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State of the art of electromagnetic energy for welding and powder compaction

Prabu Manoharan · Arun Prasath Manogaran ·
Didier Priem · Surendar Marya · Guillaume Racineux

Abstract The innovation of advanced materials and their application to engineering structures can be related to their ease of fabricating defect-free parts. The identification of various energy sources has resulted in various new processing techniques in manufacturing and electromagnetic energy is one which offers promising qualities for high-velocity forming, welding, and compaction of metals. Bimetallic joint designs were proposed in automobiles to reduce the weight and to take advantage of properties of different metals in the same construction. Joining by fusion is impossible in certain cases due to huge differences in melting point, thermal conductivity, volumetric specific heat, and coefficient of thermal expansion. In the present study, magnetic-pulse welding of a Cu/Al joint and an ODS alloy is investigated. The formation of intermetallic phases and interface morphology is presented along with a quantitative analysis for temperature in the Al/Cu joint. Also, initial investigations on the application of electromagnetic energy for compaction of aluminum powders are reported.

Keywords Pulse welding · Phase Diagrams · Magnetic-pulse welding · Oxides · Materials

1 Introduction

Automobile, aerospace, and nuclear industries have been the driving factors for the search of light-weight and high-

strength alloys and their associated process. Bimetallic joint designs were proposed in automobiles to reduce the weight and to take advantage of properties of different metals in the same location. Joining by fusion is impossible in certain cases due to huge differences in melting point, thermal conductivity, volumetric specific heat, and coefficient of thermal expansion. From the phase diagram, equilibrium between aluminum and copper, as shown in Fig. 1, clearly indicates the possible formation of several intermetallic phases during fusion. Thus, the bimetallic joints should be made without base-metal melting. In explosive welding, chemical energy is used to generate impact between parts and resulting interfacial joints has been extensively studied and exploited in industrial cases for welding thick sections [2]. Today, the use of electromagnetic energy has been successfully demonstrated for forming, joining, welding, and compaction of metal powders and it offers numerous advantages in an industrial environment such as,

- Superior quality of products when compared to its competing processes
- Can be easily automated
- High-volume production due to short process time
- Good control over process parameters
- Demands less operator skill.

However, the use of electromagnetic energy in industries is limited due to lack of knowledge about the physics of the process. In the present study, the application of electromagnetic energy for welding and compaction of metal powders is investigated. Magnetic-pulse welding (MPW), also known as electromagnetic welding, is studied for a bimetallic joint combination Al/Cu and for welding a ferritic oxide dispersion-strengthened (ODS) alloy. Electromagnetic welding looks promising for welding bimetallics and some advanced materials which are impossible to weld using conventional processes.

P. Manoharan (✉) · A. P. Manogaran · D. Priem · S. Marya · G. Racineux
Institute de recherche en génie civil et génie mécanique, UMR
CNRS 6183 Ecole Centrale Nantes, 1 Rue de la Noë, Nantes 44321
Cedex 3, France
e-mail: prabu.manoharan@ec-nantes.fr

Fig. 2 Principle of magnetic-pulse welding

magnetic field around the coil and it induces a secondary current in the nearby conducting material. In MPW, the tubes to be welded are placed concentric to the coil and are isolated to avoid short circuit effects i.e., possible changes of current flow path. The induced secondary current flows through the surface of the outer tube and in turn produces a Lorentz force. This induced electromotive force (EMF) causes mechanical deformation of the cylinder and accelerates it to a very high speed in the range of 100 to 400 m/s where subsequently, it impacts on the inner tube. The energy transferred due to the impact causes severe plastic deformation at the interface and metallurgical bonds are established between the parts. The depth of penetration of the induced current is influenced by the conductivity of the tube known as the skin effect and it can be evaluated using Eq. 3.

$$\delta \simeq \frac{1}{\sqrt{\mu \pi f \kappa}} \quad (3)$$

Where κ is the electrical conductivity of the tube, $\mu = 4\pi \times 10^{-7} \text{ NA}^{-2}$ is the magnetic permeability and f is the frequency of the discharge current. In the case of welding less-conducting material, aluminum cylinders are used on top as pushers to accelerate the outer tube. Use of thin cylindrical pushers could lead to loss of energy since the

Fig. 3 Schematic representation of the discharge current

entire induced EMF may not be captured and a thick launcher could lead to excessive energy being consumed for mechanical deformation of the pusher. Thus, a careful evaluation of skin depth is necessary to choose the size of the pusher.

