significantly. A similar effect, of comparatively lower extent, on zinc content of the weld was also been observed when at a given mean current the pulse frequency is enhanced up to 100 Hz. At a given mean current of 150 and 210A, the increase in pulse frequency upto 33 and 50 Hz, respectively, has been found to reduce the magnesium content of the weld significantly followed by an increase in it with a further increase in pulse frequency up to 100 Hz.

The zinc pick-up by the weld makes it susceptible to precipitation hardening. However, the nature of precipitation hardening shall depend upon the Mg/Zn ratio. At the mean currents of 150 and 210 A, the influence of pulse frequency on the Mg/Zn ratio of the weld has been shown in Fig. 5. The figure depicts that the Mg/Zn ratio of the weld lies within the range of about 2.04-3.68. According to phase diagram of Al-Zn-Mg system [20], in presence of magnesium and zinc at a ratio in this range, the weld becomes susceptible to precipitation of $Mg_3Zn_3Al_2$. The X-ray diffraction studies show the presence of (Al,Zn)49 Mg32, which is in close approximation by nature [21] to the $Mg_3Zn_3Al_2$, in the samples collected from the weld. The presence of (Al,Zn)49Mg32 has been confirmed by their interplanner spacing (d-value) where no other interfering d-values are observed (Table 4).

As per the Zinc content of weld bead depicted in Fig.4 the stoichiometric amount of (Al,Zn) 49Mg32, that may be present in the weld bead, has been estimated and correlated with the pulse parameters (Fig.6). The figure shows that the use fo pulse current may enhance the (Al,Zn) 49Mg32 content of the weld than that observed in the weld produced by continuous current welding. The en-

Table 5 : The effect of pulse current and pulse frequency on the hardness of the weld

Mean current (A)	150				210			
Pulse frequency (Hz)	0	25	50	100	0	25	50	100
Hardness (VHN)	88	92	98	102	90	98	-	102

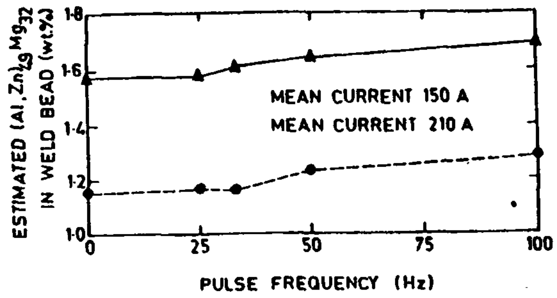

Fig. 6 : At a given mean current influence of pulse frequency on the stoichiometric amount of (Al,Zn) 49Mg32 present in the weld bead.

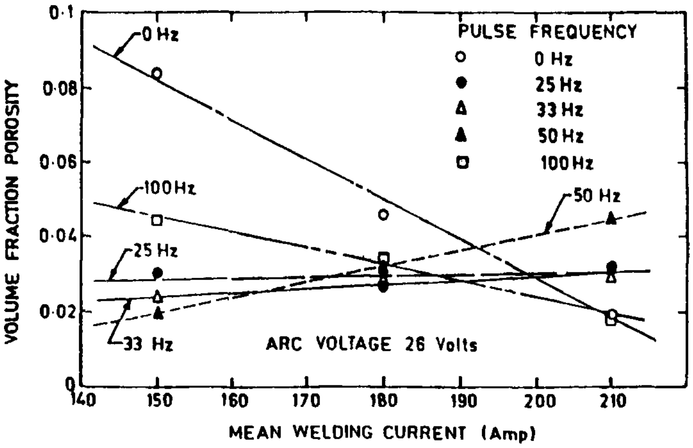

Fig. 7 : Influence of mean current on the prosperity content of weld deposit at ifferent ievels of pulse frequency.

hancement of (Al, Zn) 49Mg32 content of weld bead has been found to be favoured by the increase in mean current or pulse frequency.

Porosity Content of the weld.

