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**THE LASER WELDING OF Al-SiC_p METAL MATRIX COMPOSITES: AN
ANALYTICAL ESTIMATE FOR THE FORMATION OF ALUMINUM CARBIDE**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
University of Tennessee, Knoxville

Santosh C. Gopinathan

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DEDICATION

This dissertation is dedicated to my wife Shobha

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ABSTRACT

The present research determined the critical thermal conditions for the formation of aluminum carbide during the laser welding of Al-SiC_p metal matrix composites. The problem was studied using a combined experimental and analytical approach. The experimental approach included the performance of laser welding experiments on the composites and on the base matrix aluminum. Measurements of the thermal fields were made during laser processing and the weld profiles, weld areas and aluminum carbide areas were characterized in the samples after laser treatment.

The analytical model was based on Rosenthal's line source solution obeying modified Beer Lambert's Law. It duplicated the experimentally determined weld profiles based on material properties, laser processing conditions and input parameters such as absorption efficiency and coefficients of absorption. The model was later verified by comparing the calculated thermocouple temperatures with the experimentally measured temperatures. The calibrated model was then used to calculate the thermal fields within the weld region and to determine the critical conditions for aluminum carbide formation.

Cooling rate was determined to be the most important factor for controlling the formation of aluminum carbide. It was determined that at a minimum formation temperature of

1100 K (827°C), the critical cooling rate for the formation of aluminum carbide during laser processing of Al-SiC metal matrix composites was 12000 K/sec (12000°C/sec).

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NOMENCLATURE

T : temperature (K)
 T_0 : ambient temperature (K)
 x, y, z : length, width and thickness (cm)
 g : sample thickness (cm)
 $1/2\lambda$: thermal diffusivity (cm^2/sec)
 k : thermal conductivity (Watts/cm K)
 C_p : specific heat (Watt.sec/gm K)
 ρ : density (gm/cc)
 t : time (sec)
 v : velocity (cm/sec)
 Q_p : total absorbed power (Watts)
 Q_0 : total incident power (Watts)
 q : power input per unit thickness of the sample (Watts/cm)
 q_0 : power input per unit thickness of the sample (Watts/cm)
 q_s : power input per unit length at the surface (Watts/cm)
 α : absorption efficiency
 β : coefficient of absorption (Mazumder et al) ($1/\text{cm}$)
 β_0 : coefficient of absorption ($1/\text{cm}$)
 β_1 : modified coefficient of absorption ($1/\text{cm}^2$)
 β^* : combined coefficient of absorption ($1/\text{cm}$)
 $\beta^* : \beta_0 + \beta_1 z$
 a_c : activity of carbon
 a_{Si} : activity of silicon

CHAPTER 1

INTRODUCTION

Metal matrix composites (MMC's) consist of a reinforcing phase dispersed in a metal/alloy matrix. The reinforcing phase, generally in the form of ceramic particles, fibers or whiskers, exhibits high strength properties, while the matrix metal/alloy is extremely ductile. The high strength of the reinforcing phase, coupled with the good ductility of the metal, results in high stiffness to weight ratios. As a result, MMC's are strong candidates for applications as structural materials at a time when the demand for stronger, lighter and tougher materials is growing.

The technology for the manufacture of MMC's is now well established. There are, however, inherent problems that restrict widespread use of these unique materials. The major problem is fabrication of components from MMC's, i.e. joining/ welding and cutting. Various researchers have examined the feasibility of joining of MMC's by different methods with varying degrees of success. A brief overview of the previous work done is given below.

There are two broad types of joining methods for MMC's, non-fusion joining and fusion joining. Non-fusion joining processes involve little or no melting of the base metal.

These processes include diffusion joining, soldering and brazing. Fusion joining, on the other hand, involves the melting of at least one of the constituents of the alloy at the weld interface to complete the weld.

Metzger(1,2) has reviewed the work done on diffusion joining of metal matrix composites. The main problems associated with the process are the requirements of high pressure, the restriction on the shape and thickness of the workpiece and the time taken in order to achieve bonding. Diffusion joining has been shown to work for fiber composites such as Aluminum-Boron fiber metal matrix composites. In the case of particulate MMC's however, the diffusivities of the alloy matrix and the reinforcing particulates at temperatures below the melting point of the alloy is very low and hence this method does not result in a strong metallurgical bond.

Brazing and soldering processes involve the introduction of a low melting point material between the two parts to be joined. Robertson et al (3) have studied the soldering and brazing of Al-B fiber composites. During brazing of these composites using aluminum silicon alloys as brazing materials, it was observed that exposure to the heat caused the destruction of the reinforcing Boron fibers in the region of the joint, resulting in degradation of the weld properties.

Research on the feasibility of fusion welding of MMC's by the use of techniques such as explosive welding, gas

tungsten arc welding, plasma arc welding, capacitor discharge welding, resistance spot welding as well as electron beam welding has been undertaken by various researchers. During the explosive welding processes, the two surfaces to be joined are made to impinge on each other at high velocities through the use of an explosive charge. The high impingement velocity provides the mechanism for the two surfaces to bond. Explosive welding of wire reinforced Aluminum composites was studied by Fleck et al (4). Antsiferov et al (5) studied the explosive welding of Molybdenum-fiber reinforced Titanium composites. The wire reinforced aluminum composite displayed a tensile strength that was close to the rule of mixtures strength for the composite. The Mo-fibers in the titanium composites were found to have retained their strength after explosive welding.

The feasibility of fusion welding of Aluminum-Boron fiber metal matrix composites was studied by Hersh (6). He observed that Gas Tungsten Arc (GTA), as well as plasma arc welding processes caused extensive destruction of the boron fibers at the weld interface causing a large reduction in the weld strength.

GTA welding of titanium-tungsten composites were studied by Iseki et al (7). It was observed that the severe heat resulted in the dissolution of tungsten fibers in the titanium-tungsten composite.

Kennedy (8) studied the GTA welding of titanium-graphite composites. He observed the formation of tungsten carbide around each filament in the weld zone as a result of the heat input. This led to severe degradation of weld properties. The extent of fiber-matrix reaction was shown to be directly proportional to welding energy input.

Wu (9) studied the feasibility of resistance spot welding of Aluminum-Boron fiber metal matrix composites. The quality of spot welds produced was a function of the welding current. Since there was a difference between the electrical resistance of the matrix and the fiber, the spot welds were found to be inconsistent.