The magnetic pressure (P) acting is computed by integrating the EMF over the skin thickness and is represented as

$$P = \frac{B^2}{2\mu} \quad (4)$$

where B is the magnetic field density inside the coil.

The mechanical force acting on the cylindrical tube is computed from

$$F = \frac{B^2 S}{2\mu} \quad (5)$$

where S is the surface area of the outer tube. From the principle of motion, the acceleration γ of the tube can be expressed as

$$\gamma = \frac{B^2 S}{2m\mu} \quad (6)$$

where m is the mass of the outer tube and the velocity of the tube v can be approximated as

$$v = \sqrt{\gamma \times d} \quad (7)$$

where d is the distance of travel by the tube.

For example, an 8-turn welding coil of diameter 23 mm can be made by winding a copper wire of 2.5 mm in diameter. A magnetic density of 17 T is measured for discharge energy of 9.73 kJ. For an aluminum tube of 22-mm diameter, 20-mm long and 1 mm in thickness, from the above relations, the velocity is calculated as 207 m/s.

The expulsion of impurities and oxides on the surface takes place during impact; this phenomenon is known as jetting. Hence MPW does not require any special surface preparation.

To aid jetting, the inner tube is tapered to an angle α and this causes variation of the travel distance of the outer tube along the length of the interface. The angle of impact seems to influence the quality of welding; for welding aluminum and copper, the metals were only welded at certain impact angles. Masumoto et al. reported that the plastic deformation of the aluminum tube is initiated at about 16 kA of current. Indentation due to impact is observed on inner tubes made of aluminum and other dissimilar materials for currents of 40–50 kA. They observed partial or complete welding for discharge currents above 54 kA [13]. Rupture of joints takes place whenever large discharge energy is used and the formation of voids due to melting has been reported by several researchers (see Fig. 4). Hence, it is important to estimate the rise in temperature along the interface during the process and the influence of different process parameters on the quality of the weld. In the present study, the application of magnetic-pulse welding to the bimetallic welding of aluminum and copper is carried out and the aspect of wave formation, temperature, and intermetallic phase in the welded part is investigated. Intermetallic phases formed in the welded zone are analyzed using scanning electron microscopy and energy-dispersive x-ray spectrometry (EDS). MPW is demonstrated for welding of ODS alloy.

2.1 Bimetallic joint: aluminium and copper

2.1.1 Material and experimentation

Magnetic-pulse welding experiments were carried out using a generator with a maximum energy of 12 kJ and it has a series of six capacitors each of capacitance 60 μF . The inductance of the generator is 0.5 μH . The dimensions of the part to be joined are shown in Fig. 5. The outer tube was fabricated from 1,100 aluminum alloy and it was machined to an outer diameter of 15 mm and wall thickness of 1 mm. The inner tube was made of pure copper alloy and was tapered to an internal angle of 9° and discharge energy of 5 kJ was employed. A small gap of 0.85 mm was provided between the copper and the aluminum tube so that the

Fig. 5 Dimensions of the welded Al/Cu parts

aluminum tube has time for acceleration before the first point of impact.

The welded sample was then tested using a simple mechanical peeling test of the outer tube. After confirmation of welding, the welded joint was cut along the length of the axis and was subjected to mechanical polishing to 1- μm size. Metallographic examination of the welded surface was carried out on a Nikon eclipse LV150 optical microscope and JOEL JSM-6060A scanning electron microscope (SEM). Chemical etching of the samples was not carried out since the observation of micro structure at the welded surface is not considered for this study. Chemical composition mapping at the welded interface was obtained through EDS analysis at the interface between the copper and aluminum, to study the formation of intermetallic phases.

2.1.2 Results and discussion

During mechanical peeling, cracking, and decohesion of the interface takes place for about 2–3 mm at the start and end of the interface. This suggests that the welding has not taken place over the entire length of the sample. Figure 6 shows the images of optical microscopy observations along the length of the interface. The presence of several distinct zones can be identified. The interface at the beginning of the weld (shown in Fig. 6a), where the metals were in contact, shows that welding has not taken place. This was followed by the middle region Fig. 6b, where the wavy pattern typical to that

Fig. 4 Scanning electron images showing micro-voids on a peeled aluminum surface [14]

Fig. 6 Optical microscopy images of the Al/Cu interface

of the MPW appears. The length and amplitude of the waves tend to evolve along the welding direction. Then, the wavy interface was again followed by a somewhat flat-end region, as shown in Fig. 6c.