During pulse current welding at different pulse frequencies in the range of 0-100 Hz the variation in porosity content of the weld with a change in mean current, and during continuous current welding the variation in porosity content of the weld with a change in welding current has been shown in Fig. 7. The figure shows that during continuous current welding, the increase in welding current reduces the porosity content of the weld possibly due to enhancement in flight speed of the droplets, reducing their stay period within the inert jacket resulting in less contamination of soluble gases in them. However, during pulsed current welding at a pulse frequency upto 50 Hz, the increase in mean current has been found to show a tendency to enhance the porosity content of the weld. This may have attributed to increase in instability at the inert jacket due to fluctuation in arc pressure under the pulsed current causing air aspiration in it, which becomes stronger at higher current because of higher arc pressure. This behaviour is marked to be more pronounced at the pulse frequency of 50 hz. But at a further higher frequency of 100 Hz, where the pulsed current process tends to behave again like a continuous current process [6,9,11-14], due to lowering of pulse off time (t_b) to about 3.4 ms, the porosity content of the weld has been found to reduce with the increase in mean current as is observed in case of welding at O Hz.. Fig. 7 shows that the porosity content of the weld becomes lower than the conventional one only under certain pulse parameters. Thus, it is imperative to derive a combined

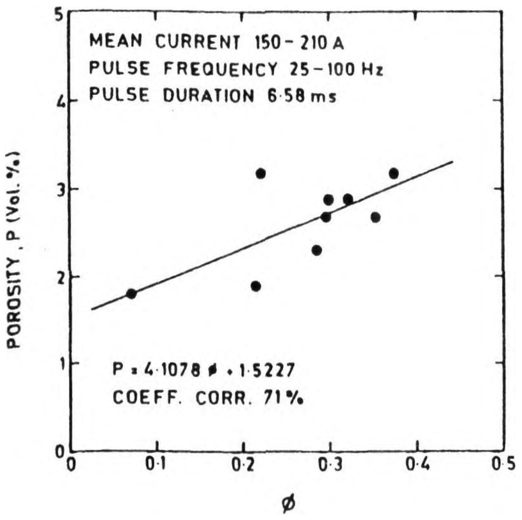

Fig. 8 : The correlationship of porosity with the φ.

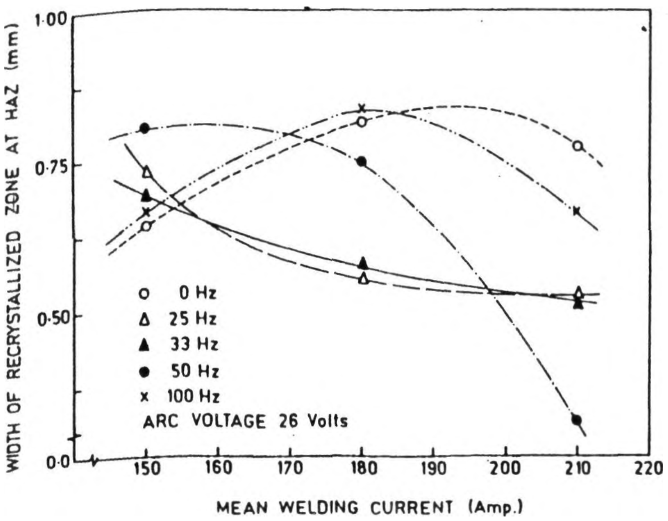

Fig. 9 : Influence of mean current on the width of recrystallized zone at HAZ under different levels of pulse frequency.

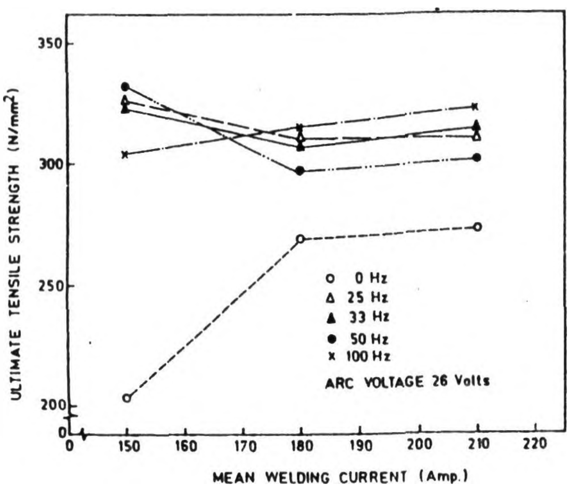

Fig. 10 : At a given pulse frequency the influence of mean current on the ultimate tensile strength of weld.

