Joining Forces

Magnetic Pulse Welding of Automotive HVAC Parts

by

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A White Paper on the Subject of HVAC

Dated July 9, 2006

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Magnetic Pulse Welding of Automotive HVAC Parts

1. Introduction

HVAC manufacturers are requested by the OEMs to push back technical boundaries to meet the OEM's demands for higher efficiency and reduced weight, size and cost, whereby the car makers consider quality to be as important as price in their deliberations. Therefore, the production technologies that are used in today's factories, have become a very important pillar for HVAC manufacturers to stay competitive in the marketplace.

Major challenges for HVAC manufacturers include to continue pushing for higher efficiency and cost reduction, to move to low cost countries and/or to try and seek revolutionary design concepts and manufacturing processes.

With today's mainstream joining technologies, the manufacturers have reached a technological ceiling in terms of quality productivity improvement and price reduction.

Within this paper we introduce a new technology called magnetic pulse welding (MP-Weld) with the goal to add magnetic pulse welding as an additional technology of choice for manufacturers to consider.

Magnetic Pulse Welding technology enables manufacturers to improve the quality and productivity while reducing the costs per part, by introducing revolutionary production designs that were not possible until today.

2. MP-Weld Overview

2a Technology

Product designers are frequently constrained by the restrictions of traditional joining technologies which place limitations on the type of joint, the materials that can be joined and the quality of the process. Pulsar's MP-Weld™ allows manufacturers to improve significantly their product designs and production results by enabling dissimilar metals to be welded together thus enabling the use of lighter and stronger material combinations. Pulsar's MP-Weld delivers

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better joining results and superior quality at a higher production rate and at less cost than any conventional joining process.
MP-Weld has been tested and machines are producing parts for leading manufacturers worldwide. MP-Weld has proven particularly suitable for the automotive and white goods industries, where reducing manufacturing and material costs, reducing weight as well as improving yield and quality, are major challenges. For the automotive industry, MP-Weld offers applications for welding climate control system components, fuel filters, earth connectors, drive shafts, engine support, body construction elements and cables.

2b. Process

The MP-Weld process is eminently suitable for large series production with quick turn-around time. The process does not require special cleaning processes (such as are needed for conventional brazing and welding processes), other than a prior vapour degrease, which does not require to be carried out in close proximity to the weld process. In addition, the process does not require any post weld cleaning (such as removal of weld spatter and flux in conventional processes). No finishing is required.

After establishment of the production process, in-process quality inspection, such as leak testing, may be radically reduced or even eliminated.

2c. Advantages

- Enables Designs Previously Not Possible
  - By welding dissimilar materials
  - By welding non-weldable materials
  - By allowing the use of lighter and stronger materials
- Cuts Manufacturing and Component Costs
  - Production rate higher than any other conventional joining process
  - Eliminates re-work: negligible process failures
  - No need for pre or post weld deburring or cleaning

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- Consumables: no filler wire or shield gases used
- Superior quality
    - Cold process: no heat treatment degradation
    - Higher strength, with lower weight
    - No corrosion development at the welding area
    - Better conductivity

'Green' Process - No Heat, Radiation, Gases, Smoke or Sparks

MP-Weld systems are well suited to high volume production. A single system can easily weld one million parts a year in two shifts. The systems require low maintenance, and can weld different parts with a short setup time.

3. Comparison of TIG/MIG with MP-Weld

Fig 3.1 shows a typical TIG weld in an R/D assembly. The material of both parts is 6061-T6. Fig 3.2 shows a 6061 accumulator, welded alternatively by MIG and by MP-Weld. In each case, the TIG/MIG welds are the weakest part of their assemblies due to the fact that their HAZ's (Heat Affected Zone) have UTS strength reduced from 310 to 125 MPa by the weld process. In addition the TIG/MIG weld itself is now made up of cast material and not the original wrought material. In comparison the MP weld remains with its original strength as there is no heating up of the assembly in welding and therefore no HAZ. Further to this, the MPW requires no post weld cleaning and provides a much more aesthetic result.

Fig 3.1: TIG Weld of Al6061 A/C R/D

Fig 3.2: Comparison of MIG welding to MP-Weld in 6061-T6 Accumulator

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In addition to the above there are other certain disadvantages with the conventional TIG and MIG processes, which are not relevant to MP-Weld:

1. Good quality welds need a relatively slow cycle to ensure freedom from leaks (normally due to porosity from trapped gases).