Electron beam welding was attempted on Aluminum Boron(_f) composites (6,9). The process produced narrow, clean welds but the destruction of boron fibers led to reduced strengths in the weld region.

It is observed that a major problem with conventional fusion welding techniques in MMC's is the formation of brittle phases due to the reaction between the matrix alloy and the reinforcing phase at elevated temperatures. These brittle phases serve as sites for crack nucleation, and, when present in the form of a continuous layer, assist crack propagation, resulting in early brittle fracture of the weldments.

The metal matrix composite chosen for this study was A356 Al alloy/SiC(_p) MMC consisting of 10 and 20 volume% of

SiC particles dispersed in an A356 Aluminum matrix. Various fusion welding techniques (described in the next Chapter), when applied to these MMC's, resulted in the formation of a brittle Al_4C_3 phase due to the reaction between the matrix Al and the reinforcing SiC particles.

Recently, studies were conducted by Dahotre et al (10,11) to determine the feasibility of the laser welding of Al-SiC MMC's. The laser was used as a heat source because the precision focussing capability of the beam resulted in a very small reaction zone. It was observed that inspite of the formation of Al_4C_3 , certain laser processing conditions produced welds with strengths comparable to that of the as-received composite. The study concluded that laser welding of Al-SiC MMC's was viable.

The objectives of the present study are to develop a methodology for predicting the amount of aluminum carbide region formed during the welding of Al-SiC metal matrix composites and to determine the critical thermal conditions that result in the formation of aluminum carbide during the laser welding of these composites.

CHAPTER 2

BACKGROUND

(A) A356Al-ALLOY/SiC_p MMC's

Al-SiC MMC's have been fabricated by several methods including the infiltration of molten aluminum alloy into a preform of SiC particles and the introduction of copper coated SiC particles into the molten aluminum alloy. The commercial production process involves the introduction of SiC particles into the molten aluminum with vigorous stirring of the melt (12). The MMC has also been fabricated using powder metallurgy techniques and rapid solidification processes (13). The chemical composition of A356-Aluminum matrix is given below in Table I.

TABLE I. CHEMICAL COMPOSITION OF A356-ALUMINUM MATRIX:

Element	Si	Fe	Cu	Mg	Zn	Al
Weight%	7.0	0.20	0.20	0.35	0.11	Bal

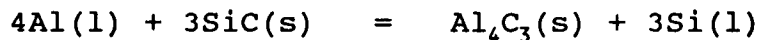
The present research made use of A356 Al-alloy/SiC(_p) MMC's fabricated using the commercial casting technique, provided by Duralcan USA.

The tensile strength of as-cast 356 Aluminum is 195 MPa

while that of A356 Al-10%SiC MMC and A356 Al-20%SiC MMC are 262 MPa and 302 MPa respectively. This results in high stiffness to weight ratios for these composites.

(B) EQUILIBRIUM METALLURGY OF THE Al-Si-C SYSTEM

The reaction between the matrix aluminum and the reinforcing silicon carbide can be represented as,



The process involves the dissociation of silicon carbide into silicon and carbon and the formation of aluminum carbide when the activities of carbon and silicon reach a threshold value at a given temperature. The above reaction is characterized by a positive free energy change at room temperatures, and hence it is not spontaneous. The reaction will proceed only upon the supply of external energy in the form of heat.

The stability domain for the Al-C-Si system was studied by Kannikeshwaran and Lin (14) and is illustrated in Figure 1. This diagram is based on an ideal case which involves the equilibrium heating and cooling of the composite. It represents the relationship between the activity of carbon (a_c), the activity of silicon (a_{si}) and temperature (T) in the Al-Si-C system.

In Figure 1, the solid lines separate the regions of stability for different phases in the Al-C system,

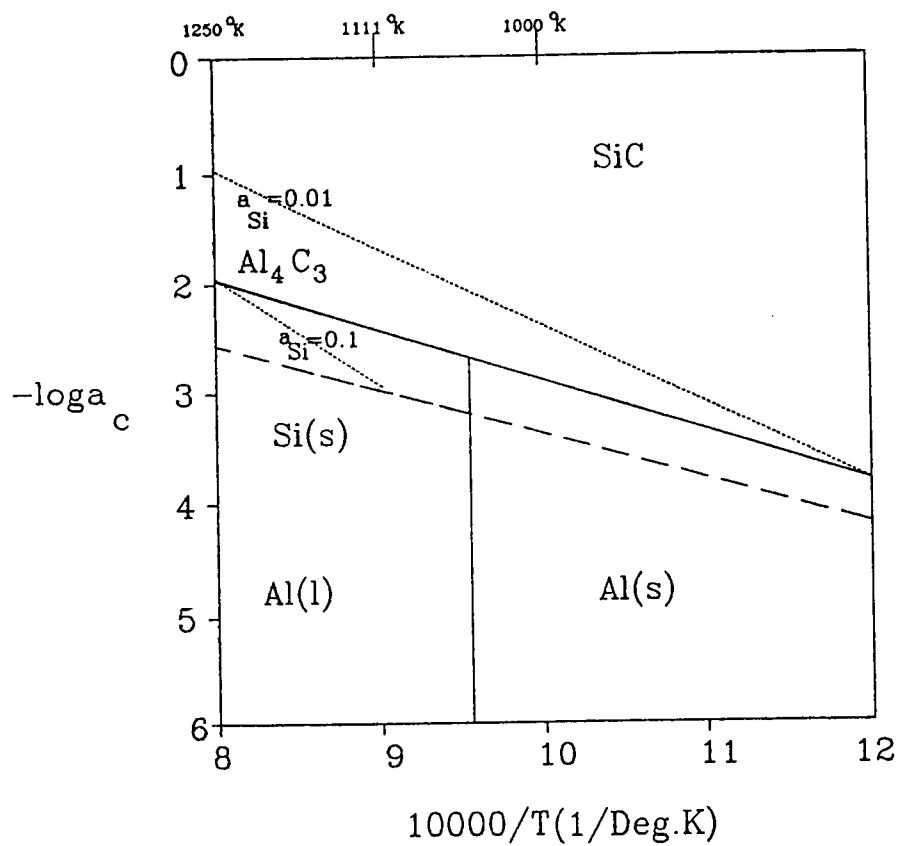


Figure 1. Stability domain of the Al-Si-C system (14).