Figure 7a–d shows scanning electron images of the interface of magnetic-pulse welds between aluminum and copper. Figure 7a shows the initial contact zone where the metals were in close contact and as we move along the interface, the formation of intermetallic phases was detected. In Fig. 7b, the third region between the brightest copper and darkest aluminum shows the formation of intermetallic phase, which was subjected to further chemical analyses. The size of the intermetallic phase

is about 10–20 μm and it is not evenly distributed along the length of the interface. Figure 7c shows the formation of the intermetallic phase in the crest of the interface wave patterns. Thus, the formation could have been influenced by surface cracking, mixing, and interpenetration of one metal in the other. However, it is not sure whether this transition zone formed due to heating and melting of the material or just due to extreme strain hardening of the interface at high-velocity impact. In Fig. 7d, the presence of micro porosity and holes was detected in the intermetallic layer at the end of the welded zone, where the velocity of impact was very high. This could have been the result of melting and rapid cooling of the intermetallic layer.

Fig. 7 Scanning electron images of Al/Cu interface

X-ray dot mapping and energy-dispersive spectral analysis was carried out in the zone where the formation of inter metallic phase was observed (shown in Fig. 8a). Figure 8b shows the chemical composition of the interface micro constituent observed in the location as indicated in Fig. 8a. Results from energy-dispersive spectroscopy demonstrate that aluminum and copper did not take an equal part in the intermetallic formation, a chemical composition of 67.5 at.% aluminum and 32.1 at.% copper was found. Comparison of this result with the aluminum–copper phase diagram shown in Fig. 1 strongly implies that transition region must be the ambient-temperature non-stoichiometric $CuAl_2$ phase. The x-ray dot mapping of the interface shown in Fig. 8c and d, corresponds to the presence of copper and aluminum concentration in the zone of interest. The intermetallic zone formation could be a direct result of atomic diffusion of one metal into the other and its formation can be accelerated with an increase in temperature [15, 16]. Hence, it should be clearly understood from the thermodynamic aspect of the material and the kinematics of transfer of energy between the metals. It is essential to quantify the growth of the intermetallic zone since the formation of a large zone could cause brittle fracture along the welded zone and the depth of diffusion could exponentially increase as a function of temperature and time. Of all the intermetallic phases in the aluminum–copper phase diagram, the $CuAl_2$ phase exhibits the most negative heat of formation, indicating a particularly strong exothermic reaction [17], and therefore increases the chemical driving force for the formation of a 2:1 aluminum–copper compound.

2.1.3 Wave formation at the interface

From the optical and scanning electron images, it is evident that the wave formation was more pronounced in the mid region than the beginning and end of the welded interface, where the bonding and formation of inter metallic phases had been observed. This wave formation is similar to that one observed in explosive welding and the associated mechanisms could be related. Allen et al. reported the formation of surface jetting during the oblique impact of hard steel plates on soft zinc surfaces [18]. Subsequently, the mechanism of wave formation has been studied and its influence on the process has been investigated. Wantanabe and Kumai studied the interface morphology in magnetic-pulse welding of aluminum/aluminum plates and copper/copper plates [19]. The variation of wave length along the length of the weld is caused due to the variation of collision angle between the flyer plate and the parent material. Also, the formation of maximum amplitude and wave length at the interface tends to increase with the increase in measured impact velocity and estimated the magnetic pressure acting on the interface. Ben-Artz et al. studied the wave formation mechanism based on the shock wave propagation in the parent material [20]. They proposed an empirical relationship relating the wavelength and the distance traveled by the shock wave inside the inner tube. The mechanism for the formation of waves was explained on the basis of interaction

Fig. 8 Electron dispersive analysis of **a** Interface between aluminum and copper, **b** Inter metallic chemical composition, **c** electron dot mapping of copper, and **d** electron dot mapping of aluminum

Fig. 9 3D x-ray microtomography analysis of the copper–aluminum weld interface

between the surface and returning secondary wave from inside the tube. To validate this explanation, they carried out experiments with inner tubes of varying wall thickness and at different energy levels.