2. Post-weld cleaning of oxidation and spattering required to ensure adequate aesthetics.

3. Start/finish of welds often produce pinholes, resulting in even lower strength in these weld areas.

Quality must also be considered:

1. Relatively high number of leak defect parts produced by MIG, as a result of pinholes, undercuts, uneven weld path and HAZ.

2. Good aesthetics are not easily achieved due to the complexity of the welding process.

3. A significant number of parameters must be controlled to ensure a quality process.

Consumable material cost such as fillers, electrodes, orifices, gases must also be taken into account.

Additional cost sources include the relatively high cycle time limiting productivity, qualified personnel to control the process, rework and scrap problems, as well as customer claims.

4. Comparing MP-Weld with Your Current Production Method

It is first necessary to identify current problems encountered by your present production method eg leak rate, scrap rate, rework rate, heat distortion, manpower proficiency, etc. These should then be listed in accordance with their level of seriousness.
The next step required is to define the success criteria of the product in the areas of quality and characteristics.
In parallel it is also necessary to understand how the MP-Weld process will suit the existing overall production line as a replacement for that existing.
After this initial self-questioning, a pilot production project should be run with an established MP-Weld vendor.
Results from this production run, based on the above-mentioned items, will lead us to an adequate technical comparison between MP-Weld and current processing.

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To complete the picture from the business point of view, a cost analysis and return of investment should be calculated, so that we can see how competitive the MP-Weld process actually is for the defined project.

5. Definition

Magnetic pulse welding is analogous to the mature and well known explosive welding process. Explosive welding is defined by the **AWS Handbook, Eighth Edition, Vol II**, as a solid state welding process that produces a weld by high velocity impact of the workpieces due to a their controlled acceleration. The metal is accelerated to a speed at which a metallic bond will form between them when they collide. The weld is produced in the fraction of a second without the addition of filler metal. This is essentially a room temperature process in that gross heating of the workpieces does not occur. The mating surfaces, however, are heated to some small extent by the energy of the collision, and welding is accomplished through plastic flow of the metal on those surfaces.

The intense pressure necessary to make a weld is generally at the collision point, when the collision velocity and angle are within certain limits. These limits are determined by the properties of the particular metals to be joined.

5a. Introduction to Magnetic Pulse Welding

As Magnetic Pulse Welding is a fairly new technology, there is not enough published scientific literature on it. We will therefore refer to the analogous process of explosive welding, which is applied to flat plate and tubular welding, where the only difference between the processes is the source of energy used to accelerate the outer work piece.

The above stated Explosive Welding principles are also relevant to Magnetic Pulse Welding, in which welding is achieved by application of the same jetting phenomenon, if we substitute explosively produced energy by magnetic pulse energy (see Fig 5.1 for comparison of the two mechanisms).

The mechanism and the quality of explosive welds have been very well documented and reported in the leading scientific journals over the last ~60 years. It has been clearly shown that the explosive weld is a truly metallurgical bond for a very wide variety of metals and metal combinations. A very few of these articles are referenced here (1) (2) (3) (4) (5) along with one on Magnetic Pulse Welding (6).

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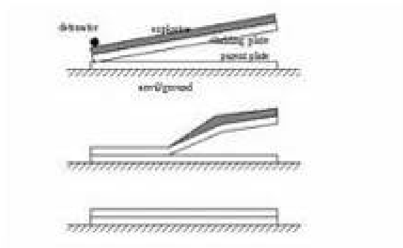
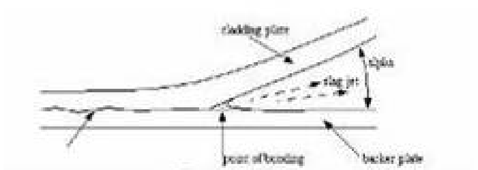
Explosive Welding





Slag Jet

MPW

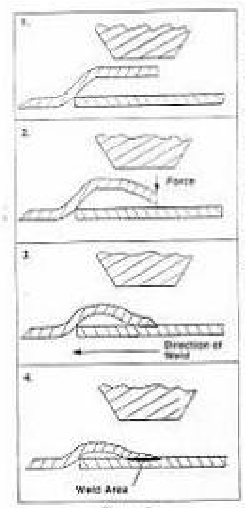


Fig 1

Information provided by the explosive welding literature states that:

The technology of explosive welding harnesses the energy found in explosives to permanently bond metal. Under precisely controlled conditions, a high-pressure collision is created between the two surfaces of the metals to be bonded. The atoms of the two adjacent metals are propelled together with such force that they actually overcome their natural repulsion forces and result in a stable equilibrium as they share electrons. The process uses pressure, not heat, and thereby avoids all the conventional heat-induced problems found in welding, such as phase changes, the formation of intermetallics, recrystallized grains, etc. The bond is generally stronger than the host materials themselves, as limit failure occurs in the weaker of the two metals and not at the bonded interface. The absence of heat in the process makes it possible to bond metals with widely different melting temperatures, such as aluminum and steel.

