Fusion Welding P/M Components for Automotive Applications

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ABSTRACT

The paper identifies welding methods that are most often used to join P/M automotive components. Various weld procedures associated with the different methods are discussed. Examples are presented along with appropriate process information. A more detailed application development involves Gas Tungsten Arc welding a stainless P/M exhaust bushing to a wrought stainless steel tube.

INTRODUCTION

New automobile design goals focus on reducing vehicle weight along with improving structural integrity and safety standards while concurrently reducing manufacturing and assembly costs. The ability to satisfy the new design criteria will require manufacturing techniques along with new materials that exhibit increased strength, greater durability, better quality and lower costs. These characteristics parallel the attributes of powder metal (P/M) parts which continue to replace other methods of manufacture for use in various automotive applications.

A significant number of P/M parts have been successfully fusion welded using joining processes common to the automotive industry. This has extended the use of P/M parts in vehicles by increasing the possibility of producing more complex components than could previously be achieved with conventional die pressed geometries.

Additional discussion will focus on the P/M characteristics that impact weldability along with identifying common P/M welding procedures and techniques. The development of a welded 409 Cb stainless P/M exhaust component by AC Rochester will also be reviewed.

P/M CHARACTERISTICS' INFLUENCE ON WELDABILITY

Powder metal part performance is chiefly determined by density, the selected alloy system and final part microstructure. Each individual characteristic plays a significant role but, more importantly, should work together by design to enhance the weldability and overall performance.

Porosity, or relative density, is most influential in regards to fusion welding. Typically, it is more difficult to obtain sound fusion welds with lower density parts because particle melting results in a greater degree of shrinkage in the weld zone. The subsequent solidification of the weld puddle causes localized tensile stresses to form at the interface between the porous substrate and weld zone which often initiates cracks. The pores in P/M parts can also harbor contaminants that may cause erratic welding performance. For these reasons, intermediate to higher density levels are preferred for fusion welding applications.

The use of various alloy systems, including admixed elemental additions, is a unique feature of the P/M process. The systems typically involve various iron, steel or prealloyed base powders that may include common premix additions of elemental copper and/or nickel along with graphite. The composition can influence the part density and microstructure which in turn impacts the weldability. Copper up to 2% and various nickel additions do not pose particular problems. Graphite additions, however, should be held to as low a level as possible because of the potential influence on the material's hardenability. Admixed additions of sulfur, phosphorus or boron should not be included because of potential adverse welding effects.

Many factors are influential in determining a P/M part's microstructure. Sintering conditions, diffusion of admixed additions, heating and cooling rates, pore size and shape are just a few of the potential factors. The greater microstructural complexity associated with P/M, however, does not change the basic tenets that are typically considered when fusion welding wrought or cast materials. The same precautions should be exercised to prevent martensite transformation or localized stress concentrations.

A more comprehensive review of P/M characteristics and their influence on weldability were detailed in a previous publication [1].

FUSION WELDING METHODS

Welding methods used in the automotive industry must be able to achieve high production rates, provide superior quality weldments, be easily mechanized with short set-up times, have the flexibility to accommodate design changes and maintain acceptable working environment standards [2,3]. The current methods used in the automotive industry to meet these requirements have also successfully welded P/M parts.

RESISTANCE PROJECTION WELDING - This is the most common large-scale mechanized process used to join many different types of parts. RPW is capable of welding low to intermediate density parts by increasing the projection height to provide a sufficient weld nugget. Several materials including plain iron, iron-carbon, iron-copper-carbon and stainless steels have all been welded successfully using this method. Weld trials have also found P/M to wrought steel weldments to have higher torsional strength than standard keyed components [4].

GAS TUNGSTEN ARC WELDING - This method is synonymous with high quality weldments and often employed when joining critical structural elements. It is well suited to meet high productivity requirements and currently used to join many automotive parts, e.g. energy-absorbing steering columns, emission-control devices and various exhaust components. The GTAW method provides a great deal of flexibility in controlling the overall process, thereby improving the ability to obtain sound welds with the more difficult high alloy or high hardenability P/M materials.

GAS METAL ARC WELDING - The evolution of this method began with automated systems producing only straight-line welds. However, subsequent generations using hard-cam and, more recently, electronic-cams with probes to track the weld path now are capable of producing complex shapes with weld speeds of 200 ipm [5]. GMAW systems currently join a wide assortment of components and sub-assemblies that include drive train, engine, axle and frame sections. Additionally, many P/M parts have been welded using this process. The short-circuiting or pulsed metal transfer modes are often used to minimize heat input. Typically, CO_2 based shielding gases are used with small diameter, solid, mild steel filler wire. However, austenitic stainless and copper based fillers with inert gas shields have also been used successfully to join high alloy or crack sensitive parts.

ELECTRON BEAM WELDING - Partial and nonvacuum modes of electron beam welding are common to the auto industry and provide many of the same desirable characteristics as the vacuum method but with minimal pump-down time to improve productivity. These methods currently join automobile frame sections, transmission components and catalytic converters [6]. The EBW process has realized some success in welding P/M parts. Unfortunately, lower density parts typically exhibit a significant percentage of shrinkage, porosity or cracks in the heat affected zone.

