P/N JOINING PROCESSES, MATERIALS AND *TECHNIQUES*

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ABSTRACT

This paper discusses the different types of joining processes most often used in conjunction with ferrous P/M material grades and components. Information from previous publications and a literature review on the various processes are highlighted. Useful design information and processing techniques are listed along with identifying the weldability of various P/M material compositions.

INTRODUCTION

Advances in materials and manufacturing processes make P/M components increasingly attractive in replacing wrought or cast materials for various applications. When doing so, this occasionally requires that P/M parts be joined to one another or with other materials as integrated components. The flexibility of P/M parts manufacture provides economic advantages because of unique alloy compositions and the ability to press complex geometrical configurations. However, these same attributes are not well understood when it comes to joining or welding P/M parts.

There are several references which detail various joining processes and the weldability of wrought materials[1,2]. However, very little comprehensive information is available on the application of these practices to P/M components. The objective of this text is to consolidate information on the subject of joining P/M components into a practical guide and useful reference. This review will identify the characteristics and physical differences between P/M parts and the wrought/cast materials as it pertains to joining, In addition, the acceptable joining procedures and techniques will be discussed along with the weldability of various P/M materials, Emphasis will be placed on the dos and don'ts associated with the respective processes and techniques,

PHYSICAL PROPERTIES

Perhaps the most important physical characteristic of a P/M component, which makes it uniquely different in regards to joining, is porosity[3]. The pore volume or relative density has a pronounced influence on several important properties which affect the following joining or welding characteristics,

Thermal Conductivity*:* The rate at which heat is transmitted through a material is dependent on the amount of porosity. Greater amounts of porosity change the heat transfer mechanism and ultimately the welding parameters.

Thermal Expansion: Metals increase in volume when heated and decrease in volume when cooled. Potential changes in porosity because of particle melting or filler metal infiltration can result in excessive shrinkage or growth with the potential for subsequent cracking to occur in or near the weld interface.

Hardenability: A material Hardenability is dependent on the rate of heat dissipation or thermal conductivity. Pores act as thermal insulators, which slows the transfer of heat making P/M components less hardenable than wrought parts of similar composition. However, because of potential densification in the heat-affected zone (HAZ), the detrimental consequence of Hardenability can occur in P/M components and may increase the materials susceptibility to cracking.

Porosity can also cause erratic fluctuations in welding performance because of entrapped oxides or impurities. Precautionary measures must be taken to eliminate any of the following residual elements that may remain in the pores:

1. Lubricant Residues
2. Quench Oils
3. Machining coolants
4. Plating Solutions
5. Impregnating Materials
6. Cleaning or Tumbling Agents
7. Free Graphite or Residual Ash

P/M JOINING PROCESSES

Joining is a comprehensive term used to denote all processes that affix one part to another. Most welding processes require the application of heat with some controlled melting of the base material and/or filler metal (fusion), while others rely on surface diffusion and/or mechanical interlocking (solid state). Both solid state and fusion welding processes have been used successfully in joining P/M components.

Lower density (< 6.5 g/cm^3) parts are most often joined using processes that do not involve molten weld metal that must solidify. The poor fracture toughness of these parts, because of the lower number of particle-to-particle bonds, does not allow the material to absorb the stresses generated by the contracting weld metal. The joining processes most often successful on these parts are diffusion welding, sinter bonding, adhesive joining and brazing. Intermediate density levels (< 6.9 g/cm$^{3)}$ can be joined using a wide assortment of processes. However, those that minimize the volume of fused metal, such as resistance projection welding and friction welding, have the highest success rates. Parts exhibiting higher densities (> 7.0 g/cm$^{3)}$ typically have the same weldability as wrought materials and can be welded using fusion processes which include Gas Tungsten Arc Welding (GTA), Gas Metal Arc Welding (GMA), Electron Beam (EBW) and Laser Beam (LBW) welding.

Resistance Projection Welding (RPW)

Perhaps one of the most often used welding procedures for joining P/M parts is Resistance Projection Welding (RPW). The resistance to the flow of current heats the surface of the materials and forms a weld. Electrodes, which carry the current also, clamp the components under pressure to provide good electrical contact. The joint must be clean and the pores free of contaminants to obtain uniform weld soundness. Projection welding generally affords good dimensional control in the weld area because of the force applied by the contacts and that the components are most often fixtured.

In general, good weldment design requires particular attention be placed on the height and density of the projections. Other parameters including the current (kva) and pressure (psi) can be preset to achieve the best results and most often are very similar to those used for wrought materials. Typical settings for current, weld time and electrode force can be found in the Resistance Welding Manual[4].

An investigation involving projection welding P/M parts to wrought materials, at densities ranging between 5.8-7.4 g/ cm^3 found that lower density (< 7.0 g/cm^3) components require greater projection heights[s]. It was also found that steam treated parts could not be satisfactorily welded at any density, and wrought chrome plated parts could not be welded to P/M components below 7.0 g/cm^3 density. All other materials tested, including plain iron, iron-carbon, iron-copper-carbon and stainless steels, were all welded successfully. In a similar investigation RPW techniques were used to join high carbon (0.4 - 0.8 %) P/M parts, with density levels between 6.5-7.5 g/cm^3, to mild steel. The results indicate the weldments were found to be of satisfactory quality and exhibited higher torsional strengths than standard keyed components. However, the highest torsional strengths were achieved after the components had been normalized.

