# Effects of Electromagnetic Stirring on Particle Mixing during GTA Welding of Al-Mg-Si Matrix Composites

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## ABSTRACT

In this paper the results are presented of a study dealing with the influence of electromagnetic stirring of the weld pool during GTA welding of the composite $6061/Al_2O_3/10p$. Attention is focussed on the mixing behaviour of the particles when welding with filler material (Al 5wt.% Si). Bead-on-plate welding experiments were carried out under different stirring conditions. After welding, cross-sections were made of each weld and these cross-sections were examined visually and using optical microscopy. The degree of mixing of the particles in the welds obtained was expressed in terms of a mixing parameter. It appears that the best mixing results are obtained with a magnetic induction higher than 20 mT and a stirring frequency of around 2 Hz and that the hardness of the stirred welds (after T6 heat treatment) does not significantly deviate from that of the base material. On the basis of the results obtained it can be concluded that electromagnetic stirring can be successfully applied in the case of welding composite material under practical conditions.

## 1. INTRODUCTION

Metal-matrix composites are relatively new materials, which are increasingly used in industrial products. They consist of a metal matrix and normally contain 5-30 vol.% non-metallic particles.

The advantages of aluminium-matrix composites over conventional aluminium alloys are their improved mechanical and physical properties, such as high strength, excellent high-temperature properties, improved stiffness maintained at elevated temperatures, high wear resistance and low thermal expansion, which is attractive for applications that demand dimensional stability.

Obviously, application of metal-matrix composites in constructions requires reliable joining techniques, preferably joining techniques that are commonly used. The most important joining techniques used in industry on a large scale are the gas tungsten arc welding process and the gas metal arc welding process. Unfortunately, however, the use of these welding processes for joining metal-matrix composites gives rise to specific problems.

The problems encountered in the case of arc welding of the composite $6061/Al_2O_3/10p$ (alloy AA 6061 containing 10 vol.% aluminium oxide particles) have been described in previous papers /1,2/. It appears that the most severe welding problem is the poor mixing between the molten base material and the molten filler material occurring when filler wire is used.

A possible way to reduce this problem is the application of electromagnetic stirring during welding /3-10/. The principles of electromagnetic stirring of the weld pool are based on the fact that the welding current and the imposed magnetic flux interact to cause a force on the current carriers. In the case of an axial magnetic field (direction of the field parallel to the axis of the arc) this Lorentz force results in rotation of the arc and to a rotating flow of the liquid metal in the weld pool as is schematically shown in Fig. 1. It is to be expected that this flow will have a positive effect on the structure and properties of welds in the composite, especially on the distribution of the particles within the matrix.

This paper deals with the effects of electromagnetic stirring of the weld pool during gas tungsten arc (GTA) welding of the composite $6061/Al_2O_3/10p$ with emphasis on the mixing behaviour of the particle containing base material and the particle free filler material.