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5b. Equipment

The electrical layout of the system is shown in Fig 5.2. An AC current is rectified and charges a bank of capacitors to the level required. A vacuum switch or vacuum switches simultaneously release the stored electrical energy into the coil, creating the process as later described. A typical system for carrying out MP-Weld is shown in Fig 5.3. The system has a remote pedestal for operating the system by means of the PLC, such that the quality of the pulse can be monitored and controlled. The system also has its own diagnostic system built-in.

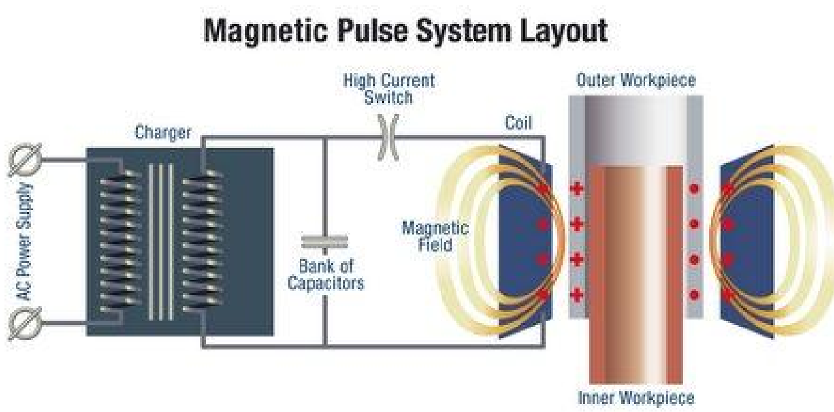

Fig. 5.2

Fig. 5.3

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5c. The Process

Figure 5.4 shows the typical part geometry before and after the welding process. Note that the weld is always accompanied by deformation in the welded area, as shown in the figure. Figure 5.5 illustrates the set-up for welding, in which a current (up to 1.6MA for larger machines) is released into the coil, creating an eddy current on the outer surface of a metal tube (outer) placed inside the coil, giving rise to a magnetic field, in addition to that produced around the coil. These magnetic fields oppose one another and cause the outer metal tube to be imploded at high velocity to impact the inner metal tube. If the impact creates the right conditions of angle of impact and velocity, jetting is created and subsequently welding takes place.

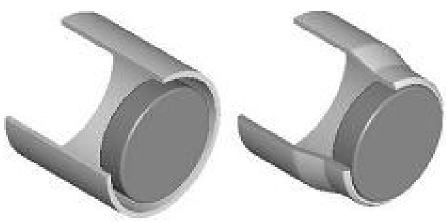

Fig. 5.4

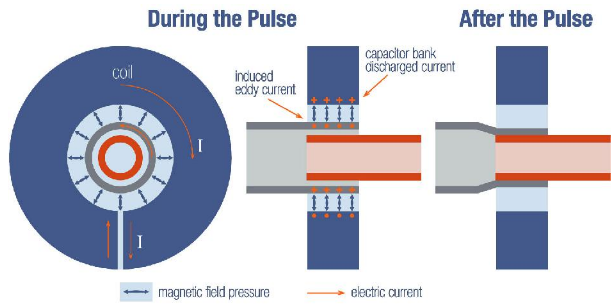

Fig. 5.5

5d. **Bonding Mechanism**

As in explosive welding, a jet is created between the two bonded surfaces by the impact force acting upon them. This jetting action removes all traces of oxides and surface contaminants, allowing the magnetic pressure caused impact to plastically deform the metals for a short instant and to drive the mating surfaces together. This allows the impact of two virgin surfaces, stripped of their oxide layers, to be pressed together under very high pressure, bringing the atoms of each metal into close enough contact with each other, to allow the atomic forces of attraction to come into play. There are a number of explanations for the precise mechanism at the point of collision, but all agree that the metals momentarily behave like liquids, even though they remain solid. Due to the rapidity of the process, temperatures at the interface do not rise significantly. For this reason, it is possible to permanently bond widely dissimilar metals. The quality of the bond at the interface is a product of many parameters, among them the magnetic force, the collision angle, the collision point velocity, and the initial standoff distance between the mating surfaces (see Fig 5.6). Typically, the pressures at the collision point between the mating surfaces are in the range of 15M psi (103,000 Mpa) (measured by University of Manchester Institute of Science & Technology, England researchers for explosive welding).