Brazing

Another very common method used to join P/M parts is by furnace brazing. This method allows P/M fabricators to use existing sintering furnaces and atmospheres to join P/M parts to one another or to wrought or cast materials. Most P/M brazing alloys require temperatures in the range of 1950 - 2100oF and can be used in endothermic, dissociated ammonia; nitrogen based atmospheres or vacuum.

The capillary force of the pores requires special consideration when choosing a brazing alloy. When using a standard copper brazing material the porosity near the joint wicks the filler into the pores leaving an insufficient amount of filler to establish a satisfactory bond strength. For this reason, these parts must be copper infiltrated before brazing or pressed to a density of > 7.2 g/cm^3 at the joint interface. An alternative method involves the use of a Cu, Mn, Ni, Fe alloy which increases its liquidus temperature as iron from the components dissolve into the filler[?,8]. This fills the pores immediately adjacent to the brazement leaving a sufficient amount of filler to establish a suitable bond.

The preferred brazement design is a lap joint rather than a butt joint configuration. The optimum braze joint gap is between 0.002 -0.005 inches. Consideration must be given to the thermal expansion characteristics of the materials to be joined when attempting to maintain the proper gap distance at temperature. Ring performs placed adjacent to the joint or the spot location of a brazing paste are preferred over sandwich positioning of the filler between the components.

Fixturin9 may be necessary for more complex geometrical configurations or when tighter dimensional controls are required. Brazed parts can subsequently be quenched & tempered or steam treated. The American Welding Society has established guidelines for this process under AWS 03.6-90, Specification for Furnace Brazing[9].

Gas Tungsten Arc Welding (GTA/TIG)

This process uses a nonconsumable tungsten electrode to establish a direct current arc (for ferrous materials) that melts the material to be welded. An inert gas shield of argon, helium or various commercial mixtures is used to protect the electrode and weld pool from oxygen, nitrogen, hydrogen contamination, and stabilize the arc characteristics for improved weldin9 performance. In some P/M applications the process includes the use of a filler metal to counteract the shrinkage that results from particle melting and subsequent densification in the weld zone. The filler must be compatible with both materials to be joined in regards to thermal expansion characteristics, strength and corrosion properties.

The GTA process provides suitable results in many situations because it allows a greater amount of control over the welding process. The travel speed, heat input, type of filler metal and feed rate can be controlled to achieve the best results for each application. For this reason, GTA exhibits better weldability with higher carbon (Hardenability) materials because of the ability to control the heat input and subsequent weld hardness.

A unique GTA application involved the replacement of a castin9 by welding two P/M components together for use in a commercial truck differential[10]. It was found that the welded P/M component exhibited higher and more consistent strength values than a bolted gray iron casting along with providing a 35 ~ cost savings compared with the previous method of manufacture.

Gas Metal Arc Welding (GMA/MIG)

This process, unlike GTA, uses a continuous wire electrode that establishes the arc and furnishes filler metal into the weld pool. A shielding gas mixture, the composition of the mixture being dependent on the mode of metal transfer and type of filler metal, is used to protect the molten weld pool from atmosphere contamination and provide the correct arc characteristics. The short-circuiting or dip metal transfer modes are particularly suited for welding P/M components because of the low energy input requirements, which reduce the HAZ and minimize distortion. Typically, 002 based shielding gases are used with small diameter (0.030-0.035") mild steel filler wire to weld sintered steel components. However, austenitic stainless steel fillers with inert gas shields can be used for higher carbon materials to reduce the potential for HAZ cracking. Like the GTA process, GMA also provides the operator greater control over the entire welding process.

A study involving the GMA (MIG-OO2) process concluded that various materials with admixed compositions of 0.3-0.996 O, 0-6,0% Ni and 0-1.0% Mo could be welded successfully The results indicate that sintered components appear to be less susceptible to hydrogen induced cracking than wrought materials with similar Hardenability (carbon equivalent). The same study also found copper (2.0-4.0~) bearing materials could not be welded successfully using the dip transfer -002 process because of liquation cracking in the HAZ.

Friction Welding (FRW)

This technique is sometimes referred to as inertia welding. Both processes are very similar in that one part is held stationary 'as a second component is rotated with an axial force being applied to both parts. When both are sufficiently heated an upsetting force is applied to complete the weldment. The AWS Welding Handbook identifies the process variables to be rotational speed, axial force, welding time and upset force[m]. Equipment power requirement range between 25 kva for smaller machines to 175 kva for lar9e machines capable of welding 5.0" diameter steel bars. Friction/Inertia welding variables can be controlled by computer program, which makes the process less technique sensitive and highly automated. The time required to load and unload parts is often longer than the weld time, which can range between 0.5 and 15 seconds. The limiting factor of this process is the part configuration. Typically, components must be nearly circular cross sections to accommodate the rotational forces at the joint interface. Most applications involve tube to tube, bar to tube, or tube to plate type configurations. In addition, materials with good dry bearing characteristics, e.g., grades with free graphite in the pores, are not well suited to friction welding. The equipment, tooling and automated material handling costs limit the use of this process to long production run applications.