LASER BEAM WELDING - LBW technology is gaining acceptance in the auto industry as a process having good flexibility, reliability, productivity and low operating costs [7,8]. Low distortion characteristics, ability to weld various joint configurations and short cycle times are a few of the reasons why it is replacing RPW and EBW processes. An investigation involving a laser equipment and automobile manufacturer is currently underway to determine the weldability of several P/M compositions at various density levels using a 5kW, CO_2 laser unit. The trial will provide the necessary data to assist in the conversion of several auto parts to P/M applications.

PROCEDURES AND TECHNIQUES

Common difficulties associated with fusion welding involve the occurrence of cracking adjacent to the weldment [9]. Fusion welded P/M components most often crack because of the stresses generated during cooling or solidification of weld metal [10]. These stresses can be minimized by using the following techniques:

- Preheating eliminates moisture (hydrogen) and lessens the thermal gradient across the weld zone.
- Post heating after welding reduces stresses, particularly for high hardenability materials capable of significant martensite transformation.
- Austenitic filler metals are beneficial for high alloy and hardenable materials because they provide superior toughness, good strength and minimize martensite transformation.
- Reduced heat energy lessens the degree of particle melting and resultant solidification stresses. Pores in P/M materials act as insulators that retain heat. Typically, P/M parts can be welded using lower heat energy than wrought or cast counterparts.
- Excessive dilution with filler metal or mating part(s) can result in the fine, well distributed P/M pores coalescing into larger pores at the weld interface.
- Good joint design can minimize stresses. Mismatched joints, excessive gap spacing or an insufficient amount of filler metal to counteract densification in the weld zone can have deleterious affects on the weldment.

Steam treated, copper infiltrated or quench and tempered parts are not good candidates for fusion welding. The oxides resulting from steam treatment act as contaminants in the weld zone promoting erratic performance and the potential for cracking. When welding infiltrated parts, copper can melt and migrate to the austenitic grain boundaries which may result in cracking. However, the use of copper based filler wire (AWS-E Cu Sn) or welding parameters that minimize heat input and particle melting have been successful. Quenched and tempered parts, even with a long temper cycle (4-6 hours) to drive off entrapped quench oil, are not particularly good candidates for welding. The high heat input associated with fusion processes changes the structural constituents and lowers the strength in the weld zone as compared with the surrounding material [11].

P/M MATERIALS FOR JOINING

Many powder compositions can be welded without difficulty. However, some additions or material grades should be avoided if possible. In general, atomized iron grades have lower residual and tramp elements than sponge or other types of reduced iron powders. The cleanliness of these materials does not play a predominant role in the weldment's success rate if held within acceptable limits. Nevertheless, the subtle influence of acid insolubles, oxides and silicates over a period of time will influence the service and fatigue performance. For this reason, the atomized grades are preferred for fusion, high strength and critical welding applications.

Carbon content has a pronounced influence on a material's overall weldability. As a general rule, the carbon content should be held to as low a level as possible. However, carbon also greatly enhances a material's strength characteristics. Joining processes and techniques have been developed to accommodate intermediate to high carbon levels that exhibit acceptable weld soundness and strength characteristics.

Materials containing sulfur additions should be avoided. The sulfur can migrate to the grain boundaries and may cause hot cracking when fusion welded. If a machining enhancement is necessary, a more appropriate choice would include a manganese sulphide (MnS) addition.

Premixes with copper additions of 2.0% can be readily joined to other materials using most processes. The exception, however, involves compositions which include both sulfur and copper additions. Too high a copper content (4.0%) was found to lower the weldment strength to levels below the strength of the parent metal [12].

Phosphorus additions (Fe_3P), somewhat like sulfur, are not particularly attractive for fusion welding applications. The low melting Fe_3P addition may promote hot cracking in the weld zone. However, the GTA process, without the use of a filler metal, has been used for a limited number of Ancorsteel 45P (0.40-0.50 wt% phosphorus) applications.

Admixed additions of nickel to iron or steel powders generally enhance the material's toughness and do not pose any particular difficulties involving weldability.

Stainless steel P/M components have been successfully welded using various joining processes. GMAW welds of 316L P/M parts at various density levels, using 316L filler metal with an argon shield provide good overall properties. The 303 free machining grade and those identified as nitrogen strengthened are not good candidates for welding applications. The 410 martensitic grade can be welded, but precautionary measures must be observed with regard to the material's hardenability.

A Ni-Mo admixed composition with a nominal 0.5% C, 5.0% Ni, 0.5% Mo with a sintered density of 7.0 g/cm^3 was successfully welded using the GMAW process with an austenitic filler metal without a preheat or postheat treatment.

WELD MICROSTRUCTURES

The following examples of P/M weldments were selected for their unique characteristics. The example identified as Figure 1 represents a P/M to a low carbon wrought steel using GMAW with E70S type filler metal. The P/M part was manufactured from steel powder with a 0.6% combined carbon level and sintered density of 6.7 g/cm^3. It is unique because the P/M part had been quenched and tempered before welding. This process requires a lengthy burn-out cycle to remove quench oil from the pores. After welding, the component is then stress-relieved to prevent cracking. Weldments on parts that contain quench oil exhibit blowholes and erratic weld performance.