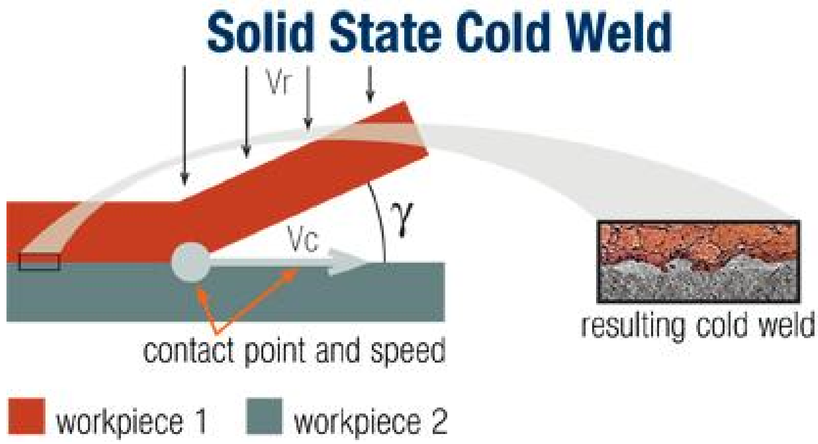

Fig. 5.6

5e. Interface Morphology

MP-Weld produces either a wavy or waveless morphology at the interface, where the precise shape is determined by the properties of the metals and by the parameters applied. In the case of Al to Al or other similar metal welds, either morphology is acceptable. Figures 5.7-5.10 give some examples of these different interface shapes:

Fig 5.7 shows a metallographic section taken from a tube to fitting (rigging and staging application), in which the weld has a wavy interface (mag x200). Materials are Al6082-T6 to itself, OD 48mm x 3mm wall thickness.

Fig 5.8 shows a wavy interface in Al6061 material welded to itself (mag x50).

Fig 5.9 shows an undulating, non-wavy interface, (mag x100).

Fig 5.10 shows a wavy interface with evidence of plastic deformation (mag x200) from an Al 7075 capsule (cap to can weld).

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Fig. 5.7

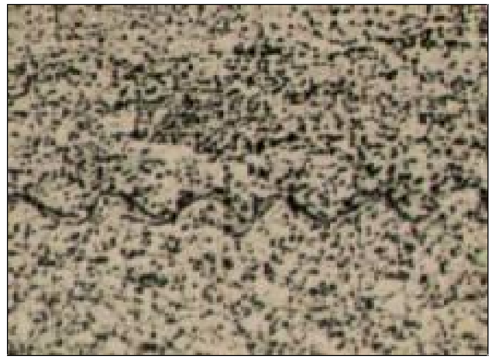


Fig. 5.8

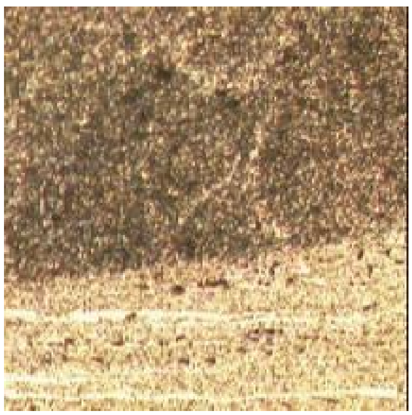


Fig. 5.9

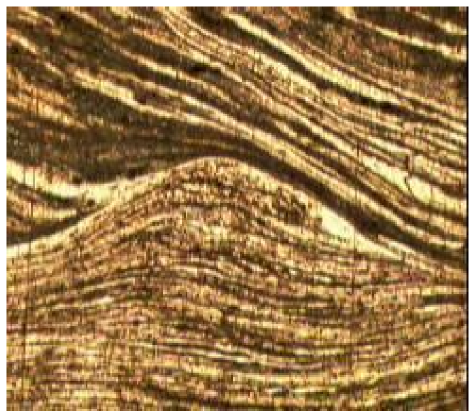
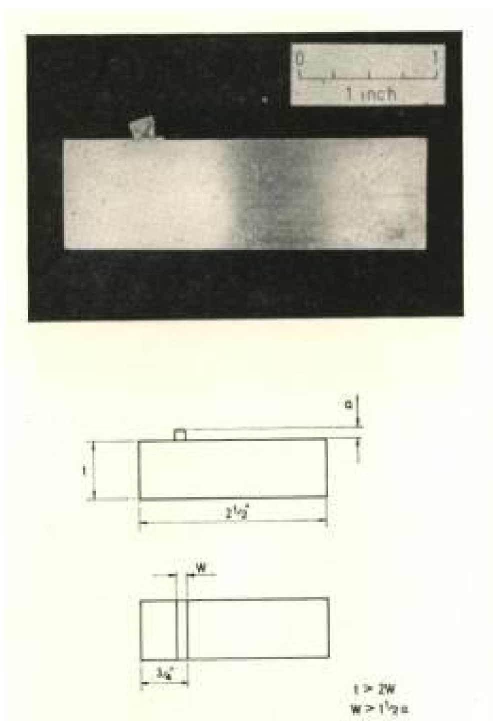
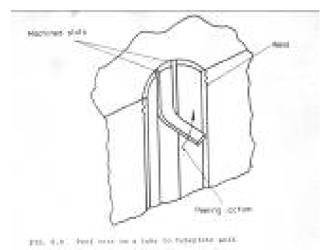