Friction welding of Fe-C and Fe-Cu-C sintered parts has been successfully accomplished. Two independent studies conducted by J.E. Middle and J.F. Hinrichs indicates this technique is capable of producing extremely favorable results when; joining a full range of admixed compositions at several density levels to similar grades, dissimilar compositions or wrought materials[3,13]. Both studies found that FRW exhibits lower hardness in the weld zone, in comparison with other processes, because of a slower cooling rate associated with this technique. Middle found the actual welding parameters are relatively flexible except for friction (axial) pressures and forging (upset) pressures. Higher friction pressures will likely cold work a greater surface area when the forging pressure is applied. While higher forging pressures produce radial cracks that originate in the flash and extend back into the base metal. This can result in failure or be detrimental to the; joints fatigue performance. Hinrichs also found that friction welds often exhibited the highest torsional load capacity in comparison with other joining techniques over a wide range of densities and admixed compositions.

Electron Beam Welding (EBW)

Electron Beam is a sophisticated welding process that incorporates a beam of concentrated high-velocity electrons to produce a narrow very intense source of heat. The weld generally is conducted in a vacuum chamber at pressures ranging between medium to high vacuum. Although, sintered parts have been welded using a nonvacuum process. EBW has proven successful particularly on higher density stainless steel P/M components. Iron-carbon sintered parts, on the other hand, have limited applications because of porosity and blowholes caused by escaping CO gas. An investigation by Y. Suezawa found that as the welding speed slows the width of the weld zone widens and the volume of escaping gases increases causing more blowholes[14]. It was also discovered that faster weld speeds produce a narrow HAZ with exceptionally high hardness values that would not be considered acceptable in most service environments. Considering the cost and disadvantages it would be hard to justify this process for joining high volume P/M structural components.

Laser Beam Welding (LBW)

Somewhat similar to EBW, this process uses a focused, coherent light beam to vaporize metal at the joint interface. Typically, C02 lasers are used with inert shielding gases such as helium. It is possible to add filler metal but additions aren't always necessary, particularly on higher density components. The joint design has a great influence on the filler metal requirements. The welding parameters generally attempt to optimize the relation between the power setting and travel speed to improve the economics, end provide a narrow weld seam which results in less internal stresses.

An investigation into the practical use of laser welding P/M components by E. Mosca found it can be used successfully in some applications[is]. This process, like EBW, can involve significant HAZ area shrinkage because of melting and resolidification in the narrow weld zone. In addition, the findings of the study indicate the laser process is sensitive to the type of sintering atmosphere. The formation of blowholes in the weld zone has a relationship to the quantity of unreduced oxides in the component(s) to be joined. Specimens sintered in endothermic 9as exhibited an unacceptable condition whereas those sintered in hydrogen, dissociated ammonia and vacuum all proved to be acceptable. The LBW process also requires that medium Hardenability materials be preheated to 250-300°C before weldin9 to reduce martensite formation. The narrow HAZ with the larger adjoining material mass extracts heat away from the joint, which accelerates the cooling rate. Another observation indicates oil quenched materials don't prove successful because oil residue in the pores vaporizes and form blowholes. Very good results, however, were obtained with 316L stainless steel P/M components. These weldments exhibited very low amounts of delta ferrite (<%0%) in the weld zone which probably relates to the narrow, autogenous fusion zone associated with the process[is]. The conclusion of Mosca's study indicates laser welding is technically feasible, but it is expensive and would be difficult to justify over other processes.

Diffusion/Sinter Bonding

This technique typically involves the use of materials that exhibit different expansion characteristics, due to either the admixed composition or density level of the green compacts, as the components are sintered. For example, an outer ring having a propensity to shrink from die size can be mated with an inner ring, which exhibits growth. The subsequent bond results from mechanical interlocking and potential alloy diffusion if carbon, copper or phosphorus were admixed to one or both components. Similar results can be achieved if two parts, placed in intimate contact, are copper infiltrated using a single step sintering technique.

Several papers detailing the procedures and materials have been written[7-20] . These methods have all proven to be viable, cost effective joinin9 techniques, which are currently used on production parts. However, diffusion/sinter bonding is limited to certain 9eometries and alloy compositions. The bond strengths are also somewhat lower than with other P/M joining processes.

Adhesive Joining

It is possible to join P/M components by gluing them together with epoxy resins, anaerobic or acrylic adhesives. The first two materials set up at room temperature, whereas the acrylic adhesive must cure at approximately 120-t30oO. An important aspect of this procedure requires the surfaces be cleaned and the pores free of any contaminants. This has effectively been accomplished using abrasives and ultrasonic cleaning with a final heating to drive off moisture.

The use of alkali or acid based cleaning agents is not recommended.

Two studies conducted by A. Delorio identified the major advantages of adhesive joining:

1. stresses are distributed uniformly.
2. galvanic corrosion is minimized because the adhesive acts as a dielectric.
3. thin components can be joined to thick parts.

Conversely, disadvantages were also listed:

1. environments temperatures cannot exceed 170^{o}C because of a severe reduction in strength at elevated temperatures.
2. hostile environments like high humidity and/or contact with chemically active materials should be avoided,
3. high pealing and/or shear stresses at the joint interface can result in failure.

The referenced investigations found the best results were obtained with heat hardened adhesives using low applied coupling pressures and at least 5 minutes time at temperature. Steam treatment before adhesive joining along with increasing the component's sintered density were found to enhance the shear resistance.