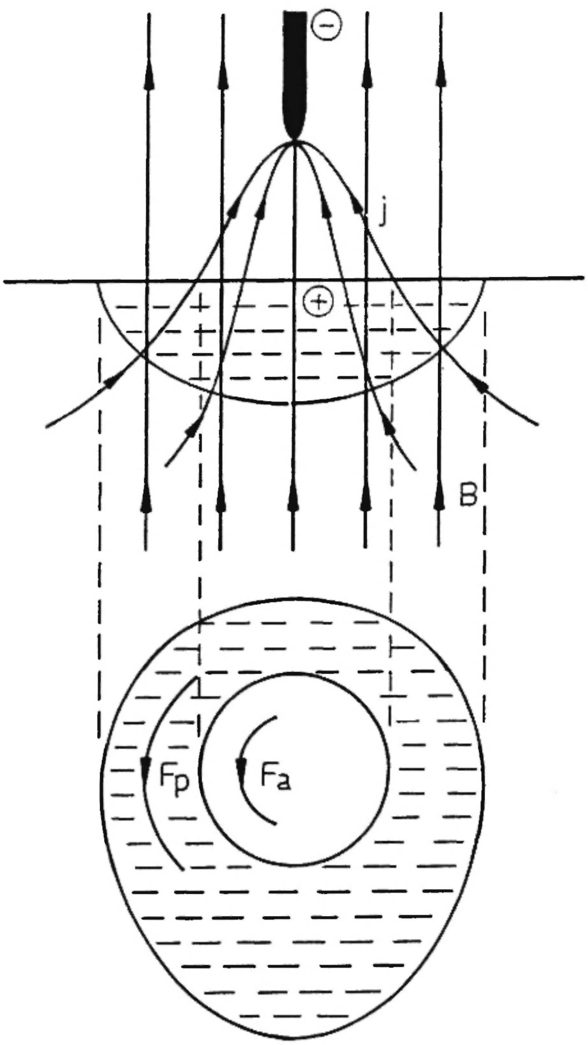



**Fig. 1:** Schematic representation of the influence of an axial magnetic field on the arc and the weld pool (j – current density; B – magnetic induction; $F_a$ - force acting on the arc; $F_p$ - force acting on the liquid weld metal in the weld pool).

## 2. EXPERIMENTAL CONDITIONS

### 2.1 Material

The base material used in this study was an aluminium-matrix composite consisting of the AA 6061 alloy as matrix and containing 10 vol. % aluminium oxide particles with an average diameter of 13 μm. The composite was produced by Duralcan San Diego, using an ingot metallurgy (IM) process. Composites produced by the IM process are less liable to pore formation than composites produced by the powder metallurgy (PM) process, and hence the material does not have to be degassed. The aluminium oxide based composite was produced by means of stir casting and is designated according to the rules of the American Aluminium Association as "matrix/reinforcement/volume fraction and reinforcement type". In this paper the designation $6061/Al_2O_3/10p$ will be used for the composite. The composite was supplied in the form of extruded bars having dimensions 19x800x80 mm. To be able to weld the composite material with the GTA welding process thinner parts are required, having reproducible thickness, structure and mechanical properties. Hence, the bars were hot rolled to plates of 3.2 mm thickness, subsequently heat treated and structurally and mechanically characterised.

The chemical composition of the composite $6061/Al_2O_3/10p$ was analysed by means of Flame Atomic Absorption Spectroscopy for the silicon content and by means of ICP-OES for the remaining elements. To make analysis possible the composite was dissolved in aqua regia. The chemical composition of the composite thus determined is shown in Table 1, together with the nominal composition of AA 6061.

### 2.2 Experimental set-up

The experimental set-up used is shown schematically in Fig. 2 and consists of a GTA welding torch, an alternating current (AC) power supply and a filler wire feeder. The axial magnetic field is provided by three electromagnets, which are placed at equal distance from each other (120 degrees apart) around the welding torch. The electromagnets are air-cooled and are fed by an external power source. The current

**Table 1**
The chemical compositions of AA 6061 and composite $6061/Al_2O_3/10p$.

| | AA 6061 wt.% | $6061/Al_2O_3/10p$ wt.% |
|---|---|---|
| Si | 0.4-0.8 | 0.64 |
| Fe | 0.7 | 0.07 |
| Cu | 0.15-0.40 | 0.24 |
| Mn | 0.15 | - |
| Mg | 0.8-1.2 | 0.90 |
| Cr | 0.04-0.35 | 0.06 |
| Zn | 0.25 | - |
| Ti | 0.15 | 0.072-0.078 |
| Zr | - | <0.0035 |
| Al | bal. | bal. |

and phase as that of the welding current. For this purpose a standard audio amplifier is coupled to a function generator, which can produce square, triangular or sinusoidal waves. The amplifier can supply a maximum current of 5 A (at 4 Ω impedance). The time needed for the linear increase of this current at the start of the welding run is set to three seconds (up-slope). The same time is set for the linear decrease at the end of the welding run (down-slope).