$\text{Al(l)}, \text{Al(s)}$ and Al_4C_3 . The dashed line separates the regions for stable solid Si and SiC. When $a_{\text{Si}} = 1$, the area above the dashed lines represents the stability region for SiC, and the region below the dashed region represents the region where Si is stable. The dotted lines correspond to constant a_{Si} lines. The activities of carbon and silicon and the temperature dictate the formation of Al_4C_3 . In an Al-SiC system, the activity of C in Al is almost zero at room temperature, since no carbon is dissolved in Al. The system is hence unstable. As a result, when the material is heated, SiC begins to dissociate resulting in the increase in the activity of carbon and silicon. If the activity of carbon builds up to a value at which Al_4C_3 is stable, while the activity of Si is still below that for equilibrium dissociation of SiC, then Al will react with SiC to form Al_4C_3 . This corresponds to the region above the $\text{Al(l)}-\text{Al}_4\text{C}_3$ equilibrium line (the solid line). This occurs at temperatures above 1250 K (977°C). If the activity of Si rises faster than that of C, then, at a threshold a_{Si} , the dissociated Si recombines with the carbon and SiC is reprecipitated. This phenomenon occurs in the region between the $\text{Al(l)}-\text{Al}_4\text{C}_3$ equilibrium line and the dotted Si-SiC line at a temperature range between 1100 K (827°C) and 1250 K (977°C).

In the case of a system with pure Al and SiC, the activity of Si and C is extremely low. In order to reach the equilibrium concentration of Si, dissociation of SiC takes

place. The activity of C rises and this results in a severe attack of the Al and subsequently the formation of Al_4C_3 . If however, Si exists within the matrix alloy, such as in the case of Al 1100 (< 1% Si), it was observed by (14) that the domain of stable SiC is increased and this results in reduced formation of Al_4C_3 .

The A356 Aluminum matrix used in the present research, contains 7 weight% of silicon. Therefore, the activity of silicon is about 0.1 (15) which results in the reduction in the SiC stability region in Figure 1. The limit of stable SiC solid phase regions at corresponding Si activities used in the present study is represented by the dotted line, $a_{\text{Si}} = 0.1$. This line, however, lies in the zone where SiC is stable. As a result, under equilibrium conditions, no Al_4C_3 is expected to form.

Experimental work done under near equilibrium conditions seems to agree with this analysis. Iseki et al (16) conducted experiments in which a mixture of SiC containing pure silicon and pure aluminum powders were heated to temperatures between 973 K (700°C) and 1473 K (1200°C) for 15 to 180 minutes in 10^{-2} Pa vacuum. It was observed that the amount of Al_4C_3 formed in the sample reduced with the increase in Si content. The mole fraction of Al_4C_3 was found to be around 0.09 for a sample containing 10 wt% Si in the SiC powder heated at 1273 K (1000°C) in vacuum for 180 minutes. Iseki et al performed a separate experiment in which a

sintered disc of SiC was placed between two discs of pure aluminum and heated for 1 hour at 1373 K (1100°C) in 10^{-2} Pa vacuum. The Al-SiC interface showed a reaction layer of Al_4C_3 that was 10μ thick. The Al_4C_3 was in the form of particles, 0.1μ to 1μ in diameter. Hence it can be seen from the above study that a very small amount of Al_4C_3 was formed after prolonged equilibrium heating of the Al-SiC-Si samples.

According to the Al-Si-C equilibrium diagram, it can be concluded that the addition of Si into the matrix inhibits the formation of Al_4C_3 . Under the conditions of equilibrium, no Al_4C_3 is expected to form in the case of A356 Al due to the presence of large amounts of matrix Si.

(C) JOINING OF Al-SiC MMC'S

The fusion joining of Al-SiC MMC's has been studied by several researchers by employing various joining techniques such as transferred arc plasma welding, gas tungsten arc welding, capacitor discharge welding and laser beam welding.

Reynolds and Yang (17) studied transferred arc plasma welding of 6061 Al-30%SiC(_p) composites. In the transferred arc welding process, a plasma arc is established between an electrode and the workpiece resulting in fusion. Al-SiC, Al-Ti-SiC and Al-Zr-SiC powders were used as filler materials and were deposited at the interface of the composite plates. The resultant microstructure exhibited a clean fusion line

free of SiC particles.

Gas tungsten arc welding is an arc welding process which produces coalescence of metals by heating them with an arc between a non-consumable tungsten electrode and the workpiece. In the case of GTA welding of Al-SiC(_p) metal matrix composites it was observed by Ahearn et al (18) that a large weld area was exposed to very high temperatures for an extended period of time, resulting in the destruction of the reinforcing SiC phase. If expensive degassing was not performed on the specimens, the extended exposure to heat also resulted in hydrogen porosity. The final result was a weldment with unacceptable properties.

Capacitor discharge welding is an arc welding process in which heat is obtained from an arc produced by the rapid discharge of a capacitor bank. The two surfaces to be joined act as electrodes and they are impacted against each other. Just before the impact, the capacitor bank discharges giving rise to an arc. This arc causes the surfaces of both materials to melt. When the two surfaces impact, the arc is extinguished and excess molten material is expelled and the weld is complete. Capacitor discharge welding of 6061 Al-SiC composite was studied by Devlethian (19). A stud of the composite was welded on to a plate of the same material. The stud and the plate were in a circuit with a capacitor bank. This process did produce good welds, but the size and shape of the components and speed of welding were very restrictive.

Laser joining of these composites was recently attempted with a large degree of success. This process is discussed in detail in the following section.

(D) LASER JOINING

Laser beam welding is a joining process that produces melting and the subsequent joining of two surfaces with the heat obtained from an impinging concentrated coherent beam of light. With laser-beam welding, it is possible to precisely focus the beam on to the material and hence control the energy input and the area over which it is incident. This results in a very small reaction zone with minimum impact on the microstructure. Laser welding, unlike electron beam welding can be performed at atmospheric conditions and with the use of a shielding gas if necessary.

BEAM-MATERIAL INTERACTION

When a laser beam is incident on the surface of a sample, a part of the beam is absorbed and the rest is reflected depending upon the absorptivity of the material. The absorbed energy causes rapid heating at the surface of the material. If sufficient energy is applied, melting of surface material takes place. The molten surface continues to absorb radiation and this results in an increase in its temperature. Eventually there is vaporization of the surface

material. Heat is transferred within the material by conduction and convection and from the vapor to the material through radiation heat transfer.