P/M JOINING TECHNIQUES

The best method of insuring a successful P/M weldment is by proper design. The most important considerations involved in the design are the choice of materials and joining process. Before this can be done, one must have a thorough understanding of the performance characteristics required to satisfy the applications requirements. These include, but are not limited to, the following characteristics:

- **Strength Requirements** - what stresses will be applied; tension, shear, torsion, etc.
- **Dimensional Restrictions** - will there be potential problems with distortion and/or shrinkage; will critical dimensions be affected.
- **Environmental Factors** - will joining dissimilar metal combinations promote galvanic corrosion; will elevated temperatures potentially influence the joint strength.
- **Appearance** - will exposed surfaces have appropriate aesthetic appeal if polished or plated.
- **Economics** - is the joining process cost effective in comparison with other manufacturing methods.

Once the application requirements have been established, consideration can be given to the major factors involved in the joining process.

***Type(s)* of Material** - First and foremost, the material must satisfy the applications strength requirements. If this necessitates materials, which exhibit high Hardenability, careful consideration must be given to the joining process so as to control the hardness of the weldment. Also, the potential for any metallurgical incompatible elements must be eliminated. Compositions containing sulfur or high phosphorus levels are particularly suspect.

Joint Design - The primary factor is to insure the joint interface can be placed in an area that is not subject to high loads or stress concentrations. In addition, the component geometry must lend itself to the type of joining process to be used, e.g., the ability to press and control density in projections for RPW.

Joining Process - This also must be considered when evaluating the applications minimum strength requirement. Typically, the fusion processes GTA, GMA, EBW, LBW provide the highest joint strengths, while FRW and RPW are often near parity with these techniques. Brazing, diffusion and adhesive bonding provide somewhat lower levels in regards to potential joint strength.

Techniques for Fusion Processes

The most common problem with fusion welding involves cracking in or near the weld interface23. The potential for cracking to occur must be minimized if you expect to be successful. This can be accomplished if proper consideration is given to why P/M weldments crack,

The formation of cracks in welded P/M components are most often associated with the stresses generated during solidification and cooling of weld metal. The mass of material surrounding the weld puddle and HAZ resists the contraction forces as the metal cools, which results in tensile stresses that initiate cracks, These stresses can be minimized by the use of several techniques,

- Preheating can drive off moisture (hydrogen) and lessen the thermal gradient across the weld zone.
- Post heating immediately after completing the weldment also reduces stresses, particularly for high Hardenability materials, which form appreciable amounts of martensite in the weld metal and HAZ.
- Austenitic filler metals on steel or low alloy components can be beneficial because of its superior toughness, strength and lack of martansitic transformation,
- Processes, which allow the operator to manipulate the amount of heat input, can also assist in minimizing stresses (GTA, GMA).
- Joint configuration plays a major role in stress formation. Mismatched; joints, poor gap spacing, or narrow (low width to depth ratio); joints along with an insufficient amount of filler metal to counteract densification can all have deleterious affects on the weldment.

It's not recommended that steam treated, copper infiltrated or quenched & tampered P/M components be fusion welded. 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, any free copper present is likely to melt and subsequently migrate to the former austanitie grain boundaries because of its inherently low solubility in austanite. This may result in hot tearing or liquation cracking. Quenched & tampered parts even with a sufficient tamper to drive off entrapped quenchant are not good candidates for welding. The high heat input associated with the fusion process changes the structural constituents and lowers the strength in the weld zone as compared with the surrounding matarial2S.

P/M Brazing Techniques

Joint Design - Lap; joints are always preferred over butt designs. When using a lap; joint the amount of overlap is determined by a handy reference called the "rule of three", which suggests a lap distance of three times the thickness of the thinnest component. The fit between components should range between 0.002/0.005" to achieve the highest; joint strength, which is typically, 55,000 psi ultimate tensile strength. For some applications the parts can be placed on top of or adjacent to one another without exercising any additional precautions. The exception involves brazing dissimilar metal parts having significant differences in density and/or composition. The density affects the thermal expansion coefficient whereas the composition influences dimensional change, both of which can influence the gap distance. The best procedure utilizes a method of gap width control, such as, a fixed diameter wire or nipple projections placed between the mating surfaces. The brazing alloy should be placed immediately adjacent to the; joint interface to assist in capillary action and flow into the; joint. For large surface areas, shallow channels or gutters may be pressed into the joint face to assist in uniform flow·

Filler Metal - The most often used P/M brazing alloy is a patanted (U.S. patant 4,029,47G) Cu, bin, Ni, Fe alloy powder (Ancorbraze 72 / SKC 72) that can be admixed with flux and a lubricant for performing into slugs/rings, or dispensed as a pasta. This material is suitable for use with iron, steel, low alloy or stainless P/M components. Typically, 3-4 grams of filler metal is required for each square inch of surface area to be joined. The quantity is dependent on joint design, gap spacing and component density. Closer gap spacing and higher component density favor lower amounts. Some applications requiring specific properties may require the use of silver or nickel based brazing alloy for electrical, high temperature or corrosive environments.

Heating Cycle - Uniform heating of the components along with sufficient dwell time, to equalize the temperature between the parts to be; joined, is important for proper flow and; joint fill. A component having a lower mass or thinner section size will likely achieve the flow temperature before a larger mating part. This results in a greater capillary force towards the area having the highest temperature or heat energy, and may cause poor; joint fill. If this does occur, it's sometimes helpful to reposition the components on the furnace belt to assist in achieving uniform temperature between the parts. It may also help to increase the preheat temperature so parts can equalize before reaching the liquidus point (approximately 1950^{o}F for Ancorbraze 72).