Fig 5.10

6. Standard Tests for MP Welds for HVAC Applications

To our knowledge there are no international specifications specifically defining the MP-Weld process or its quality control. Due to the similarity of the results obtained from Explosive Welding, the following tests, which are currently applied to explosive welding, can be adopted for the MP-Weld process. They are:

1. Shear strength test, based on ASTM/ASME A-263, A-264 or A-265 (see Fig 6.1), or peel test (as shown in Figs 6.2 - 6.4)
2. Pressure or vacuum leak test (assisted by helium or other inert gas)
3. Pressure burst test (see Fig 6.5)

 Fig 6.1: Shear test in accordance with ASTM	  Fig 6.2: Peel tested part

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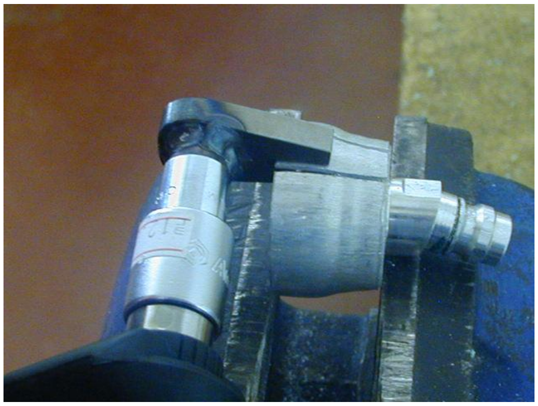

Fig 6.3: Torque tool head mounted for peel test

Fig 6.4: Torque tool being applied for peel test

Examples of Testing Performed on Various Welds

Figures 6.5 and 6.6 give some examples of testing that has been performed on various MPW applications:

Fig 6.5 shows the result of a burst test on a tubular weld of Al3003-H12 to austenitic stainless steel 304. The failure occurred in the Al tube outside the weld area. See also Appendices I. II and III for extracts from customer reports.

Fig 6.6 illustrates the quality of the Al weld, after being peel tested. The weld is shown in section.

Fig. 6.5

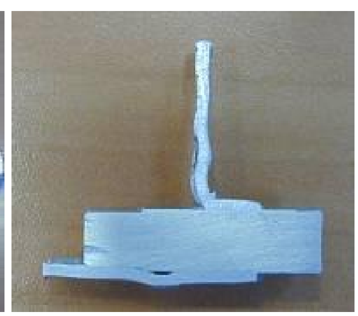

Fig. 6.6

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7. MP Weld Process

7a Simulation, Parameters and Control of the MP Process

As opposed to arc welding processes, in which there are a large number of variables that may cause in-process problems with quality, MPW is very precisely controlled and has only one possible variable parameter after the process cycle has been fixed. Equipment is normally computer controlled with electrical and magnetic parameters being precisely measured. Characteristics defining the process parameters are the coil geometry/material, coil resistance/inductance, machine characteristics, material to be welded and the energy level. These are fed into the simulation software (developed in-house) which produces an output of peak magnetic pressure, frequency, impact velocity and splash energy, machine kJ, contact time and weld length, the specific parameters required to produce the product. Fig 7.1 presents an example of one of these calculations.