Under the conditions described above, the magnetic field is directed upward during one half cycle of the welding current, while the magnetic field is directed downward during the next half period of the welding current. Hence, the Lorentz force is continuously acting in the same direction on the liquid metal in the weld pool, which will result in a continuously rotating flow of the liquid metal in the weld pool in one direction (uni-directional flow).

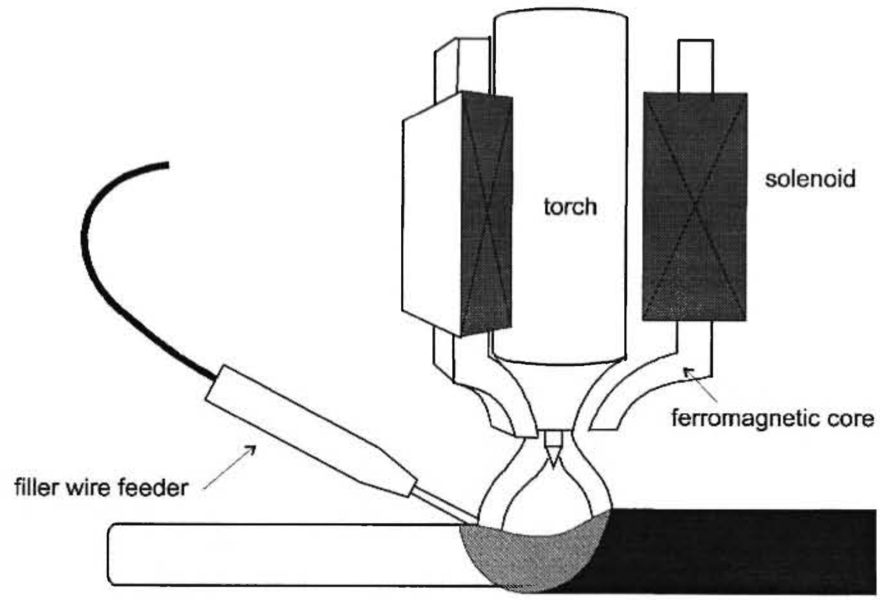



**Fig. 2:** Experimental set-up with three electromagnets surrounding the welding torch. Two electromagnets are visible, the third one is located behind the torch.

through the solenoids (1200 windings) of the electromagnets is such that the magnetic field produced by each of them has the same (axial) direction.

To generate electromagnetic stirring in the case of AC welding, it is necessary to apply an alternating current through the solenoids with the same frequency

However, when the frequency of the magnetic field ($\nu_B$) is different from that of the welding current ($\nu_l$), the direction of the flow will alternate with a frequency equal to $\nu_s = \nu_l - \nu_B$. In the present work the frequency $\nu_s$, referred to as the stirring frequency of the system, was varied within the range from 0 to 35 Hz.

Calibration of the axial magnetic field was carried out with the help of a LOHET II linear Hall probe device.

### 2.3 Experimental procedure

Bead-on-plate and Y-groove welds were produced under different process conditions. The magnetic induction was varied between 0 and 30 mT, and the stirring frequency was varied between 0 and 35 Hz. The welding and stirring parameters used are listed in Table 2.

The experiments were carried out using plates of thickness 3.2 mm. During extinction of the arc at the end of each welding run a current down-slope (5 seconds) was used, with the aim to prevent cracking of the end crater of the weld.

After each welding experiment cross-sections were made of the weld obtained and the structure of these cross-sections was examined using a Leitz Neophot 2 optical microscope.

Hardness measurements were performed using a Vickers hardness testing machine.