Atmospheres & Fluxes - Most of the commonly used sintering atmospheres can be used for P/M brazing. To assist in oxide reduction, a flux is 9enerally added to the braze alloy. In some circumstances an additional borate or fluoride type flux may be swabbed onto the mating surfaces, particularly, when brazing sintered parts, stainless steels grades, materials containing sulfur / manganese sulfide and wetting large surface areas to be joined. It has also been determined that high CO2 percentages in the sintering atmosphere can oxidize the fluxing agents and reduce the flowability of the brazing alloy.

By far, the most common difficulty experienced with furnace brazing P/M components is the lack of fill in the joint. This is generally associated with the following conditions.

1. Improper cleaning or oxide reduction.
2. Excessive; joint clearance.
3. Low sintering temperature or non-uniform part temperature.
4. Insufficient filler metal.

5. Entrapped lubricant, flux or 9asses.
6. Movement of the mating parts before solidification.

P/M Diffusion/Sinter Bonding Techniques

Essentially this process requires that an inner component which has a tendency to grow and an outer component with lower growth, or in some cases a propensity to shrink, are fitted together as green briquetes and sintered at conventional time and temperature. Elements that enhance diffusion - copper, carbon, phosphorus, also increase; joint strength. Density gradients between components also promote diffusion.

When choosing a combination for diffusion bonding, consideration must be given to the desired strength level for each component alon9 with the respective dimensional change characteristics to insure the parts can be made within the print tolerance and strength requirements.

P/M Materials for Joining

Most iron and steel powder compositions can be joined or 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 doesn't play a predominant role in the weldment success rate if held within acceptable limits. Nevertheless, the subtle influence of acid insoluble, 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 materials overall weldability. As a general rule, the carbon content should be held to as low a level as possible. However, carbon also greatly enhances materials strength characteristics. Joining processes and techniques can be developed to accommodate intermediate to high carbon levels that exhibit acceptable weld soundness and strength characteristics.

Materials containing sulfur additions should be avoided for welding and brazing applications. The sulfur can migrate to the grain boundaries and may cause hot cracking when fusion welded, When brazing sulfur bearing components the manganese in the brazing alloy can form manganese sulphide in the presence of free sulfur which reduces the material's ability to flow. 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.

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 filler metal, has been used for a limited number of Ancorsteel 45P applications,

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

Stainless steel P/M components have been successfully welded using various joining processes GMA welds of 31GL P/M parts at various density levels, using 316L filler metal with an argon shield, provided 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 GMA process and an austenitic filler metal without a preheat or post heat treatment. The Friction/Inertia process also provided a satisfactory, high integrity weldment with this composition. The Disteloy grades would respond in a similar manner if processed using the same techniques.

SUMMARY

The ability to join P/M components increases the possibilities of manufacturing more complex configurations than conventional die pressed geometries. As the paper attempted to express, there are very few P/M materials that cannot be welded or joined. However, not every potential welding application will be cost effective in terms of labor intensity, equipment and overall manufacturing costs.

Included, as a quick reference is a welding process matrix, which identifies the applicable combinations of material grade, density and joining process. As indicated in the matrix, most materials can be joined by several processes. Conversely, most processes can also join a wide assortment of material grades. Those grades/processes identified as optional selections generally require precautionary or additional measures to insure the highest success rates. Moreover, each application should be reviewed individually in greater detail for potential exceptions.

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Table IV: Properties of Material A: Ancorsteel 4600V, 2% Cu, 0.9% Graphite, 0.5% Zinc Stearate

		Tensile						Impact			
Pressure (tsi)	Condition	Density (g/cm³)	0.2% Proof Stress (psi)	UTS (psi)	Elong. (%) in One Inch	Hardness HV	Sintered Carbon (%)	Density (g/cm³)	D.C. (%)	I.E. (ft.lbf)	Hardness HV
30	Conventional	6.57	NY	44,800	0.3	230	0.87	6.43	+0.13	3	193
45	Conventional	6.94	NY	67,090	0.5	234	0.86	6.85	+0.19	5	220
45+45	Conventional	7.16	NY	91,670	0.6	275	0.81	7.09	+0.28	8	257
30	Accelerated	6.57	NY	77,512	0.5	275	0.81	6.46	-0.03	5	282
45	Accelerated	6.94	NY	78,790	0.3	335	0.79	6.87	+0.09	8	353
45+45	Accelerated	7.14	NY	119,350	0.6	393	0.78	7.08	+0.28	11	393

Table V: Properties of Material B: Ancorsteel 85HP, 2% Cu, 0.9% Graphite, 0.5% Zinc Stearate

		Tensile						Impact			
Pressure (tsi)	Condition	Density (g/cm³)	0.2% Proof Stress (psi)	UTS (psi)	Elong.(%) in One Inch	Hardness HV	Sintered Carbon (%)	Density (g/cm³)	D.C. (%)	I.E. (ft.lbf)	Hardness HV
30	Conventional	6.81	73,820	78,620	0.7	171	0.87	6.67	+0.23	4	164
45	Conventional	7.11	91,022	93,460	0.8	193	0.86	7.00	+0.26	6	198
45+45	Conventional	7.38	94,440	120,030	2.5	240	0.81	7.32	+0.26	12	227
30	Accelerated	6.81	NY	89,400	0.4	344	0.85	6.71	+0.03	6	335
45	Accelerated	7.12	NY	118,760	0.5	393	0.82	7.02	+0.12	9	404
45+45	Accelerated	7.36	NY	149,720	0.6	452	0.78	7.31	+0.20	12	440