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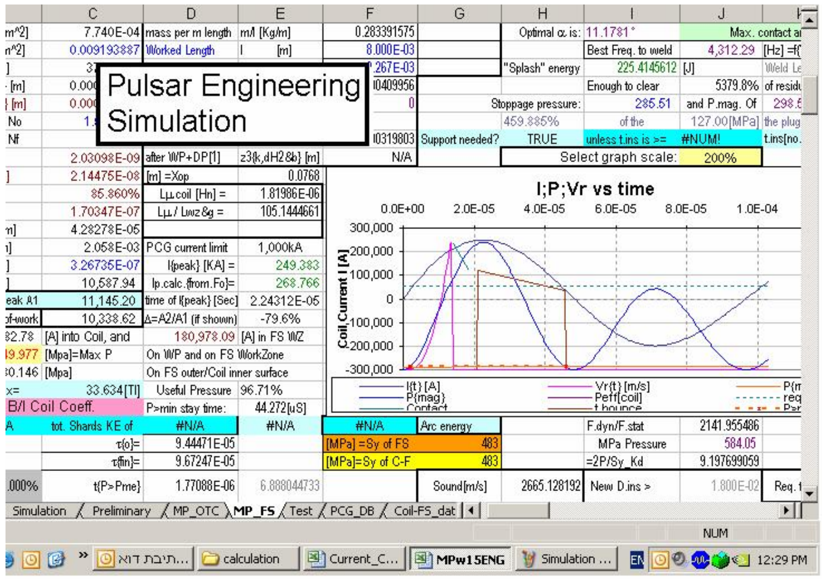

Fig 7.1: Typical Process Simulation

The resulting Current v Time curve in Fig 7.1 defines the P v Time curve. Control of the process, deciding whether or not a successful result has been achieved, is monitored by the PLC, which will warn the operator of the status of any particular part in a production series.

A Few Words on Coil Design

Coil design is one of the major influences on the work parameters of the process. Different coil designs may produce very different results (see Fig 7.2) from the same input parameters.

Figs 7.2 and 7.3 show multi-turn (Bitter) coil and single turn coil respectively.

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Fig 7.2 Multi-turn coil

Fig 7.3: Coil design

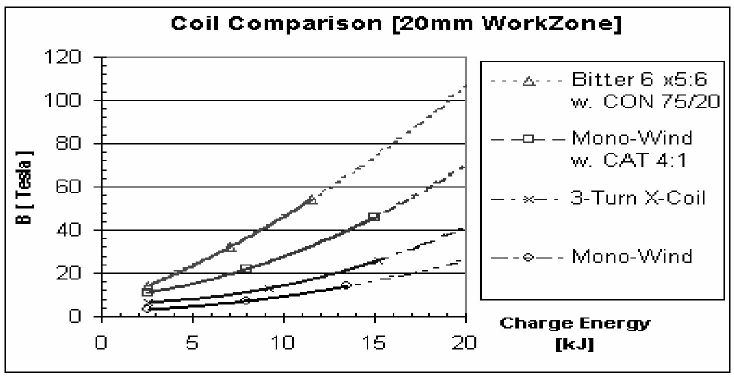

Fig 7.4: Distribution of magnetic field power in the axial direction as a function of coil type and bank energy

7b Material Handling

Although material may be manually handled initially, the aim of any production process is to achieve efficient productivity. To this end, semi-automatic or fully automatic machines and robots could be applied to the process to ensure that the maximum is obtained from the magnetic pulse equipment, which is designed specifically for large quantity serial production.

7c Cycle Time

The cycle time of any particular MP process is built up of loading, charging, welding and unloading. The loading and unloading processes may be manual or automatic. The advantage of the latter is that, not only is it intrinsically very

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much faster, but the charging process may be performed parallel to the loading process, something not possible in manual feeding, due to safety aspects. Typically the weld takes <100 µsecs, while recharging in standard machines is approximately 6 seconds, depending on the energy level. This means that with automatic MP Weld, it is possible to reduce the cycle time to less than 10 seconds.

7d Infrastructure

The infrastructure required for magnetic pulse machines is simply a three phase electrical power source. No other inputs are required to operate the systems. However, air pressure lines may be required to operate tooling. All cooling liquid is applied in closed circuit processes and does not require infrastructure.

7e Safety Considerations

MP machines have been designed and built to meet the safety requirements of EN 60204 Safety of Machinery – Electrical Equipment of Machines, ANSI C57.12.58-1999 and IEEE Standard C95.1, 1999 Edition for EMF exposure compliance. The meeting of the requirements of these specifications ensures the safety aspects of the machines and their operation

8 Future Applications in HVAC: CO_2

The latest direction in HVAC systems calls for the use of Freon replacement gases such as CO_2. These CO_2 systems work under very high pressure and are required to meet a burst test requirement of +/-300 bar. Therefore, capsules for these systems will require increased wall thicknesses to combat this need. With conventional arc welding processes for heat treatable aluminium alloys, such as 6082-T6, a reduction of strength from T6 condition (Yield 260 Mpa) to a near T0 condition (Yield 55 MPa) will occur in the heat affected zone of the weld and thus a 6-10mm capsule wall will be required to compensate for this reduction. A major problem facing this solution is the deep drawing of capsules with these wall thicknesses. However, a different solution is the use of MP-Weld, which creates a weld, while maintaining the original heat treat condition. This will enable the use of thinner walled capsules, which can be deep drawn satisfactorily. In Appendix IV, Fig IV-3, such an MP-Weld to meet this situation is illustrated.