**Table 2**

Welding and stirring parameters used.

| | Bead-on-plate | Y-groove joint |
|---|---|---|
| current | 105 A (AC) | 106 A (AC) |
| voltage | 16.0 V | 16.0 V |
| travel speed | 3.0 mm/s | 3.0 mm/s |
| arc length | 3.0 mm | 3.0 mm |
| shielding gas | argon | argon |
| gas flow rate | 10 l/min | 10 l/min |
| filler wire type | AlSi5 | AlSi5 |
| filler wire diameter | 1.2 mm | 1.2 mm |
| wire feed rate | 25 mm/s | 37 mm/s |
| magnetic induction | 18, 24, 30 mT | 24 mT |
| stirring frequency | 0-35 Hz | 2 Hz |

## 3. RESULTS AND DISCUSSION

### 3.1. General observations

The results of experiments carried out under different conditions clearly show that application of an axial magnetic field during welding has a considerable effect on the behaviour of the weld pool and, hence, on the shape and structure of the solidified weld. It appears that in the case of uni-directional stirring the weld metal tends to move transversely and normal to the welding direction, which results in a somewhat asymmetrical and sagged weld bead. However, the observed asymmetry is much smaller than that observed in the case of stirred non-reinforced aluminium alloys /11/. This is due to the fact that the higher viscosity of the composite results in a smaller flow velocity. As expected, this effect disappears with increasing stirring frequency when alternating stirring is applied.

It was also found that in the case of alternating stirring a regular pattern corresponding with the stirring frequency becomes clearly visible at the weld surface. This pattern is directly related to the alternating transverse movement of the weld metal.

Furthermore, it was observed that at low stirring frequencies (smaller than 1 Hz) filler wire melting starts to occur periodically with the stirring cycle. Consequently, filler wire addition takes place in an apparently pulsating way. This may enhance filler wire mixing in the interior of the weld pool.

### 3.2. Mixing

The most important effect of electromagnetic stirring in the case of welding with filler wire on the structure of the weld is increased mixing of the molten filler wire material and the molten composite material.

To study this effect in more detail, bead-on-plate welding experiments were carried out under different stirring conditions. After welding, cross-sections were made of each weld and these cross-sections were examined visually and by means of optical microscopy. In Fig. 3 macroscopic weld cross-sections are shown obtained by welding using electromagnetic stirring with a magnetic induction of 18 mT and various stirring frequencies. The figures clearly show that electromagnetic stirring leads to severe mixing of the base material and the filler wire material.

To obtain a quantitative estimate of the degree of mixing of composite and filler wire, use can be made of