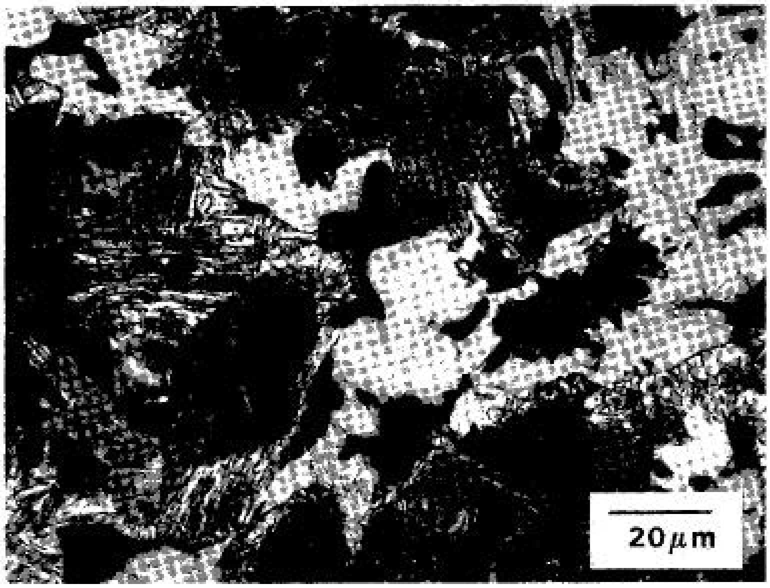

Figure 1: Photomicrograph of material A following conventional cooling from the sintering temperature. Etched with a combination of 2% nital/4% picra Original magnification 750X.

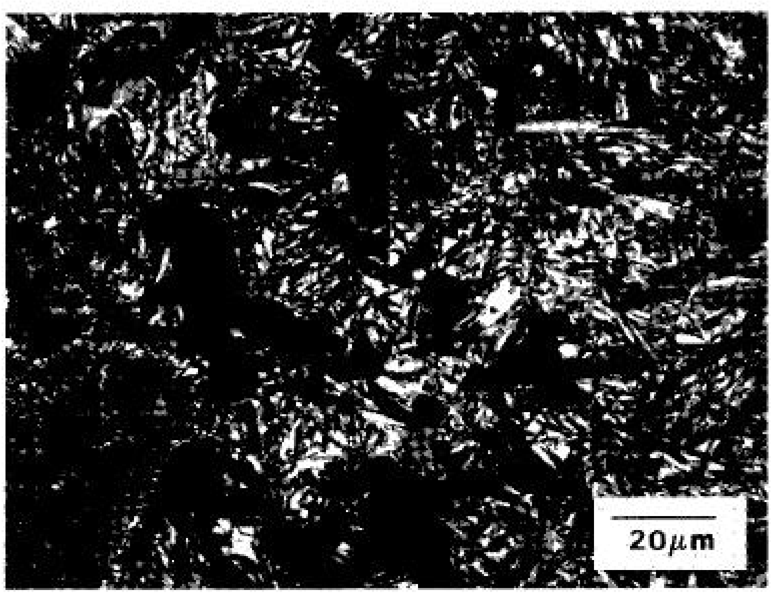

Figure 2: Photomicrograph of material A following accelerated cooling from the sintering temperature. Etched with a combination of 2% nital/4% picra Original magnification 750X.

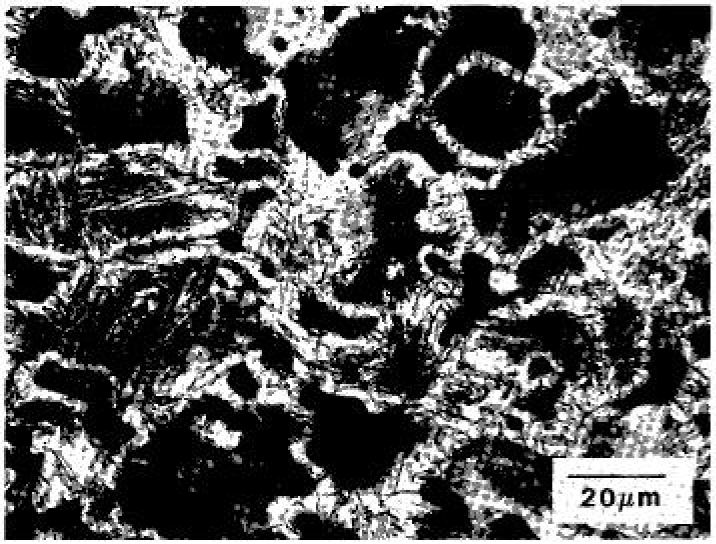

Figure 3: Photomicrograph of material B following conventional cooling from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