Increased heat input into the material results in the increased vaporization of the constituents. The vapor pressure of these constituents and the surface tension gradients in the melt region result in the formation of a keyhole. The keyhole is a cavity filled with vapor or plasma, formed within the material directly below the beam and it behaves like a black body, absorbing all the incident energy from the laser beam. As a result, a linear heat source is created within the material and energy is distributed along a line through the material. The keyhole is narrow and the cooling rates around the region of the keyhole are very high. This results in a very small reaction zone around the keyhole and hence within the resulting weld. This is a major advantage of the laser welding process.

The feasibility of laser welding of metal matrix composites has been shown by Dahotre et al (10,11). The tensile properties and the changes in microstructure of Al-SiC MMC were characterized in that study. They observed that the formation of Al_4C_3 was related to the laser processing conditions. It was also observed that inspite of the formation of Al_4C_3 , certain laser processing conditions produced welds with strengths comparable to that of the as-

received composite. This was due to the fact that the Al_4C_3 phase formed was fine and well dispersed in the weld zone and hence served as a strengthening agent. The study validated the promise of laser welding of Al-SiC MMC's.

(E) COMPUTER MODELLING OF WELDING PROCESSES

Modelling of welding processes have been attempted by several researchers. Mazumder et.al.(20) developed a 3D numerical heat transfer model for continuous wave laser processing. In this method, the keyhole was modelled by a series of solid matrix points operating at very high temperatures. Beer Lambert's Law was used in order to represent the absorption of heat by the plasma and vapor. Convection and radiation effects were also taken into account in this study.

The first analytical model of welding with a moving source was developed by Rosenthal (21). He solved the conduction heat equation in order to obtain the temperature fields while welding semi-infinite plates. He considered cases in which the heat input per unit thickness was constant and linearly varying with depth.

Rosenthal's approach was modified by Tsai and Kuo (22) to model the temperature distribution during laser welding. They used the modified Beer Lambert's law in order to represent the absorption of heat by the plasma and the vapor.

CHAPTER 3

APPROACH

A dual experimental and analytical approach was adopted in the present research in order to study the problem of aluminum carbide formation.

The experimental approach was to produce autogenous, bead-on-plate welds on the matrix A356 Aluminum and on the two Al-SiC metal matrix composites and to characterize the laser-treated microstructures, weld areas, weld profiles, aluminum carbide areas and the temperature fields that were developed outside the weld region during laser processing. Since the thermal fields inside the fusion zone were impossible to measure experimentally due to the intense heat and associated destruction of the thermocouples, these thermal fields were obtained with the help of an analytical model.

The analytical approach included the development of an analytical model (based on Rosenthal's line source heat conduction model obeying the Modified Beer Lambert's Law) which was calibrated to duplicate the experimental weld profiles. This model was validated using thermal fields measured outside the fusion zone in the actual laser welding experiment.

The validated model was then used in order to determine the critical thermal conditions for the formation of aluminum carbide within the weld.

CHAPTER 4

Al-SiC_p LASER WELDING EXPERIMENT

In order to produce autogenous, bead-on-plate welds and characterize the temperature fields during laser processing of metal-matrix composites, a series of experiments was conducted. Samples of A356 Al, A356 Al-10%SiC MMC and A356 Al-20%SiC MMC were selected and prepared. These MMC's were so chosen because they were commercially available. Thermocouples were spot welded to the samples at predetermined distances from the designated weld center. The samples were then processed at selected laser powers. During the laser treatment, the thermocouples were monitored by a special high speed temperature measurement system. The resulting temperature-time profiles were hence determined for each thermocouple location. The laser treated samples were then sectioned, mounted and polished for microstructural analysis.

(A) SAMPLE PREPARATION

The samples of Al-10%SiC(_p) MMC, Al-20%SiC(_p) MMC and 356 Al were cut from cast billets. The rough samples were then milled into the dimensions of 76.2mm X 25.4mm X 2.54mm (3" X 1" X 0.1"). The machined samples were measured and the

designated weld center-line was marked with a scribe.

Chromel-alumel thermocouples 0.76mm (0.03") in diameter were spot welded at measured distances, approximately 2mm, 3mm, 4mm and 5mm from the scribed centerline of each sample. In order to insulate the wires from the metal surface, the part of each thermocouple assembly exposed to the sample surface was sheathed in a double holed ceramic tube about 13mm long. The remaining length of the thermocouple wire was sheathed with teflon tubing. A fifth thermocouple was placed in the path of the laser beam, at a known distance ahead of the four spot welded thermocouples. It was designed to separate upon contact with the laser beam and serve as the reference point for correlating the position of the laser beam with respect to the four spot welded thermocouples.

A schematic of the sample with the spot welded thermocouple assembly is shown in Figure 2 and a single thermocouple assembly is illustrated in Figure 3. The samples to be welded were placed on a copper fixture as shown in Figure 4.

(B) HIGH SPEED TEMPERATURE MEASUREMENT SYSTEM

The leads from the five thermocouples were connected to the temperature measurement system (Figure 5) which features independent insulated signal conditioning for each

sample

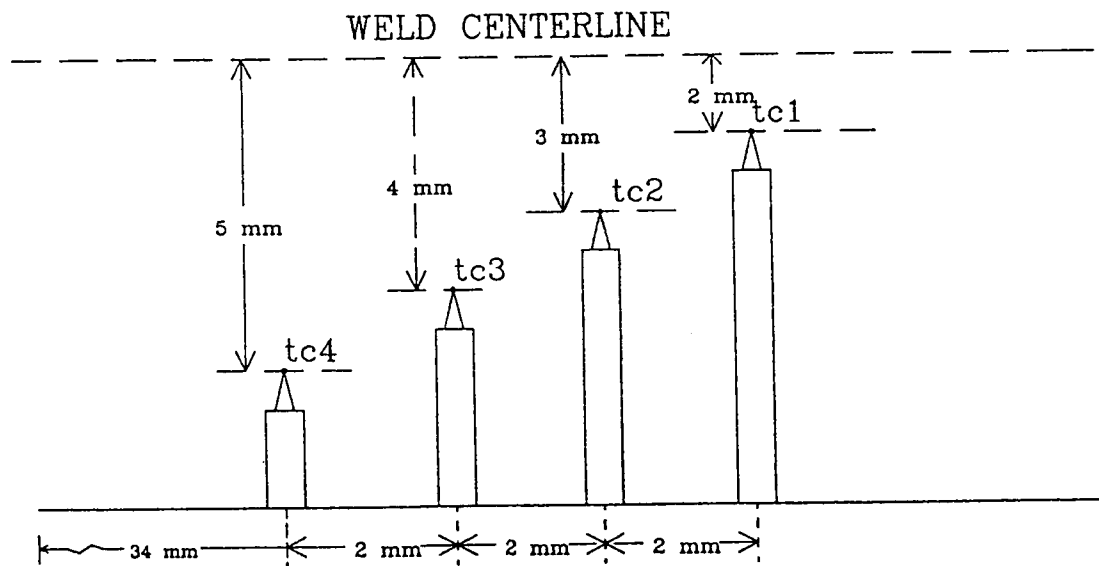


Figure 2. Sample with the thermocouple assembly (Schematic).