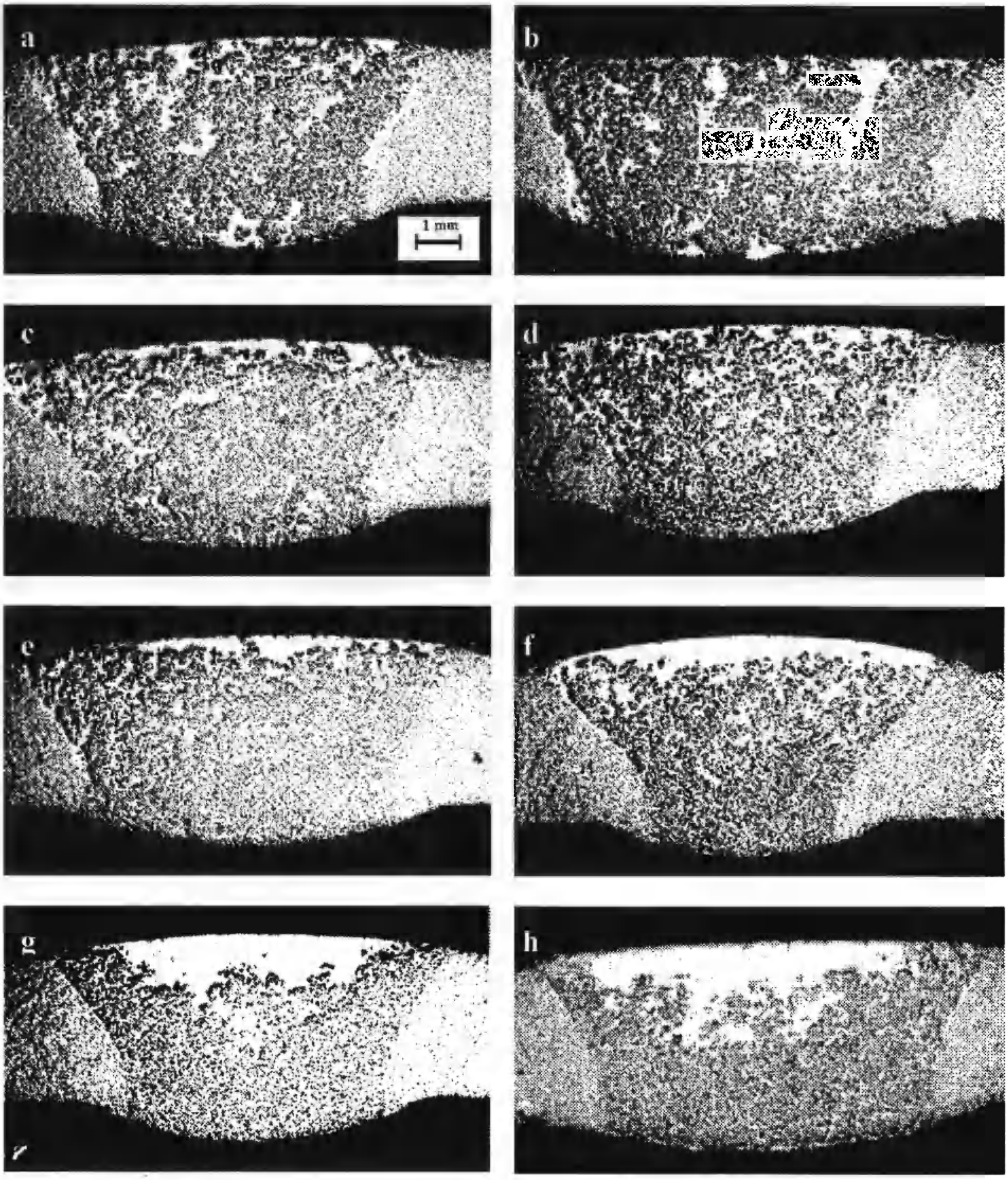



**Fig. 3:** Evolution of mixing with increasing stirring frequency: a) 0.1 Hz; b) 0.5 Hz; c) 1 Hz; d) 2 Hz; e) 3 Hz; f) 5 Hz; g) 10 Hz and h) 35 Hz (B = 18 mT).

the mixing parameter M, which is defined as /2/:

$$M = \left(\frac{A_f - A_1}{A_f}\right) \cdot \left(\frac{A_2}{A_2 + A_3}\right) \times 100\%$$

with: $A_1$ = cross-section surface area of the region containing only filler wire material,

$A_2$ = cross-section surface area of the region containing a mixture of filler wire material and composite material,

$A_3$ = cross-section surface area of the region containing only composite material,

$A_f$ = Increase of total cross-section surface area due to the addition of filler wire material.

In Fig. 4 the mixing parameter is plotted as a function of the stirring frequency for three values of the magnetic induction (18, 24 and 30 mT, respectively).

The results presented in Figs. 3 and 4 clearly show that the degree of mixing is strongly dependent on the stirring conditions. At low stirring frequency relatively good mixing is obtained, although some particle denuding occurs along the top surface of the weld metal and along the partially melted zone. Furthermore, regions with high particle content and regions with low particle content can be observed in the centre of the weld pool. This inhomogeneity can be explained by the alternating character of the weld pool flow: denuded matrix originating from the surface and from the region along the fusion boundary is periodically dragged into the weld pool.