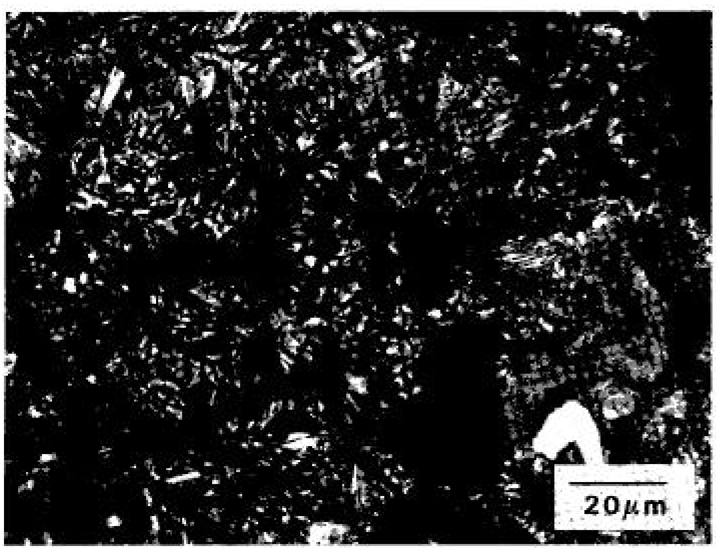

Figure 4: Photomicrograph of material B following accelerated cooling from the sintering temperature. Etched with a combination of 2% nital/4% picral. Original magnification 750X.

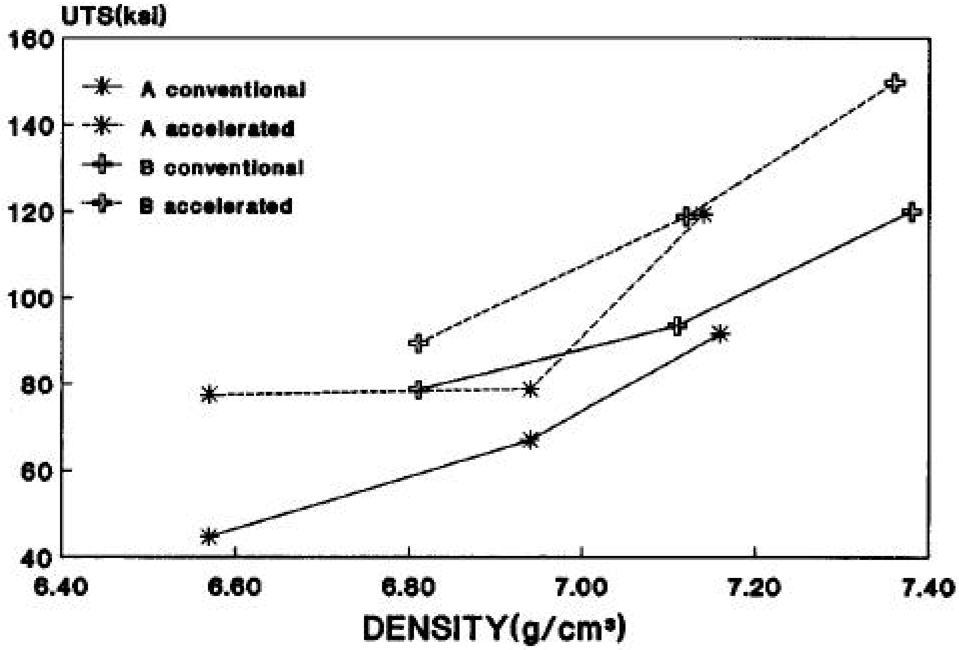

Figure 5: The effect of sintered density and cooling rate on the ultimate tensile strength of materials A and B.

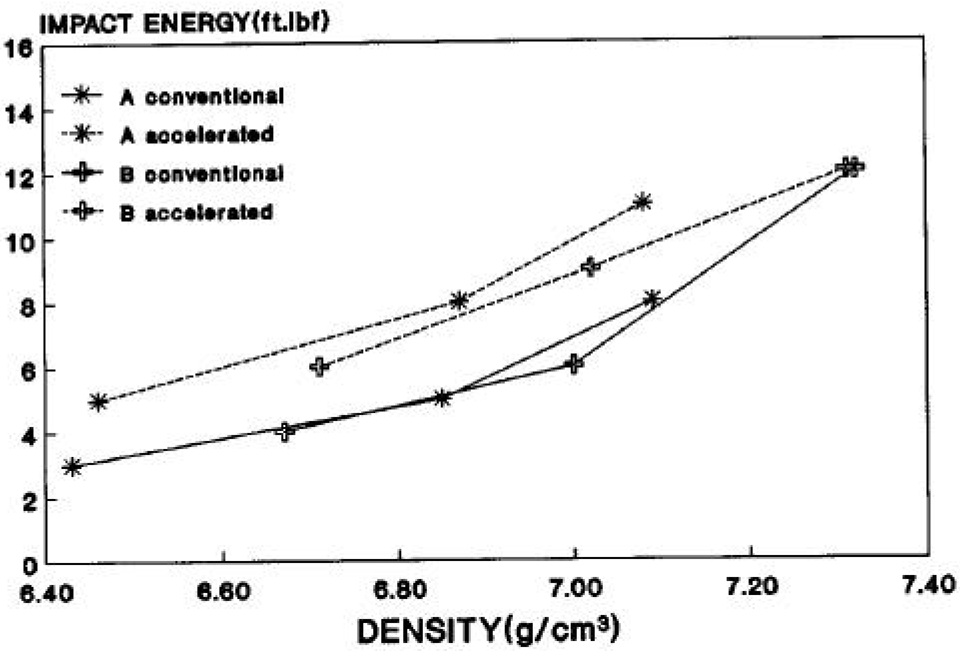

Figure 6: The effect of sintered density and cooling rate on the unnotched Charpy impact energy of materials A and B.