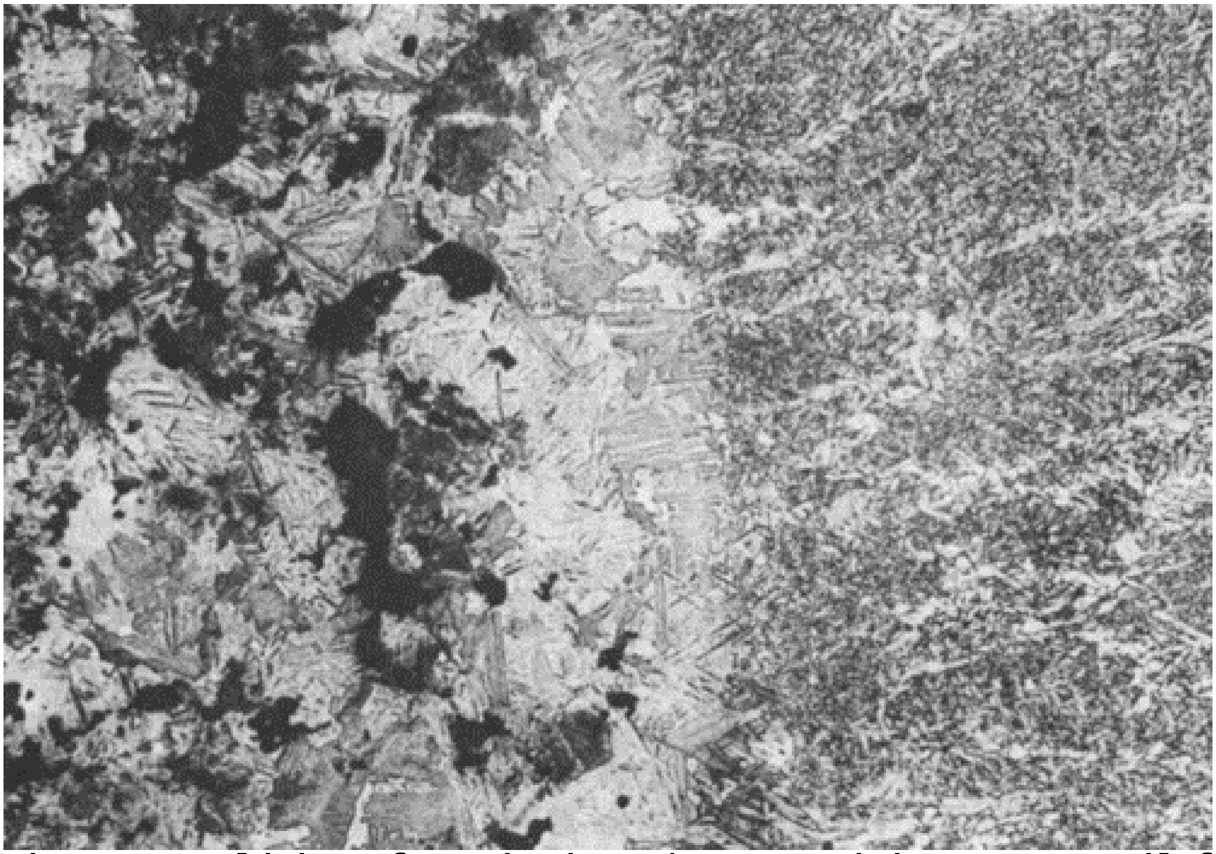

Figure 1: Weld interface showing P/M martensitic structure (left) and low-carbon filler metal with dendritic structure (right).200X

The second example, Figure 2, is a 6.7 g/cm^3 sintered density P/M part welded to a wrought AISI 6150 alloy steel using GTAW without a filler metal. The P/M material has 2.0 wt.% admixed nickel and a 0.3-0.4% combined carbon level. The joint design has the high alloy wrought steel overlapping a step pressed into the P/M part. The GTAW arc must be positioned correctly to insure proper joint integrity. The weld parameters were developed to minimize dilution between the two materials.