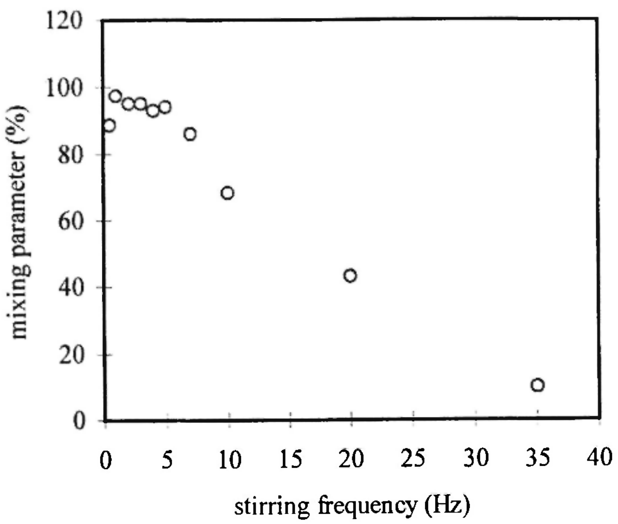



**Fig. 4:** Mixing parameter as a function of applied stirring frequency at a magnetic induction of 30 mT.

Optimal mixing is found to occur in the stirring frequency range of 1-3 Hz. Under these conditions the mixing parameter can reach values from 80 to 95 %, depending on the magnetic induction used. The particles appear to be homogeneously distributed in the weld metal, whereas denuding along the weld pool boundary and the top surface of the weld pool is relatively small.

With increasing stirring frequency the degree of mixing gradually decreases, due to mass inertia of the liquid metal, which reduces the effective fluid flow. However, relatively good particle distributions can still be obtained when welding with intermediate stirring frequencies (4 - 7 Hz) and high magnetic induction, although under these conditions a small denuded zone at the top surface of the weld pool remains.

When further increasing the stirring frequency the mixing parameter drops rapidly. For instance, application of a 35 Hz stirring frequency yields a mixing parameter of around 10 %.

In Fig. 5 the mixing parameter is plotted as a function of magnetic induction at a stirring frequency of 2 Hz. As can be seen the mixing parameter strongly increases with increasing magnetic induction and reaches its maximum value above about 25 mT. It appears that especially the mixing in the interior of the weld pool is improved by increasing the magnetic induction.

When considering the results obtained in the foregoing it appears that optimal particle mixing is obtained when electromagnetic stirring is carried out with a magnetic induction larger than about 20 mT and a stirring frequency of about 2 Hz. As an example, the cross-section of a weld obtained with B = 24 mT and $v_s$ = 2 Hz is depicted in Fig. 6.

At this point it should be realised that even under optimal mixing conditions the particle distribution at a micro-scale is not homogeneous, but characterised by regions of high particle density, surrounded by particle