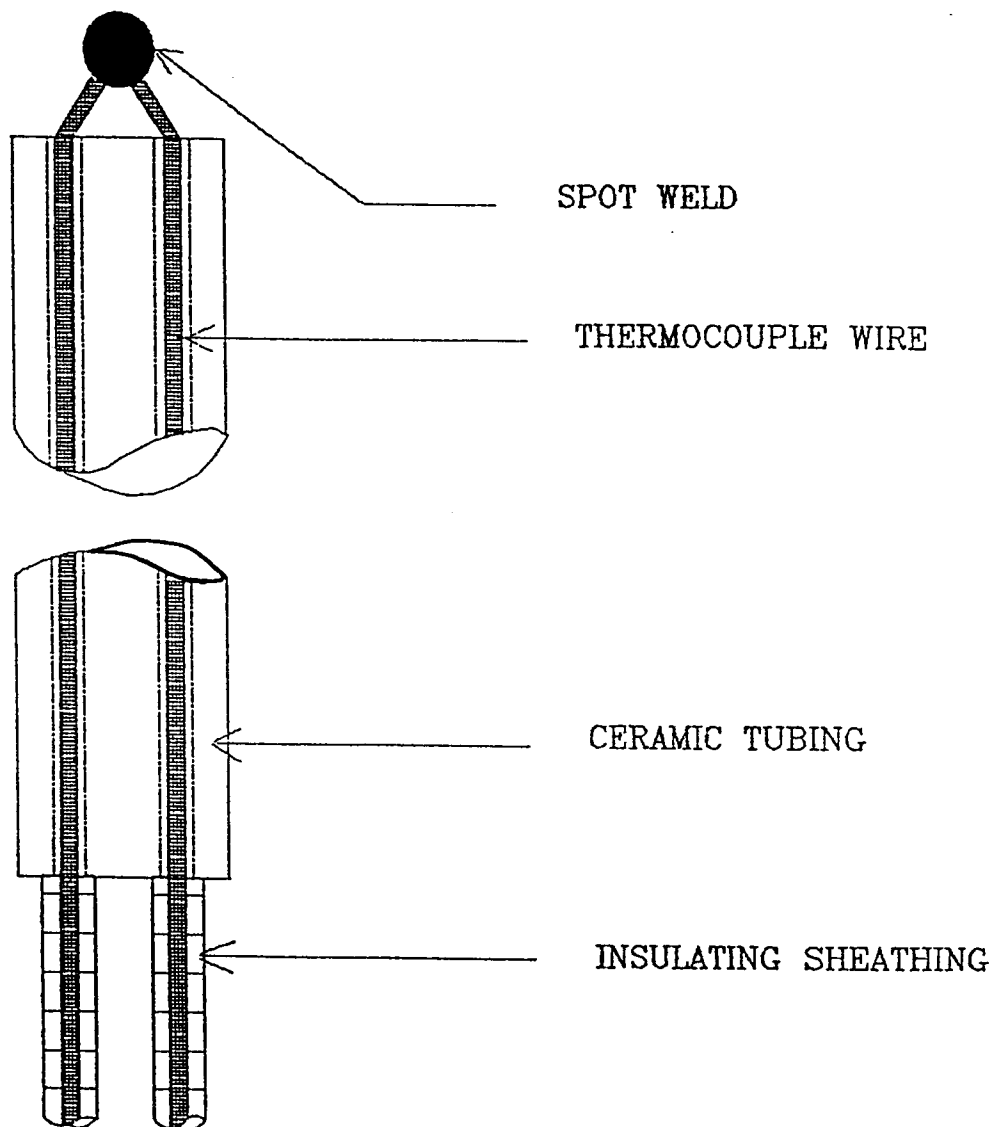


Figure 3. Individual thermocouple assembly (Schematic).