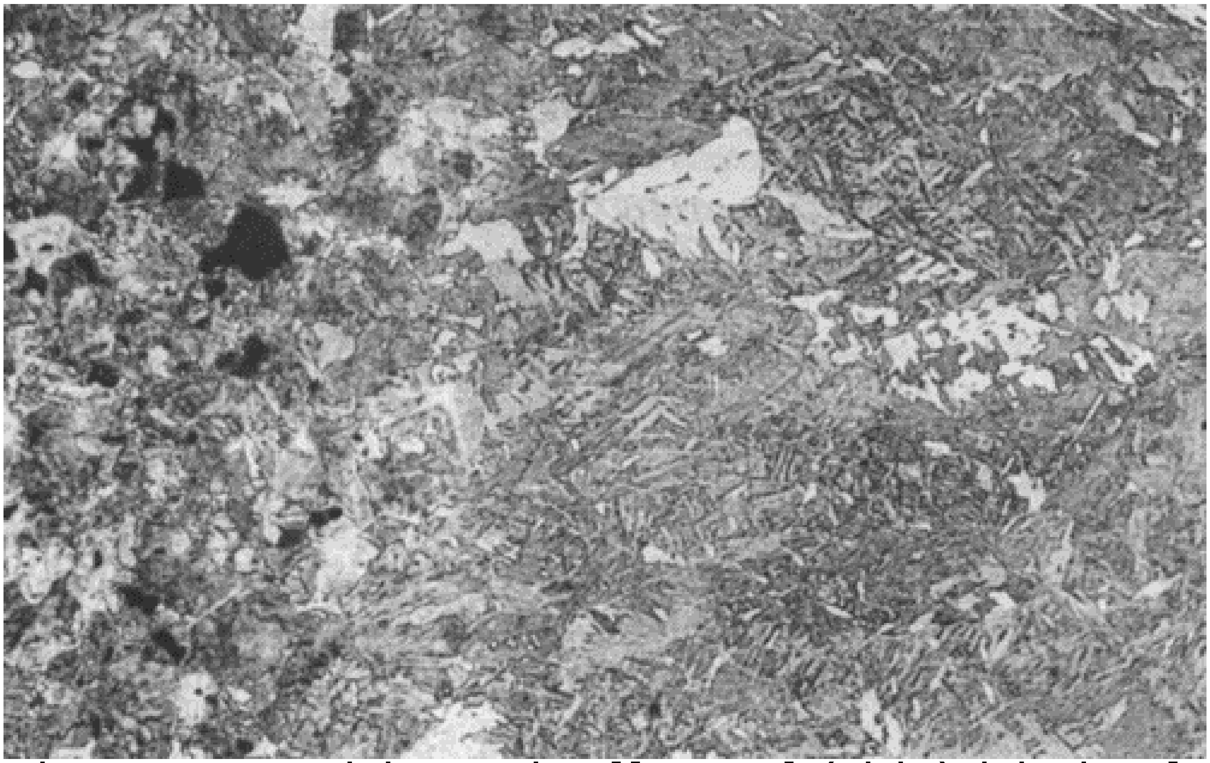

Figure 2: Martensitic wrought alloy steel (right) joined to low-carbon P/M steel (left). 200X

DEVELOPMENT OVERVIEW - 4O9Cb P/M STAINLESS EXHAUST FITTING

APPLICATION REQUIREMENTS - With the adoption of 100,000 mile passenger car emissions standard requirements in 1993 and 1994, stainless steels are increasingly being considered for exhaust fitting flanges and connectors. A specific example is a tube/bushing/flange assembly attached to the outlet end of a catalytic converter, shown in Figure 3. The bushing serves as a sealing interface between two bolt flanges, one fixed to the connecting exhaust pipe, and the other with rotational freedom at the catalytic converter outlet. Stainless steel was specified for all components in the assembly.