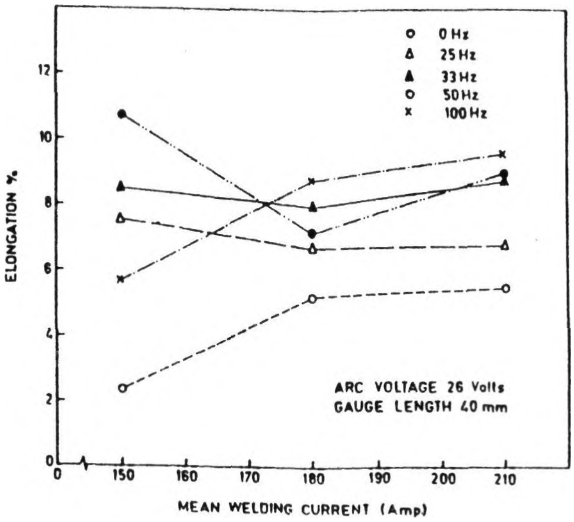

Fig. 11 : At a given pulse frequency, the influence of mean current on the elongation of the weld.

functional aspect of the pulse parameters affecting the porosity content of the weld. The above observations infer that the porosity content of the weld is primarily governed by the fluctuation in arc characteristics defined as function of ϕ. The ϕ is directly governed by the ratio of base current to peak current (I_b/I_p) and pulse off-time fraction ($t_b f$). Thus, ϕ, as a function of $I_b T_b f/I_p$, is correlated to the porosity content (p) of the weld as shown in Fig. 8. The correlationship of ϕ with the ϕ, having coefficient of correlation of the order of 71%, has been found as

$$P = 4.1078\ \phi + 1.5227 \quad \text{........ (1)}$$

Hardness of the Weld

The variation in hardness of the weld with a change in pulse frequency from 0 to 100 Hz at the mean current of 150 and 210A has been shown in Table 5. The table shows that at a given mean current the increase in pulse frequency enhances the hardness of the weld. It is also observed that the hardness of the pulsed current weld is comparatively higher than that of the continuous current (O Hz) weld. The variation in hardness of the weld with the change in pulse parameters is primarily governed by its precipitate content , which is in agreement to that shown in **Fig. 6**.

Recrystallization at HAZ

During welding of aluminium alloys the HAZ of base material is largly characterised by the extent of recrystallization in the region adjacent to fusion line. In general, the behaviour of recrystallization is directly proportional to the weld thermal cycle, which in case of continuous current welding varies with a change in welding current governing the globular and spray mode of metal transfer, and in case of pulse current welding varies with the pulse parameters affecting the interruption in metal deposition. At a given pulse frequency, varied from 0 to 100 Hz the influence of mean current on the width of recrystallization in HAZ adjacent to the fusion line has been shown in Fig. 9. The figure shows that, the recrystallization at HAZ is comparatively higher and lower during pulsed current welding at the low and high mean currents of 150 and 210A, respectively, than that observed in case of continuous current (O Hz) welding. However, it is observed that at a given mean current, the width of recrystallization at HAZ significantly depends upon the pulse grequency. At the high mean current of 210A, the recrstallization at HAZ is found to be lowest at the pulse frequency of 50 Hz, where possibily the influence of interruption in metal deposition on the weld thermal cycle becomes significantly effective. But at a further higher pulse frequency of 100 Hz, where the pulsed current process tries to behave like a continuous current process the recrystallization at HAZ approaches that observed in case of continuous current welding.