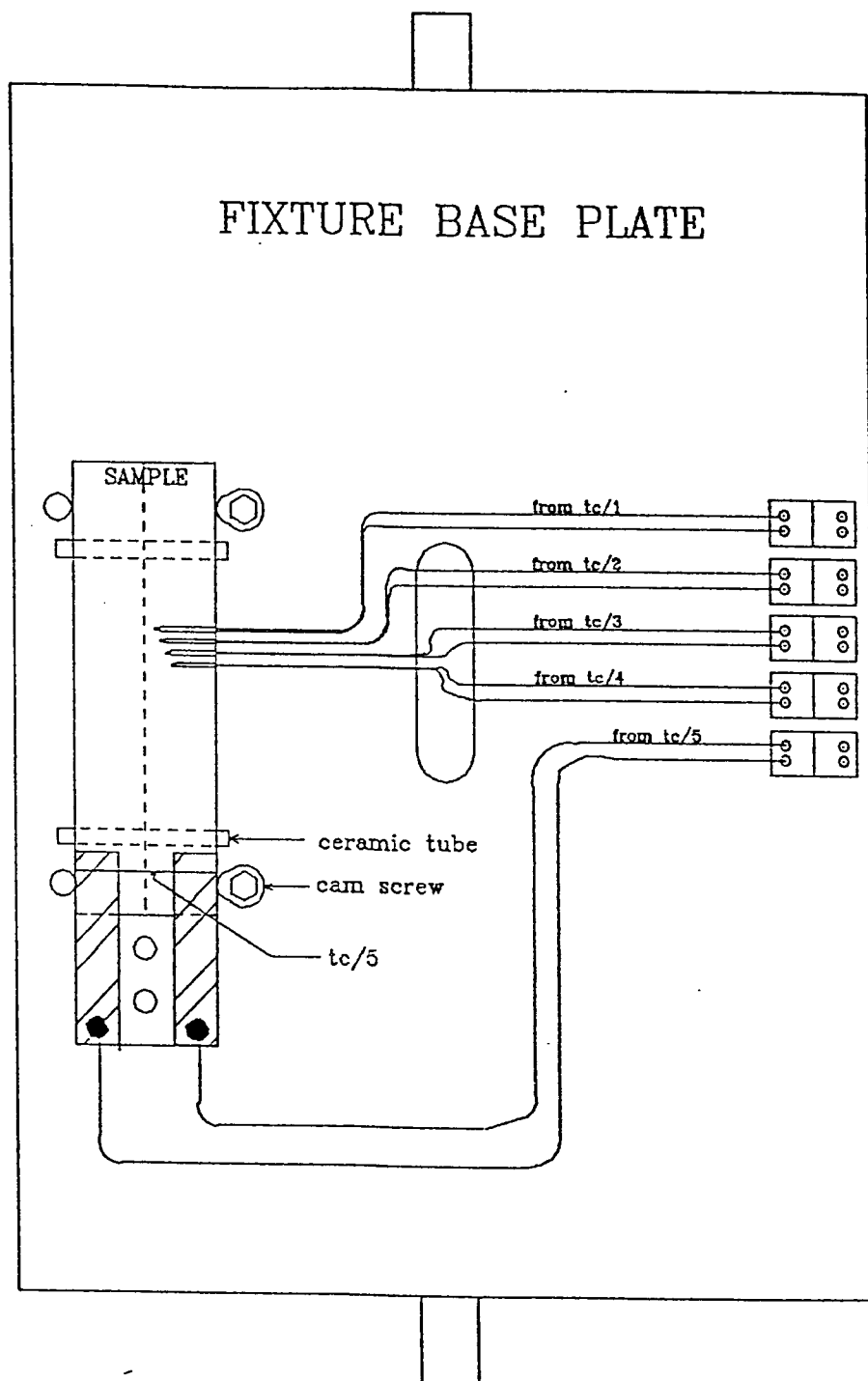


Figure 4. Sample mounted on the fixture (Schematic).

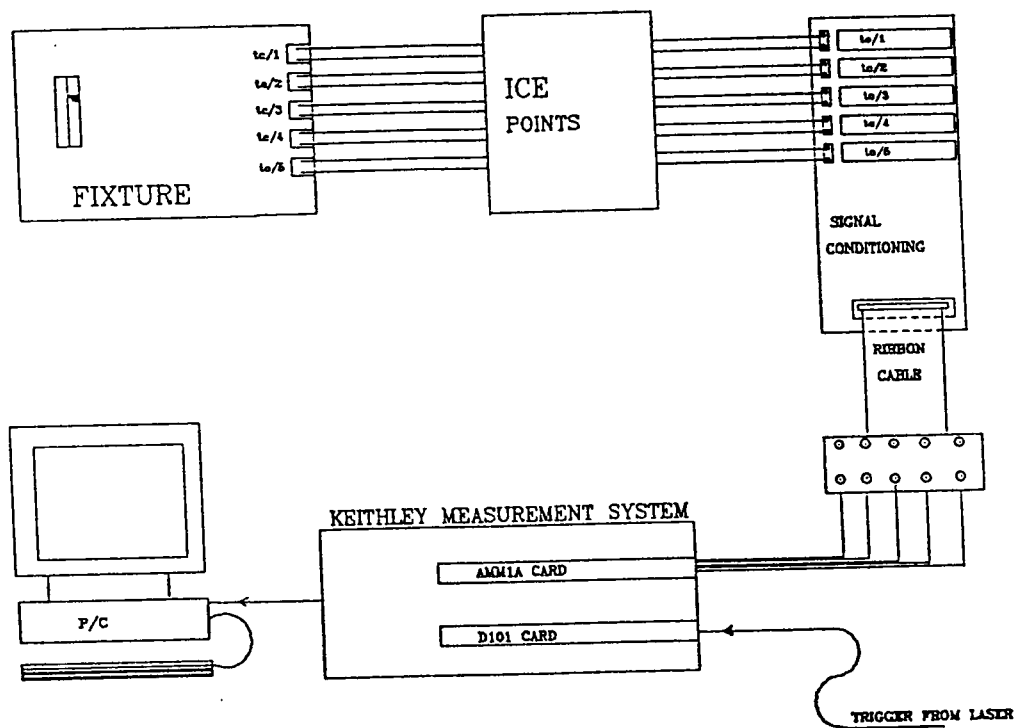


Figure 5. Schematic diagram of the high speed temperature measurement system.

thermocouple. The signal conditioners were isolated wideband with millivolt input range of $\pm 5\text{mV}$ and output of ± 5 Volts and hence provided a fixed gain of 100 to the signal voltage across the thermocouples. The signal from each thermocouple was routed through individual Omega Ice Points to achieve Cold Junction Compensation. The signal was transferred to the analog/digital (AMM1A) card resident in a Keithley 500 Series Measurement and Control system. The AMM1A card provided a combined programmable gain range from 1 to 100 and a working voltage range from -10 to 10 Volts. The trigger circuitry was effected through the D101 card in the Keithley System. The amplified voltage was stored in a computer and was post-processed to yield temperature values.

The temperature measurement system was operated with a combination of menu driven and user programmed software. The menu essentially assigned array strings or IONAMES to individual thermocouple channels and set up filters and gains. The configuration table used is illustrated in Appendix 1. The user programmed software was SOFT500 BASIC. The software enabled the setting up of the number of samples (SN!) and the interval (in 10 microsecond intervals) between readings (SINTV%). In these research experiments, 2000 readings were taken per thermocouple at an interval of 3000 microseconds thus yielding 6 seconds of temperature data. The BASIC code is listed in Appendix 2. The thermocouple output was voltage, and this was converted into temperature

values using the code listed in Appendix 3.

(C) LASER PROCESSING PARAMETERS

The laser parameters used are tabulated in Table II.

TABLE II: LASER PROCESSING PARAMETERS

MATERIALS	A356-Al, Al-10%SiC MMC, Al20%SiC MMC
SAMPLE DIMENSIONS	76.2mm X 25.4mm X 2.54mm
DELIVERED POWERS	1000,1200,1400,1600,1800,2000,2200 W
BEAM MODE	TEM ₁₀
TRAVERSE VELOCITY	25 mm/sec
FOCAL POSITION	0.5 mm below focus
SHIELDING GAS	Argon (4 liters/min, coaxial)
# OF SAMPLES PER POWER SETTING	4 samples of each material (2 with thermocouples and 2 without
PEAK POWER	3000 Watts

Bead-on-plate laser welding of the samples was accomplished with a Rofin Sinar RS3000 laser. This laser is a fast axial flow, radio-frequency excited CO₂ laser with an operating power range from 200 to 3700 Watts. For the

experiments carried out in this study, the laser was operated in the pulse width modulated (pwm) mode with the peak power set at 3000 Watts. The required input powers were obtained by adjusting the duty cycle.