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9 Choosing your MP-Weld Vendor

When choosing an MP vendor, here are some of the questions you should consider: Do they have:

1. Suitable and good quality equipment?
2. Equipment which is computer controlled with adequate diagnostics
3. Experienced engineers in the fields of electricity and magnetism
4. Experienced engineers in the fields of welding and metallurgy
5. Project management and technical support
6. Metallurgy laboratory support
7. Authorisation to recognized QA standards, international or local
8. Track record for applications with references in this field
9. Flexibility of the system: changing time for welding other applications, system also usable for other applications eg forming, etc.
10. In-time delivery of projects
11. Organised facility

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12. Appendices

Appendix I – Extract from Customer Test Report: Leak and Burst Test

Test Setup Notes – Samples were charged with 25 grams of R134 Refrigerant and pressurized with 400 psi of Nitrogen. Samples were then leak checked using an Inficon leak detector set at 5.9g/yr.

Acceptance Criteria – A leak rate greater than 0.15 oz/yr. Constitutes a failure.

Sample #	Leaks (Yes/No)	Met Specification?
1(9.0 mm Cap)	None	Yes
2(11.5 mm Cap)	None	Yes

Section 2.4.3 – Burst Test

Test Setup Notes – Assemblies were connected to a burst tank capable of applying at a rate of approximately 1000 psi/min until burst occurred.

Acceptance Criteria – The assembly shall not fail at a pressure less than 1400 psig. No permanent deformation to the body is permitted below 1000 psig.

Sample #	Burst Pressure (Psi)	Failure Mode	Met Specification?
1	3311	Side of can split	Yes
2	3386	Side of can split	Yes

Conclusion
All samples met specification requirements.

[redacted]
Test Technician

[redacted] 1/26/04
Test Engineer/Manager Approval Date

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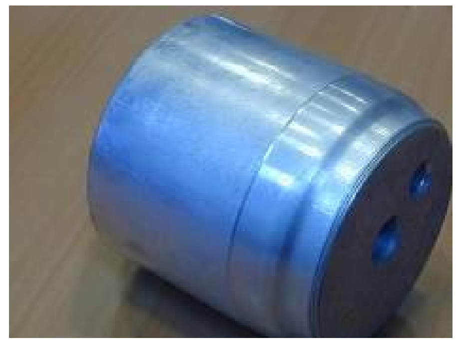
Appendix II – Extracts from Customer Test Report: Temp Cycling, Helium Leak and Burst Tests

Figure 1: Welded Sample Assembly

2. A modification of standard test procedure (since there was only one can) for the PHN style accumulator was followed to assess the joint integrity. This procedure consisted of a helium leak test, a temperature cycling test (10 cycles of: 1 hr 200°F, 1 hr 68°F, 1 hr -20°F, 1 hr 68°F) followed by another helium leak test, an impulse test (10000 cycles, 1.3-1.4 Hz, 0-275 psi), and finally a burst pressure test (hold at 500 psi for 1 minute, then increase pressure until failure). The assembly passed all of the required tests. The test reports are attached to this report.
3. The weld sample was sectioned and the bond area was visually examined. The joint was found to consist of several distinct areas. There is a relatively large flat interface in the middle of the joint (Figure 2). Near the ends of the joint the interface is rippled (Figure 3, Figure 4), then a wider band of oxides/jetted material is evident at the ends (non-bond area) (Figure 5). The jetted material also accumulated at the corners of the head-fitting groove (Figure 6, Figure 7). The joint interface is visible across most of the weld (to varying degrees) as a dark band. Since the jetted material at the ends of the joint appears to be Spinel ($MgAl_2O_4$) and MgO, the dark line is likely of a similar composition. The bonded interface appears to be visible in small segments of the wavy region (especially at the leading and trailing portions of the wave) as a break in the oxide band.