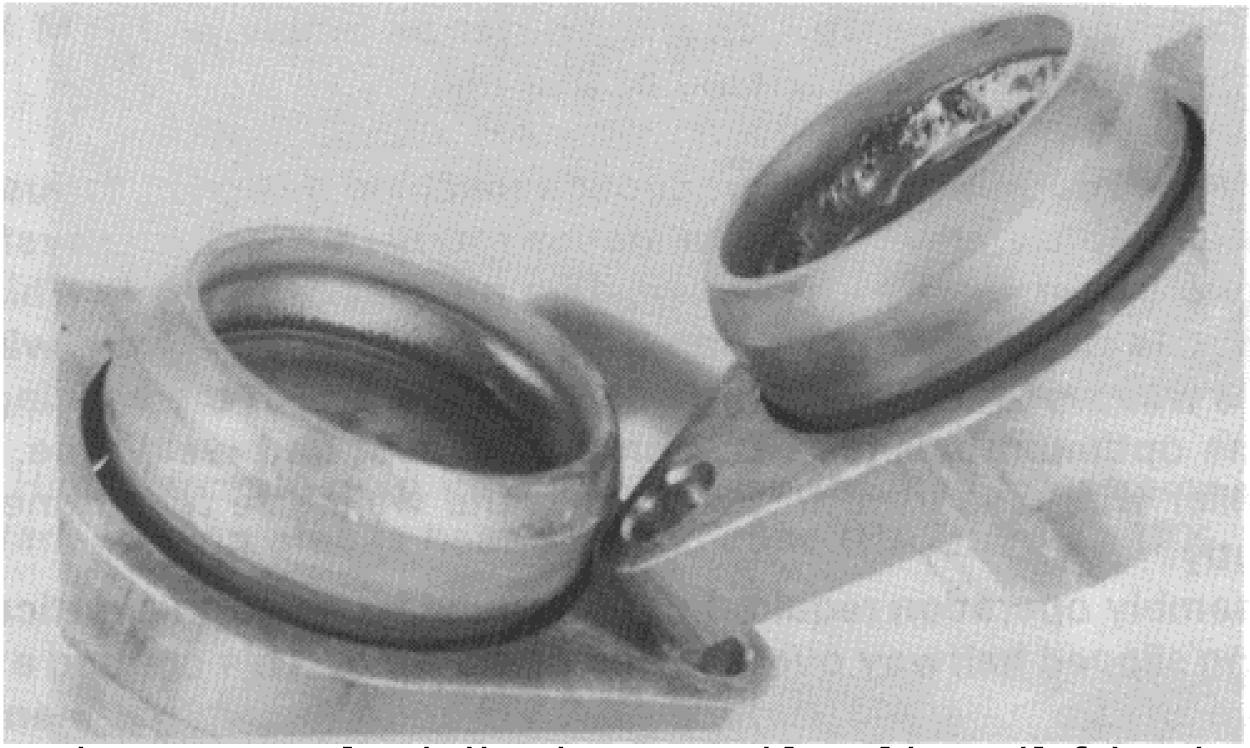

Figure 3: Examples indicating acceptable weldment (left) and extreme porosity (right).

MATERIAL SELECTION - Material selection and an appropriate fabrication method for the bushing were a significant challenge because it required joining the part to a mating 409 stainless wrought tube. Screw machining would be a relatively straightforward process to fabricate the bushing. However, compatible free machining ferritic stainless steel bar stock is not commercially available in the appropriate diameter. Also, material from the center section would be unnecessarily wasted at a significant cost.

Powder metallurgy was considered the most cost effective processing method assuming the component would pass physical durability and weld specifications. Water atomized, stainless metal powder meeting AISI 409 chemistry specification, with the exception of the substitution of Columbium - Cb (Niobium - Nb) for Titanium -Ti, was chosen. This was selected over standard powder SS-410, since this is a martensitic grade which is not desirable for welded components.

PERFORMANCE CRITERIA - Static and dynamic characterization and durability tests were performed on samples of the tube/bushing/flange assembly and catalytic converters with these assemblies attached. A static test of weld strength demonstrated that the bushing/tube interface weldment could withstand an axial force averaging 151 kN (34,000 lbs), after which the tube would elongate, and the GTAW weldment between the opposite tube end and fixture plate would fracture. Dynamic room temperature bending moment testing also demonstrated that the tube was a weaker link in the assembly than the bushing/tube weldment.

A converter assembly was run on a standard engine dynamometer durability test, correlated to over 160,000 km of typical North American vehicle exposure and 80,000 km of European applications and conditions. The test was run on a 2.3 liter 4-cylinder engine on a 2 step schedule - an idle low step, and a severe temperature and vibration exposure high step. The converter assembly and P/M bushing/tube weldment passed all appropriate criteria of this test.

WELDING EQUIPMENT - The production machine designed to fusion weld the tube/bushing/flange assembly was a four station rotary table transfer system with two welding and two loading stations. The welding process selected for this application was automatic gas tungsten arc welding (GTAW) with auxiliary cold wire feed. The GTAW process was selected since it provided good control of the welding parameters and offered the optimum balance between capital cost and weld time. In addition, 409Cb solid filler wire was used to assure that the weld size requirements could be met consistently.

The assembly operation required that the tube be set in the vertical orientation and the bushing slipped halfway over the end of the tube. This created a lap joint that was comprised of the tube end surface as the bottom horizontal member and the inside bushing wall as the vertical side member.

WELD REQUIREMENTS - The lap joint specifications include weld size and quality requirements. Fillet weld leg size needed to be at least 1.8 mm. Cracks and through-type porosity were not allowed. Pores were acceptable provided they did not exceed 0.60mm diameter.

WELD DEVELOPMENTS - When the prototype assemblies were built for characterization and durability testing, the automated welding equipment was not installed or available for sample preparation. The 409Cb P/M bushings were therefore attached to the assemblies using manual GTAW equipment. Although cracks were observed, the weldments passed fillet size and porosity requirements and were therefore determined to be sufficient for “worst case” testing purposes.

Upon tryout of the automatic equipment, a weldment meeting specifications could not be achieved with these same production intent 409Cb P/M bushings. The parts showed unacceptable gross weld porosity and heat-affected zone cracking in the P/M bushing, Figure 4.