(D) POST PROCESSING OF DATA

The samples of A356 Al, Al-10%SiC MMC and Al-20%SiC MMC which were prepared and laser treated were cross-sectioned, polished and etched for microstructural evaluation.

Low-magnification (10X) photographs of the weld cross sections were taken. The etching process clearly revealed the fusion zone. Total weld areas and the actual weld profiles were hence determined from these photographs.

Measurement of the area containing aluminum carbide (the aluminum carbide area) was done with the help of a series of high magnification (50X) photographs put together to reconstruct the weld region. The aluminum carbide showed up in the form of thin plates/needles after the etching process. The aluminum carbide area in these photographs was hence measured and then converted into actual area values.

The voltage-time data collected by the high speed temperature measurement system during laser processing of the metal matrix composites was converted into temperature-time data using the code described in Appendix 3 and plotted using Jim's Plot Program v7.0. These temperature-time plots were to

be used later in order to compare the experimentally determined peak thermocouple temperatures with those calculated by the model and hence to validate the predictions of the analytical code.

CHAPTER 5

EXPERIMENTAL RESULTS

(A) MICROSTRUCTURAL EVALUATION

The samples of A356 Al, Al-10%SiC MMC and Al-20%SiC MMC which were prepared and laser treated as described earlier were cross-sectioned, polished and etched with Keller's Reagent in order to reveal their microstructure. The weld cross sections were observed under an optical microscope and their microstructures were photographed. The microstructures of as-received A356 Al, Al-10%SiC MMC and Al-20%SiC MMC were also characterized for comparison purposes and they are illustrated in Figures 6,7 and 8, respectively. The as-received A356 Aluminum exhibits a large grain size that is typical of as-cast materials. The large grain boundary area is filled with the Al-Si eutectic. The structures of as received Al-10%SiC MMC and Al-20%SiC show the A356 Aluminum matrix reinforced with particles of SiC (average size 10 microns). The SiC particles tend to segregate in the grain boundary area, mainly as a result of the casting process used in their manufacture. This is particularly apparent in the case of the Al-10%SiC specimen.

The schematics of the laser processed microstructure of A356 Al and the Al-SiC MMC's are illustrated in Figures 9(a)

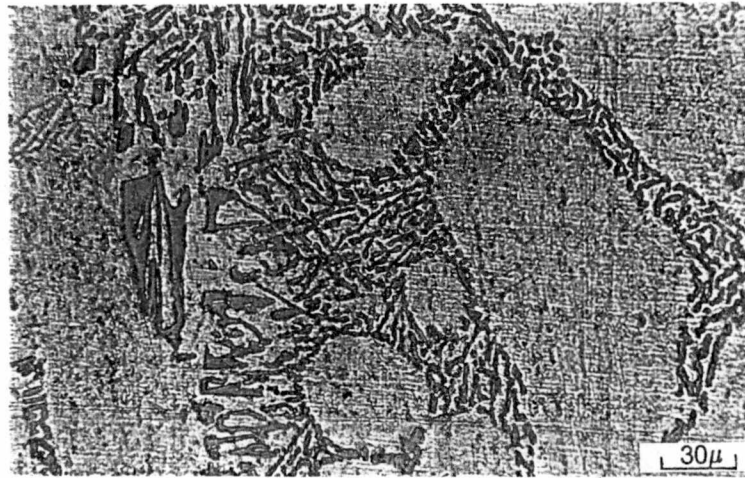


Figure 6. Microstructure of as-received A356 Aluminum.



Figure 7. Microstructure of as-received A356 Al-10%SiC_(p) MMC

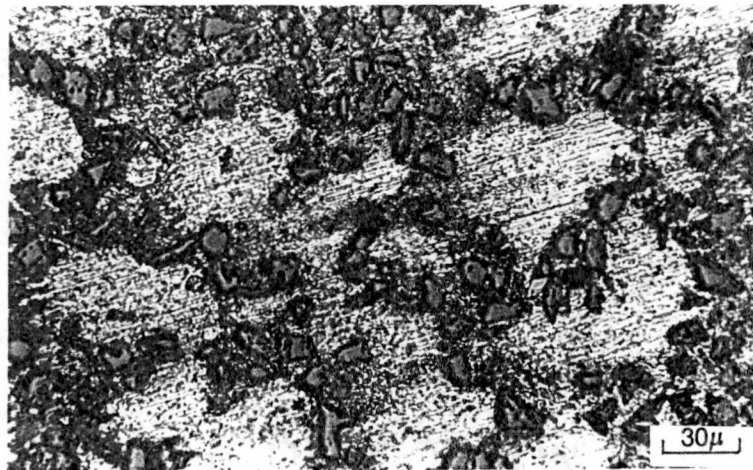
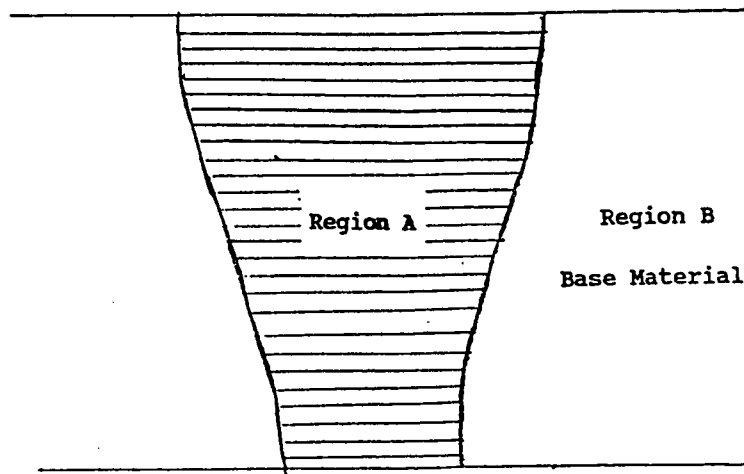
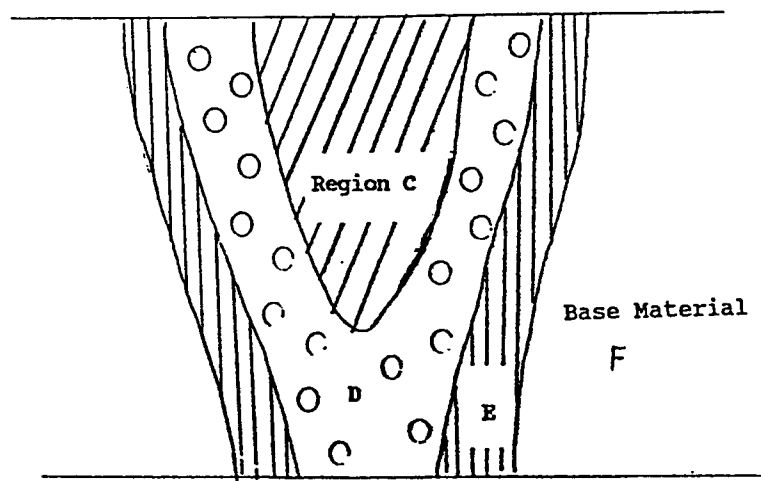