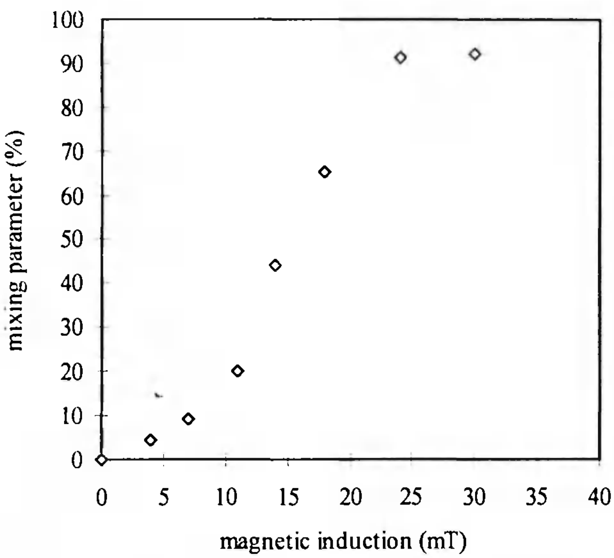



**Fig. 5:** Mixing parameter as a function of applied magnetic induction at a stirring frequency of 2 Hz.

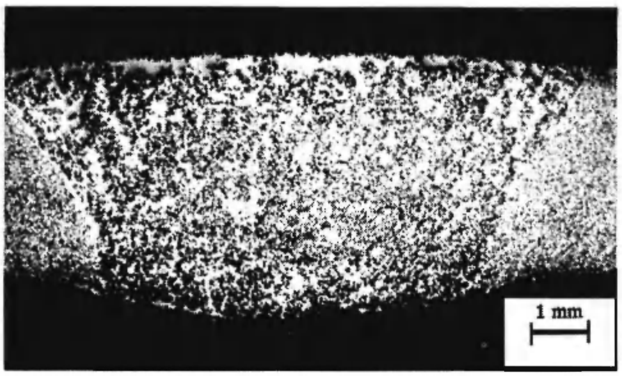



**Fig. 6:** Transverse cross-section of a weld produced with magnetic induction of 24 mT and a stirring frequency of 2 Hz.

free regions. This clustering effect, which is also observed in non-stirred welds, is presumably due to particle pushing /1/. An illustration of the particle distribution in a typical weld cross-section is shown in Fig. 7.

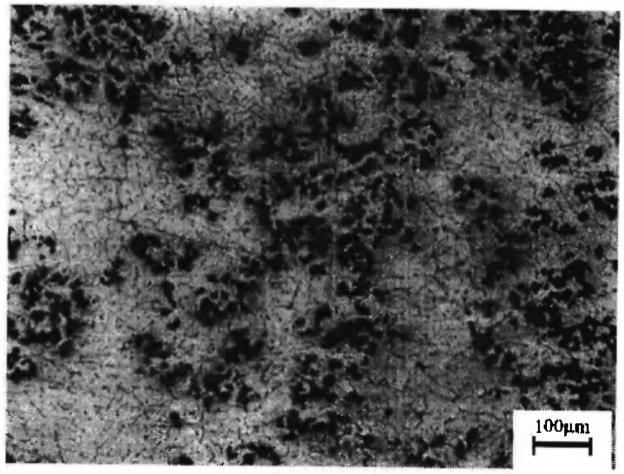



**Fig. 7:** Particle distribution in a transverse cross-section of a stirred weld (24 mT and 2 Hz).

### 3.3. Welding under practical conditions

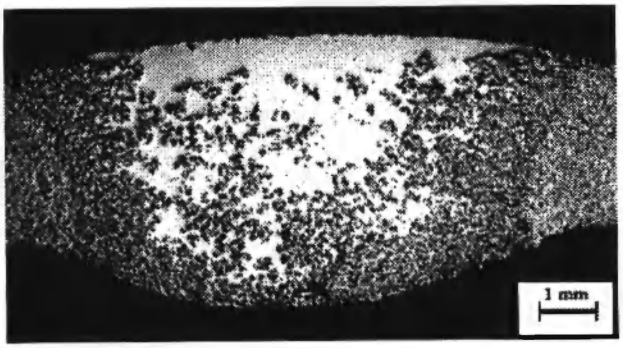
In addition to the bead-on-plate welds discussed in the previous sections, welds were also produced under more practical conditions, using a workpiece consisting of two plates provided with a Y-groove. Welding was carried out without and with electromagnetic stirring, the latter under optimal conditions (24 mT, 2 Hz). The filler wire rate was adjusted in such a way that the Y-grooved gap was just filled.

In Fig. 8 transverse cross-sections are shown of welds obtained without and with electromagnetic stirring, respectively.

In the case of electromagnetic stirring the required filler wire rate was about 35 mm/s, whereas in the non-stirred case the required filler wire rate was about 40 mm/s. This behaviour is reflected by the smaller weld (less overpenetration) when applying electromagnetic stirring. Apparently, electromagnetic stirring facilitates control of the weld pool shape.