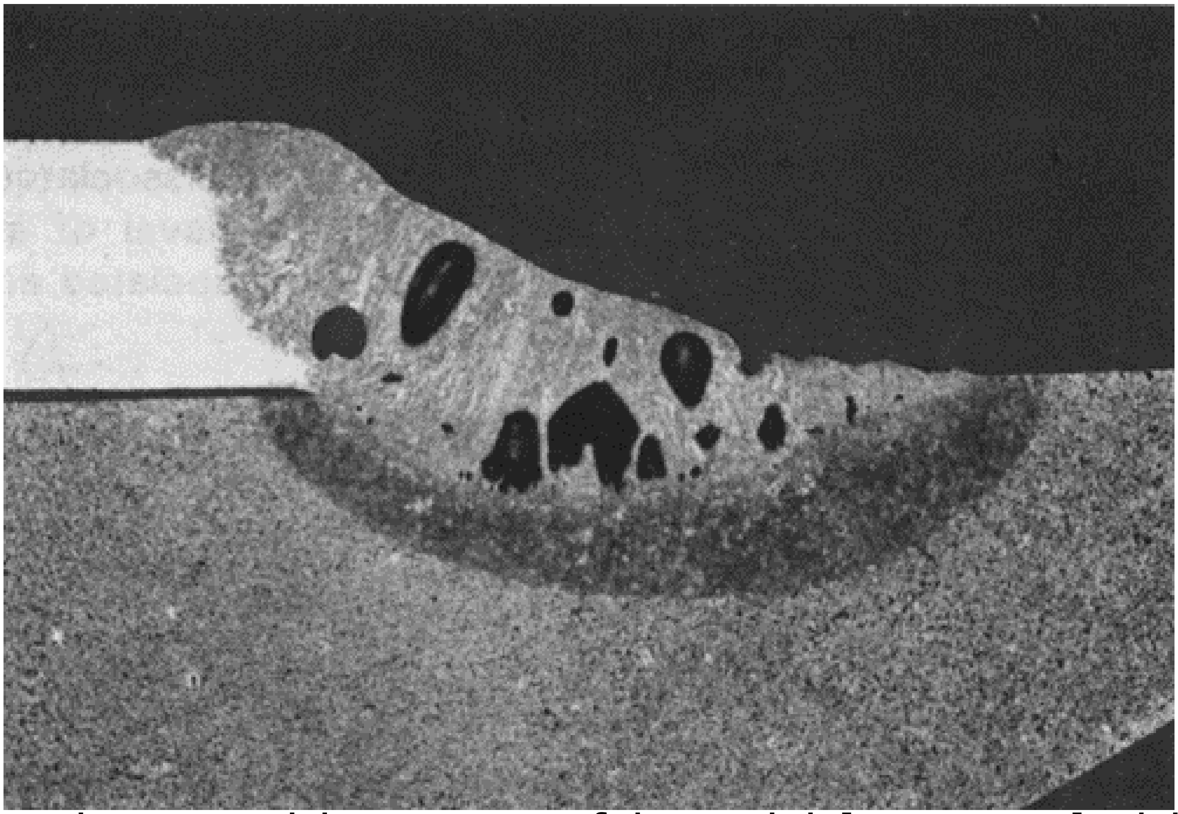

Figure 4a: High percentage of interstitial gases resulted in extreme porosity. Dark etching area is heat affected zone (HAZ). 12X

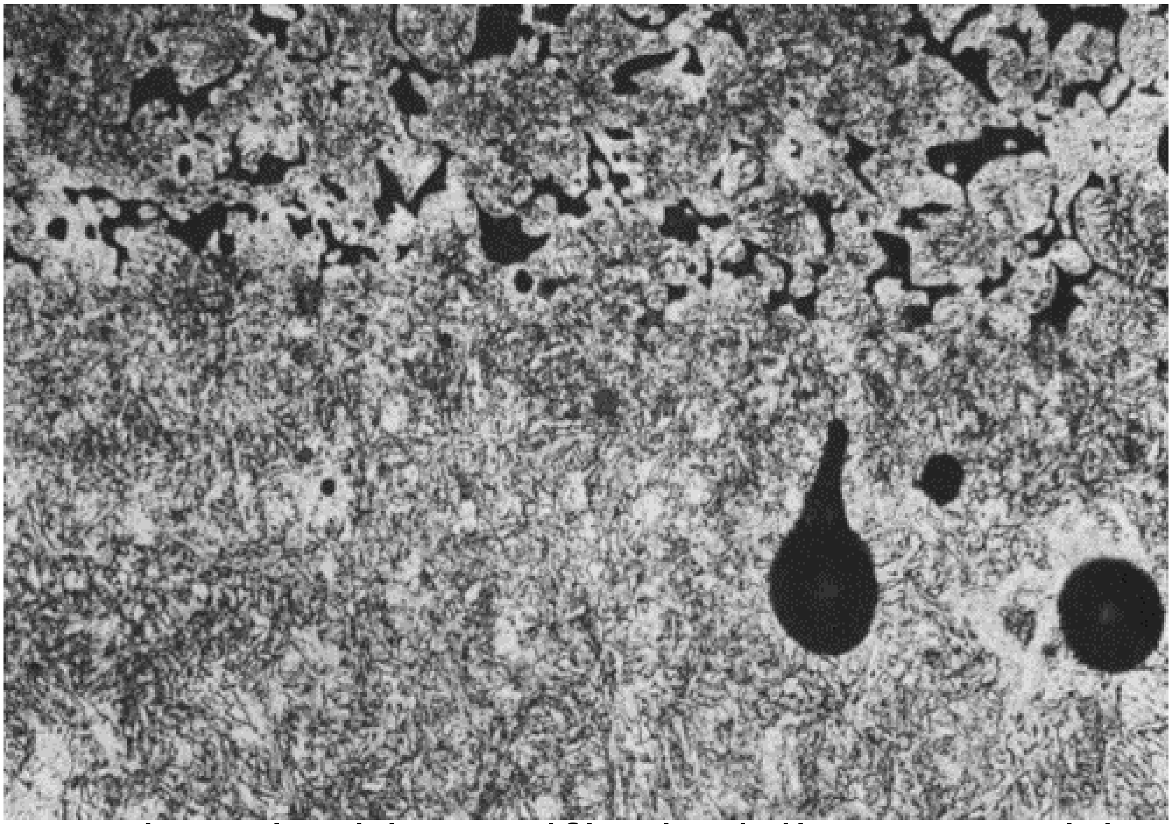

Figure 4b: Higher magnification indicates martensitic transformation in HAZ and P/M part. 200X