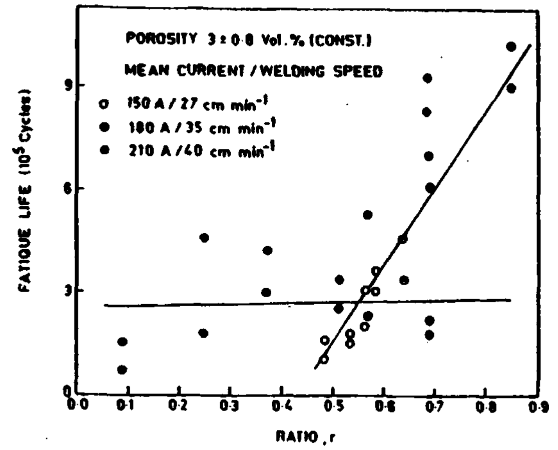

Fig. 12 : The effect of weld geometry on the fatigue life of the weldment.

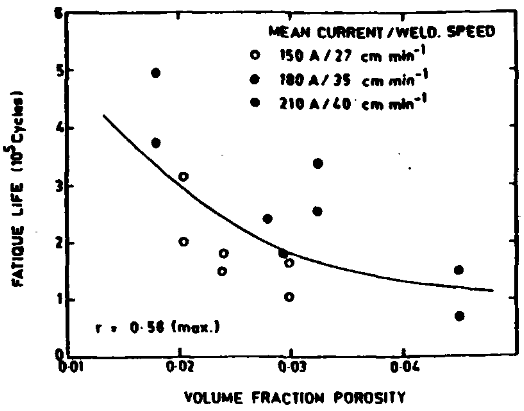

Fig. 13 : Influence of porosity on the fatigue life of the weldment.

Tensile and fatigue Properties of Weldments

During tensile testing, the weldments are always found to fracture from the weld. At a given pulse frequency, varied from 0 to 100 Hz, the influnce of mean current on the ultimate tensile strength (UTS) and elongation (El.) of the weldment are shown in Figs.10 and 11, respectively. The figures depict that the use of pulse current imporves the UTS and El. of the weldment over that observed in case of continuous current (O Hz) welding. This may be primarily attributed to increase in precipitate content (Fig.6) of the weld during pulsed current welding. As such the best combination of UTS and El. is observed when the welding is carried out at the pulse frequency of 100 Hz using a mean current of 210 A.

The fatigue fracture of the weldments has also been found to occur at the weld and the fatigue life is marked to be primarily dependent on the geometry and porosity content of weld bead (6). A correlation of the weld geometry, defined as r, with the fatigue life of the weldments (Fig.12) depicts that the enhancement in value of r upto about 0.56 does not influence the fatigue life significantly, followed by a considerable increase in it with a further increase in r beyoned 0.56. The reason behind the influence of r on the fatigue life of weldment are possibly related to its effect on stress distribution in the weldment and should be studied further in detail. However, in case of the weld geometry having r within 0.56 increase in porosity content of weld up to about 3.0 vol% reduces the fatigue life of the weldment significantly (Fig.13) following a relationship as

$$N = 487258.7 - 256771.4 \ln P \quad \text{......(ii)}$$

where, N is the number of cucles and P is the porosity content (vol.%) of the weld. The significant scattering of results observed in Fig. 12 and 13 is primarily attributed to the size and distribution of porosity in the weld bead, especially in case of its presence at the surface and sub-surface of the specimen [6]. The presence of porosity at the surface or sub-surface of the weld has been found to reduce drastically its fatigue life.

CONCLUSION

During pulsed current MIG welding of Al-Zn-Mg alloy, the variation in mean current and pulse frequency affects the geometry, chemical composition, porosity content and hardness of the weld, and consequently also influences the tensile and fatigue properties of the weldment. In general the tensile properties of pulsed MIG weldments are found to be better than those of the conventional continuous current MIG weldments. The fatigue life of the weldments is found to be sensitive to the geometry (r-ratio) and porosity content of the weld. The increase in r beyond about

0.56 and the decrease in porosity below 3.0 vol% of the weld bead improve significantly the fatigue life of the weldment. The best combination of tensile and fatigue properties are observed in the weldments prepared at a mean current of 210A using pulse frequency of 100 Hz.

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