Summary:
Temp Cycling Test
Helium Test
Burst Test
Assembly passed all required tests

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Appendix III - Extract from Customer Test Report: Metallography, Burst Test and Salt Spray Tests

2.2.2 Burst Tests

Sample Type	Tube Dias	Test Type	Test Result	Notes
Al/Al	½"	Hydraulic burst test	No failure	Tested up to 220 bars*
Al/Al	1"		No failure	
Al/Cu	½"		No failure	
Cu/Brass	½"		No failure	
Al/Cu	1"		No failure	

*The burst tests were discontinued prior to bursting due to limitations of the test equipment.

2.3 Metallographic Examination
Weld sections of all metal combinations and dimensions were evaluated by microscopic examination of metallographic sections. The sections showed good, clean weld interfaces in all cases. Some typical microsections are shown in Figures 1-4 for the copper brass combination.
Fig 1: Weld interface with typical wave formation - unetched (X50)
Fig 2: Weld interface with typical wave formation – unetched (X100)
Fig 3: Weld interface with typical wave formation – etched (X50)
Fig 4: Weld interface with typical wave formation – etched (X100)

2.4 Salt Spray Test
Salt spray testing was carried out on samples of Cu/Brass manufactured by MPW with brazed Cu/Brass and Al/Cu, as well as a copper sample(untreated) for comparison supplied by Electra. Testing was carried out in accordance with MIL STD 810E Method 509.3 (Equivalent to ASTM B117-85) for 72 hours. Samples were withdrawn from the test chamber and examined every 24 hours for detrimental effects. These test were performed by
The Israel Standards Institute. Test results are reported in Report # 2912244318 of the Israel Standards Institute.
It can be seen from this report that Pulsar welded components showed no signs of detrimental effects after 24 hours while regular brazed components supplied by Electra had signs of corrosion products on or in the vicinity of their joint areas.
On the completion of 168 hours, metallographic analysis revealed that there was no sign of corrosion in the joint areas of MPW welded components. There were, however, traces of white and green powders (sodium aluminate and copper chloride)on the parts showing the beginning of corrosion. As opposed to this Figs 5-10 show defects discovered in micro examination of the Electra brazed components in their brazed areas.
Fig 5: Corrosion of brazed material at joint of brazed assembly (Mag X100)
Fig 6: Corrosion of brazed material at joint of brazed assembly (Mag X200)
Fig 7: Corrosion pit found in braze material in brazed joint (Mag X50)
Fig 8: Corrosion pit found in braze material in brazed joint (Mag X100)
Fig 9: Corrosion pit found in brazed material in brazed joint (Mag X50)
Fig 10: Crevice corrosion of non-welded connection supplied by Electra (Mag X50)

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Appendix IV - Typical Weld Applications

Figures IV-1 to 4 illustrate some typical Al/Al weld applications:

Fig IV-1 shows an automotive fuel filter manufactured from Al1050 material. This part undergoes pressure pulse testing at 7 bars for 250k cycles.

Fig IV-2 provides a close look at automotive HVAC MP welded parts. Caps are manufactured from Al6061-T6 while cans are manufactured from Al6061-F. These parts underwent stringent leak (including helium) and burst testing to prove the product.

Fig IV-3 shows a welded section of the **latest automotive A/C development in the area of CO_2 system welding**. In this case an Al6082-T6 R/D with canister wall thickness of 4 mm has been successfully welded to a cap and tested. The advantage here is that the T6 heat treatment is maintained by the MPW process, and not degraded, as would occur with conventional arc processes, reducing the material to the annealed condition.

Fig IV-4 shows a welded automotive A/C accumulator manufactured in 6061 material.

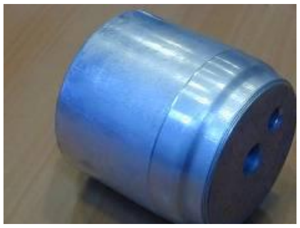

Fig. IV-1

Fig. IV-2

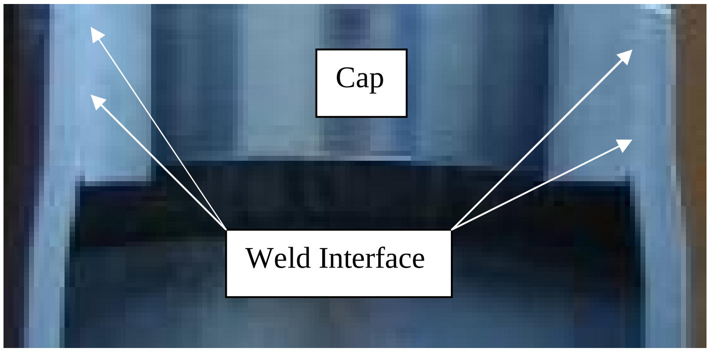

Fig. IV-3

Fig. IV-4

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