Laboratory evaluation of the samples found the 409Cb bushing had unacceptably high levels of carbon, nitrogen, and oxygen. These high interstitial levels affected weldability on several fronts. The high carbon and nitrogen promoted the formation of fine martensite during welding that was susceptible to cracking. The high oxygen and nitrogen levels promoted formation of various gases during welding that were believed to lead to the large amount of porosity observed.

Sintering conditions were found to have a pronounced influence on welding performance. Development efforts indicated a change from dissociated ammonia to a pure hydrogen sintering atmosphere could reduce the level of interstitials to acceptable levels. The composition and density of the dissociated ammonia* and hydrogen** sintered bushings are shown in Table 1.

Table 1: Influence of Sintering Conditions on Properties.

Sinter Environment	NH3*	H2**	vacuum	vacuum	vacuum
Temperature	2250°F	2300°F	2100°F	2200°F	2300°F
PROPERTIES:					
Density g/cm^3	6.57	6.70	6.68	6.95	7.02

Dimensional Variance from Nominal	---	0.6%	0.8%	2.0%	3.5%
%C	0.189	0.060	0.017	0.007	0.007
%N	0.339	0.042	0.018	0.003	0.001
%O	0.376	0.144	0.225	0.209	0.176
Weldability	poor	good	good	good	good

Vacuum sintering was evaluated in the laboratory and demonstrated the potential for even lower interstitials and higher densities. However, the potential for chromium depletion at the required vacuum levels, due to the low vapor pressure of chromium, was a concern [13].

RESULTS - Weld trials using the hydrogen sintered bushing proved to be successful. All welds met the size and quality requirements. The P/M structure was ferritic and there was no transformation to martensite during welding, Figure 5. To improve the robustness of the process, the arc was targeted to preferentially direct the heat onto the end surface of the 409 tube rather than the 409Cb bushing. This reduced the amount of penetration into the bushing.
The characterization and durability tests were not repeated since the “worst case” samples initially tested met the necessary criteria for applied strength and durability.