In order to investigate the wave morphology, a thin slice of the interface of 1 mm in width and 2 mm in length as shown on the right of Fig. 9 were cut from the middle region. The middle region was chosen, since the wave formation was predominant and the inter metallics were observed in this region. This small volume was x-ray scanned in a microtomography machine to construct a 3D image of the interface. A 3D view of the wave morphology is shown in Fig. 9 and observation of the surface morphology shows that the wave patterns were uniform along the angular direction (axi-symmetric). Even though the pixel accuracy of the reconstructed image is less than 1 μm , it is not possible to clearly distinguish the presence of an intermetallic layer on the welded surface through tomographic analysis. Figure 10 shows the projection of interface wave from the 3D-scanned image from which

the wave length of 132.4 μm and the amplitude of 23.8 μm are measured.

2.1.4 Influence of impact velocity on temperature

Experimental evaluation of temperature during the magnetic-pulse welding process is very difficult because of the high speed process involving a very high energy. Komelkov proposed a simple model where the increase in interface temperature (ΔT), was related only to the maximum amplitude of magnetic field B_{max} :

$$\Delta T \approx 0.34 \times B_{\text{max}}^2 \quad (8)$$

Based on this model, the increase in temperature is of the order of 100 $^{\circ}\text{C}$ even in cases of welding at a high-energy level [21]. However, the reported melting of metals along the interface suggests otherwise; thus, a better model to predict the rise in temperature is required. In the present study, a model to predict the temperature

Fig. 10 2D projection of the copper–aluminum weld interface showing a wavy pattern

Fig. 11 Change in enthalpy as a function of impact velocity for different efficiency factor and the increase in temperature corresponding to the change in enthalpy

Fig. 12 The ODS parts along with the coil and pusher are shown on top and the welded specimen on the bottom of the image

based on the energy balance between the transferred kinetic energy and the enthalpy in the system is discussed. In MPW, the welding is caused by the high-velocity impact of the outer tube with the inner tube. The kinetic energy of the outer tube is transferred at the point of impact to the inner tube and changes the enthalpy in the surrounding mass. Considering adiabatic heat transfer, the simple balance of energy can be expressed by the conservation law as shown below

$$\frac{1}{2}(\rho_1 A t_1) V_1^2 \eta = \rho_2 A t_2 \Delta H \quad (9)$$

where ρ_1 and ρ_2 are the density of the outer and inner tube and $A t_1$ and $A t_2$ are the atomic weight of the inner and outer tube, respectively. V_1 is the velocity of impact of the

outer tube on the inner one, ΔH the change in enthalpy in the system, and η is the efficiency factor based on the ratio of conversion of kinetic impact energy in to heat at the interface. Considering that the change in energy causes heating of the system, the rise in temperature can be quantified as shown below

$$\Delta H = \int_{298K}^T C_p dT + \left(\Delta h_f + \int_{T_m}^T C_p dT \right)_{T \geq T_m} \quad (10)$$

Where C_p is the average specific heat, Δh_f is the change in enthalpy due to fusion, and T_m is the melting temperature of the metal. Considering the outer tube as aluminum and the inner tube as copper and using Eq. 9, the change in enthalpy as a function of impact velocity is plotted for different efficiency factors (see Fig. 11) and the calculated enthalpy changes the rise in temperature is evaluated using the relation Eq. 10. From the graph, for an efficiency factor of 0.8, the upper-cut off limit for the velocity can be fixed at 170 m/s. An experimental value of 13 T is measured for the discharge energy of 5 kJ and if the travel distance of the outer projectile is taken as 1 mm, a velocity of 158 m/s is obtained from the expressions (Eqs. 6 and 7). Using Fig. 11, the change in enthalpy in the aluminum could be anywhere between 400 and 1,300 J/g depending upon the value of efficiency factor and the rise in temperature could be between 250 and 900 °C. The chance of the efficiency factor being close to one is higher than close to zero.