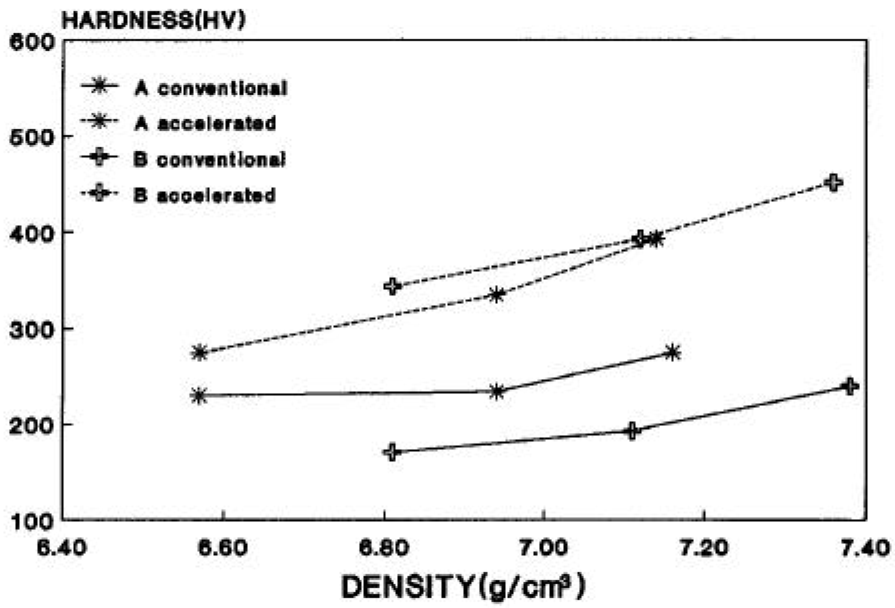

Figure 7: The effect of sintered density and cooling rate on the apparent hardness of materials A and B.

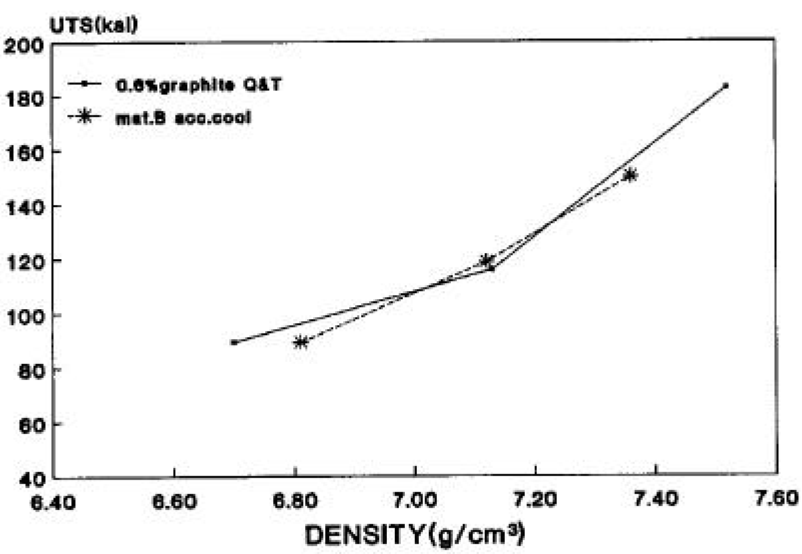

Figure 8: Comparison between the ultimate tensile strength of quenched and tempered Ancorsteel 85 HP, 0.6% grpahite, and material B following accelerated cooling from the sintering temperature.

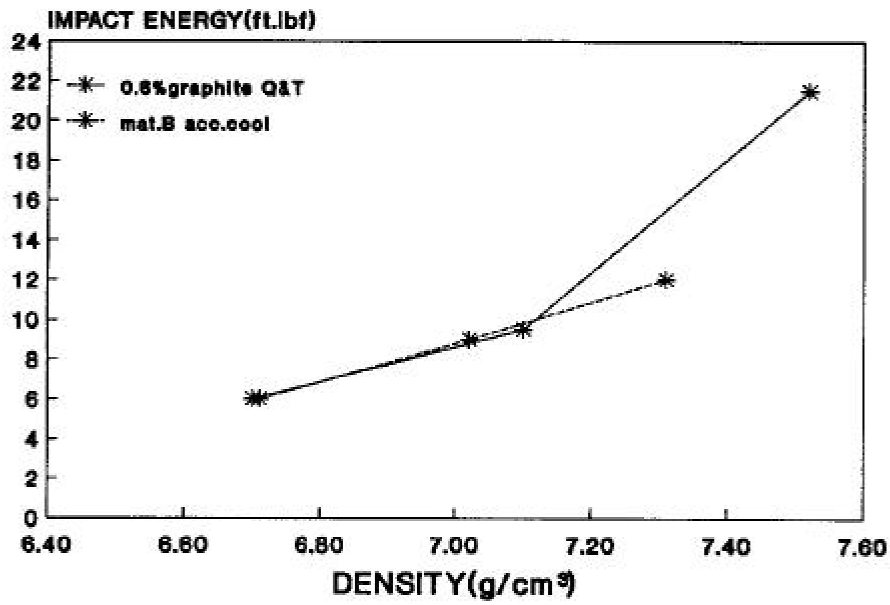

Figure 9: Comparison of unnotched Charpy impact energy of quenched and tempered Ancorsteel 85 HP, 0.6% graphite, and material B following accelerated cooling from the sintering temperature.