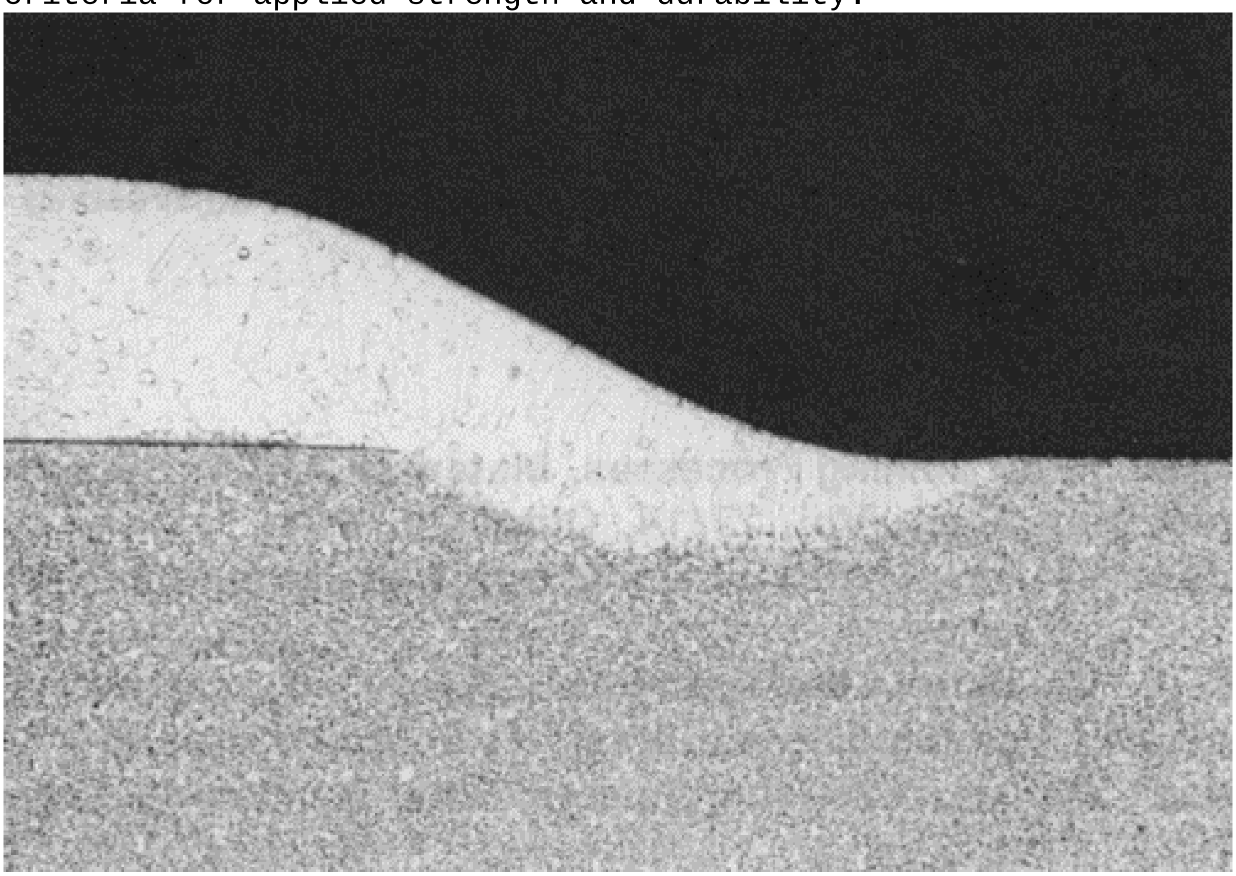

Figure 5a: Illustrates a sound weldment to a hydrogen sintered bushing. 12X

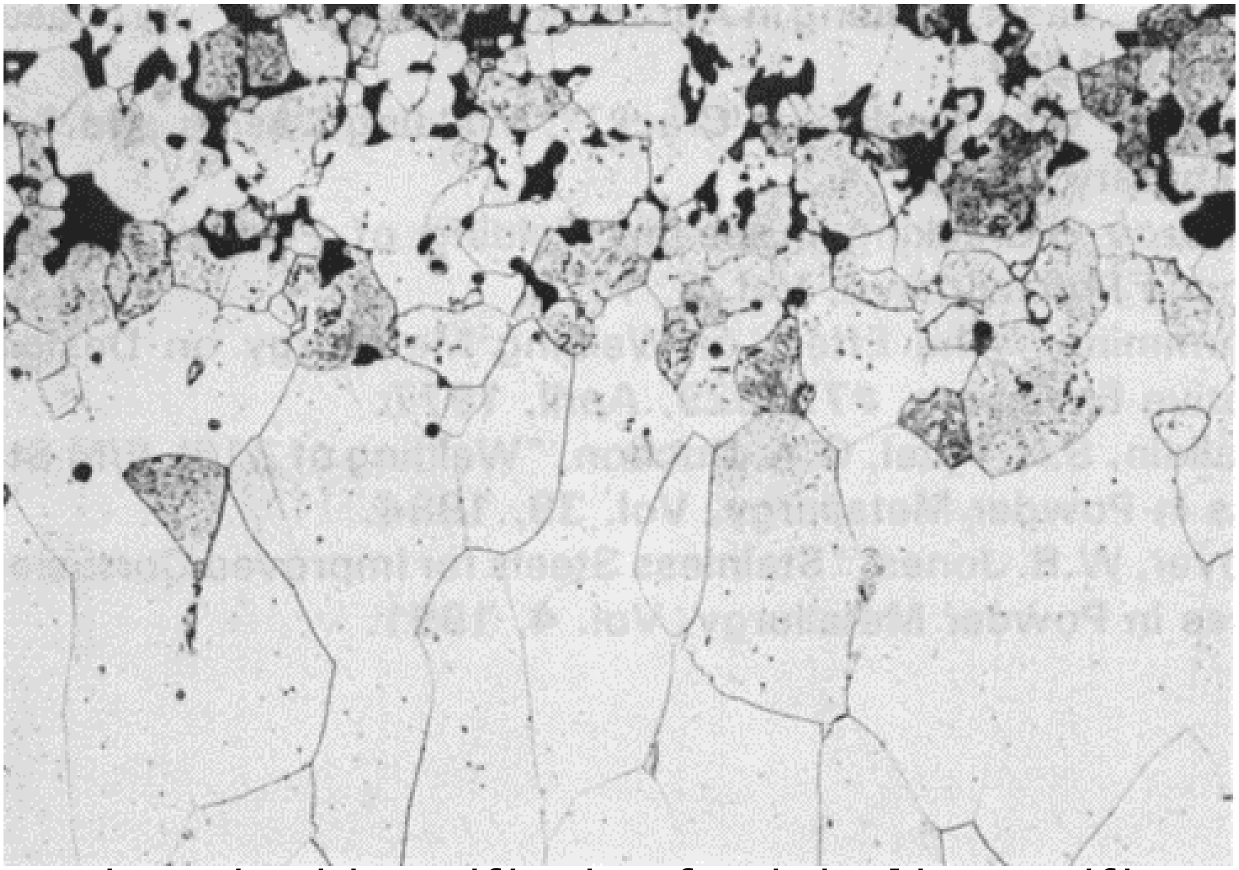

Figure 5b: High magnification of etched weldment verifies ferritic microstructure. 200X

SUMMARY

It has been demonstrated that automated production welding methods can be used to join P/M parts. Several techniques have been developed to join a wide range of density levels and alloy systems which help achieve various design and performance criteria. This provides opportunities for converting fusion welded automotive components to P/M applications.

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