3 Welding of ODS alloy

Innovation in materials technology has lead to the creation of advanced materials by combining the known metals with other non-metallic particles, known as metal matrix composites (MMC's) and ODS alloys. ODS alloys could be of nickel or steel alloy base reinforced with oxide particles usually less than 2 %. Steel-based ODS alloys are being developed for

Fig. 13 Interface between the welded sample for the ODS alloy **a** Initial impact zone, **b** Intermediate zone, and **c** Weld region

Fig. 14 Schematic representation of the dynamic compaction system

high-temperature applications. But their application is hindered due to the lack of suitable manufacturing route, and specifically for joining. The welded joint should have high-temperature creep strength and the process should not alter the reinforcement structure and to some extent, the microstructure of the base material. Welding by fusion leads to considerable damage to the reinforcement structure such as particle agglomeration and also, significantly changes the alloy microstructure. The entrapped gases during the fabrication of ODS alloy could cause the formation of porosity during fusion welding. Solid-state welding these materials becomes an obvious choice and several techniques such as friction welding, friction-stir welding, and diffusion bonding have been tried. Inkson and Threadgill investigated the friction welding of ODS alloys and observed the welded samples using a transmission electron microscope (TEM) [22]. The TEM observations revealed distinct micro-structural zones with different grain size and the agglomeration of the particles. Mathon et al. studied the micro-structural evolution in friction-stir welding of PM2000 ODS alloys and found that the average particle size in the welded zone is larger than the parent alloy [23]. Residual stresses determined by

neutron diffraction showed an increase of the residual stresses in the weld zone and it is more pronounced in the direction of welding than in the transverse direction.

MPW could be an ideal process to weld ODS alloy for applications such as nuclear-reactor cladding tubes. Since ODS alloys are less-conducting materials, the acceleration of the tube was carried out using an aluminum pusher and this demands a very high-energy level. The ODS alloy used in the present study was fabricated by mechanical alloying of high chrome ferritic steel (18 % Cr) with nanometric Y_2O_3 particles (0.5 vol.%) and then the alloyed powder was compacted through hot extrusion. The magnetic-pulse welding of the ODS alloy was carried out using a generator with a capacitance of 272 μF , and a maximum energy level of 30 kJ. An outer tube of 10 mm in diameter and 0.5 mm thickness and an inner cone with an inclination angle of 8° was machined from the extruded cylindrical rod. The cone was placed inside the tube and the assembly was fixed using a fixture to arrest the movement during impact. A 6-turn solenoid coil of diameter 13.6 mm was made using a wire of 2.5 mm diameter for the experiment. Figure 12 shows the parts used for welding along with the coil and pusher used

Fig. 15 Dynamic compaction system used for the experiments

Fig. 16 Dimension of the projectile and the envelope are shown on the top and the compacted sample is shown below

for the experiment. A discharge energy of 14 kJ was discharged through the coil and the welded specimen (on the bottom of Fig. 12) was subjected to mechanical-peel testing to confirm bonding.

Secondary electron images of the welded ODS alloy shown in Fig. 13 reveals three distinct regions of the interface (a) an initial impact zone, (b) an intermediate zone, and (c) a weld region. In the initial impact zone, the parts were in contact with a deep crack. As we move away, the wavy morphology was observed along the interface in the intermediate zone which was visible during microscopy observation and was followed by the welded region where the interface was almost invisible during SEM observations. This confirms the bonding in this zone and also corresponds to the results observed in the mechanical peeling test. However, the analysis of structural modification of the dispersed

Fig. 17 Measurement location and corresponding value of porosity for the compacted sample

Fig. 18 Scanning electron microscopy image at the axis center of the aluminum-compacted sample

yttrium oxide along with the variation of the microstructure of the base metal requires further investigations and the service quality of the weld for high-temperature creep applications should be verified through elevated temperature pressure test and thermal cycling tests.

4 Magnetic-pulse compaction of powders

In magnetic-pulse compaction (MPC), the projectile accelerated by electromagnetic forces is used to compress the powders placed inside a die. Electromagnetic energy permits consolidation of powders at very high velocity close to the theoretical density of the powder and a very good aspect ratio of the specimen is possible when compared to conventional compaction. Compaction can be achieved without causing

significant heating to the powder material. Based on the direction of compression, the process can be classified as iso-dynamic and uni-axial as shown in Fig. 14 [24]. In the iso-dynamic condition, the compaction of the powder is effected in the radial direction. The powder material is enclosed in a conducting tube placed inside a cylindrical coil. The discharge of the energy stored in the capacitor bank through the coil causes the same sequence of events as in magnetic-pulse welding. An electromagnetic shock wave passes through the powder and results in compaction of very high density. Preheating of powder can be carried out by placing a furnace adjacent to the compaction coil. In the uni-axial system, the powder is filled in a die and the piston is accelerated using electromagnetic forces generated due to a high-energy discharge through the coil placed adjacent to it. Very little work has been carried out in the iso-dynamic compaction of powders and in the present study, a compaction system to realize cylindrical part is presented.