As can be seen mixing of the filler wire and the composite weld metal is relatively poor in the case of the unstirred weld, whereas in the case of stirring thorough mixing is achieved. It appears that the stirring parameters (magnetic induction and stirring frequency) used in the case of bead-on-plate welding can be directly applied to welding in case of the Y-groove geometry.

It was also found that the characteristic features (grain structure, particle redistribution) of the stirred Y-groove welds are similar to those observed in the bead-on-plate welds. However, due to the extra filler



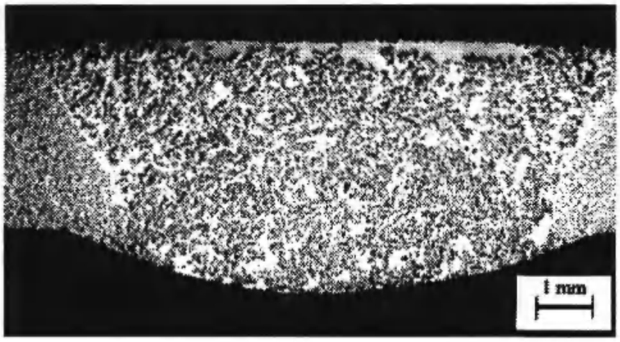




**Fig. 8:** Transverse cross-section of weld obtained without (top) and with (bottom) application of electromagnetic stirring (24 mT, 2 Hz).

wire addition required in the case of the Y-groove weld the overall chemical composition of the weld metal is different.

To determine the hardness of the stirred welds, hardness profiles were measured after T6 heat treatment. In Fig. 9 the hardness profile of a stirred weld is depicted as measured along a horizontal line through the centre of the weld. It can be seen that the average hardness of the weld metal is about equal to that of the base material. The scatter of the hardness in the weld metal is due to local differences in the particle distribution. The obtained results justify the conclusion that also under practical conditions reliable welds can be produced by applying electromagnetic stirring.

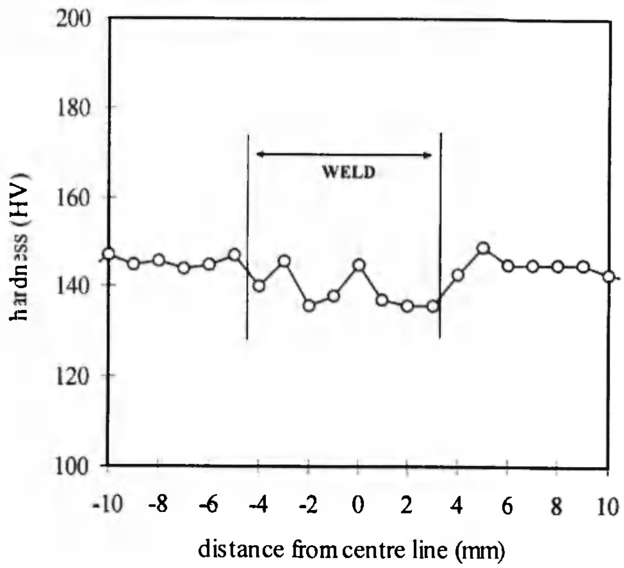



**Fig. 9:** Hardness profile measured through the centre of a Y-grooved weld stirred under optimal conditions after post weld heat treatment (T6).

## CONCLUSIONS

On the basis of the work described in this chapter the following conclusions can be drawn.

- Electromagnetic stirring during welding of the composite 6061/Al2O3/10p with filler wire addition (Al 5wt.% Si) leads to severe mixing of the composite material.
- The degree of mixing (expressed in terms of a mixing parameter) depends on the strength of the magnetic induction and on the stirring frequency. The best mixing results are obtained with a magnetic induction higher than 20 mT and a stirring frequency of around 2 Hz.
- The hardness of the stirred welds (after T6 heat treatment) does not significantly deviate from that of the base material.
- Electromagnetic stirring can be successfully applied in the case of welding composite material under practical conditions.

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