Nononenko et al. investigated the kinetic densification ratio for iron powders placed inside the thin tubes made of copper and aluminum with different wall thicknesses [25]. They concluded that aluminum could better serve in cases of thick wall applications. Baccino et al. demonstrated the use of a projectile to compact the powders placed inside an envelope and its use increases the velocity of deformation of the powder when compared to the direct compaction [26]. Chelluri performed compaction of a tungsten steel composite; after preheating the powder at 1,000 °C and subjecting the compaction to multiple compaction cycles, compaction close to 99 % of the theoretical density of the alloy was produced [27]. Popov et al. produced MMC with aluminum base and silicon carbide reinforcement through dynamic consolidation of mechanically alloyed composite powders [28]. They managed to produce sound composite materials with a homogenous distribution of reinforcement particles and the hardness of the materials seems to increase with an increase in the milling time.

In the present study, the compaction system as shown in Fig. 15 was used for the experiments. It consists of a cylindrical projectile placed inside the coil and an envelope filled with power particles placed inside the projectile. The envelope was closed using end caps with a provision to create a vacuum. Energy of 9.72 kJ was discharged through a two-layered solenoid coil made of 2 mm diameter wire. The projectile and the envelope made of aluminum were placed inside the coil. The coil dimensions are shown in Fig. 16. Discharge of high energy through the coil creates a Lorentz force and accelerates the projectile where it impacts with very high pressure on the envelope, resulting in compaction of the powder. The projectile and the envelope were then cut open to retrieve the compacted specimen. The length of the coil was made long enough to have a uniform distribution of magnetic pressure along the length of the compact and the end caps were made of non conducting materials in order not to modify

the magnetic field profile. A small gap was provided between the projectile and the envelope so that the projectile will gain sufficient velocity before impact on the envelope. The thickness of the projectile was calculated based on the skin thickness in the conductor (Eq. 3) and the envelope was made thick enough to avoid wrinkling due to compaction.

The compact produced had sufficient strength for mechanical cutting. The compact was cut in the middle and at the extremity for metallographic observations, as shown in Fig. 17. The cut surfaces were mechanically polished and subjected to optical microscopy observation. The quality of the compact is quantified by measuring the porosity using a pixel classifier. Variation of porosity along the radial direction was measured at three different angular positions and the representative mean value was taken as reference. The variation of porosity along the radial and axial direction for the compact produced is shown in Fig. 17. The measured porosity values indicate that the specimens were better compacted on the outer surface than along the axis center. A high value of 18 % porosity was observed at the axis center on the extremity of the specimen. Scanning electron microscopy observation of the cut surface is shown in Fig. 18. The particle was subjected to severe deformation and intimate contact was established between the particles. The observation shows the existence of porosity between particles and does not reveal the diffusion of material between particles. The compacts could be further densified through either hot extrusion or sintering to achieve full strength.

5 Summary

The application of electromagnetic energy for welding and powder compaction is investigated in the present study. The results suggest that magnetic-pulse welding technology can be used to produce high-quality welds between dissimilar metals and advanced materials such as ODS alloys. The formation of an intermetallic phase is observed along the interface in the welded aluminum and copper sample. Chemical analysis carried out through energy-dispersive spectra analysis suggest that the observed inter metallic phase could be $CuAl_2$. The model relating the impact velocity to the interface temperature predicts a significant increase in temperature between 250 and 900 °C based on the choice of efficiency factor. The formation of intermetallic phases could be accelerated and melting of metals is possible when a very high energy is applied during welding. A good quality weld is produced for the ODS alloy, however, the service quality of the weld for high-temperature creep applications and modification caused to the reinforced Y_2O_3 particles at the interface should be verified. Magnetic-pulse compaction of cylindrical parts was realized using aluminum powder and the measured porosity values indicate that the specimen is

better compacted on the outer surface than along the axis center.

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