Figure 8. Microstructure of as-received A356 Al-20%SiC_(p) MMC



(a)



(b)

Figure 9. Schematics of the laser processed microstructures of (a) A356 Al and (b) Al-SiC MMC. Region A: A356 Al weld region, Region B: Base A356 Al, Region C: Al_4C_3 region, Region D: SiC redistribution region, Region E: Partially melted region, Region F: Unaffected base MMC region.

and (b) respectively. The weld microstructure of laser treated A356-Aluminum shows a weld region (Region A) containing an extremely refined grain structure surrounded by the unmelted base material (Region B). Micrographs corresponding to the above two regions are illustrated in Figure 10. In the case of the Al-SiC MMC's, Figure 9(b) shows that the weld is comprised of three regions. The central fusion region (Region C), shows the presence of plates/needles. These plates/needles were previously identified as Al_4C_3 by several researchers (10,11,14) during experiments involving fusion joining and casting of SiC/Al-alloy composites. Surrounding this region is an area where there has been a redistribution of SiC particles (Region D). The particles show some degree of surface modification. The edges have been smoothed as a result of surface melting. This region is followed by a partially melted zone (Region E), in which a fine cellular/dendritic structure in the base matrix material is apparent. The weld is surrounded by unmelted base material represented by Region F. Both composites exhibit these features under similar laser processing conditions. Figures 11 and 12 show the representative microstructures of each the above mentioned regions in both composites after laser treatment (Input Power = 2000W).

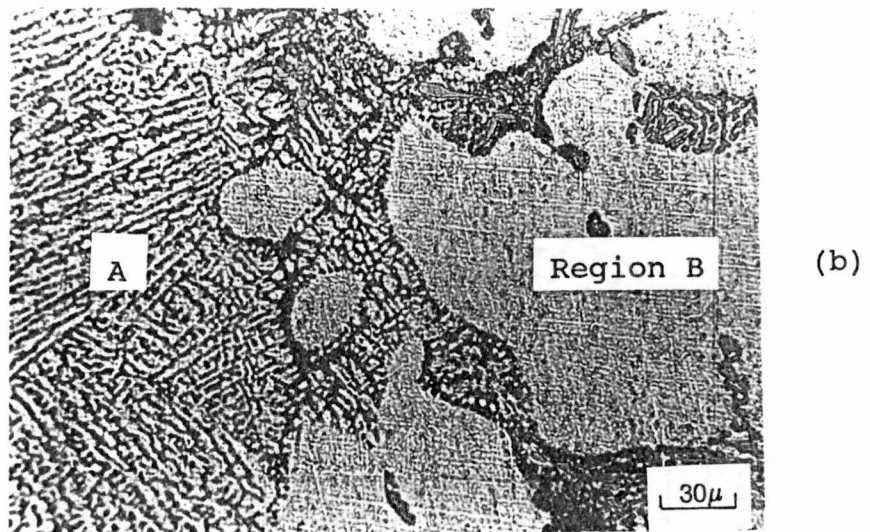
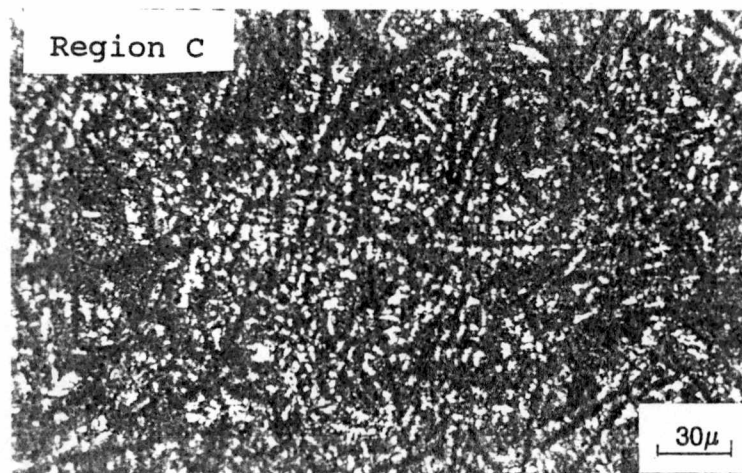
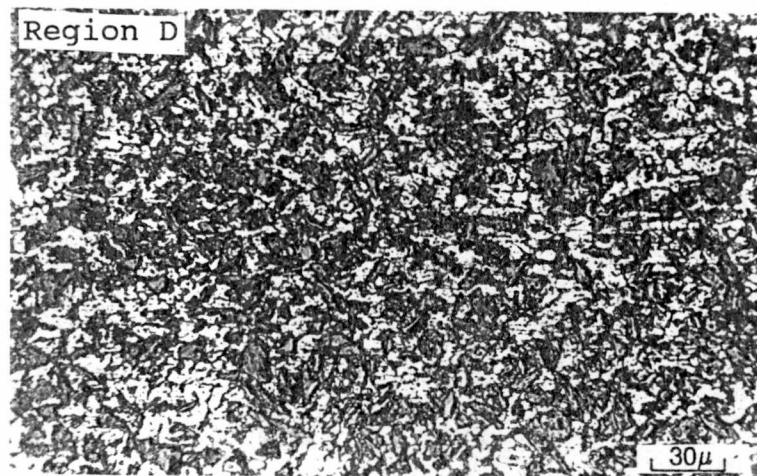


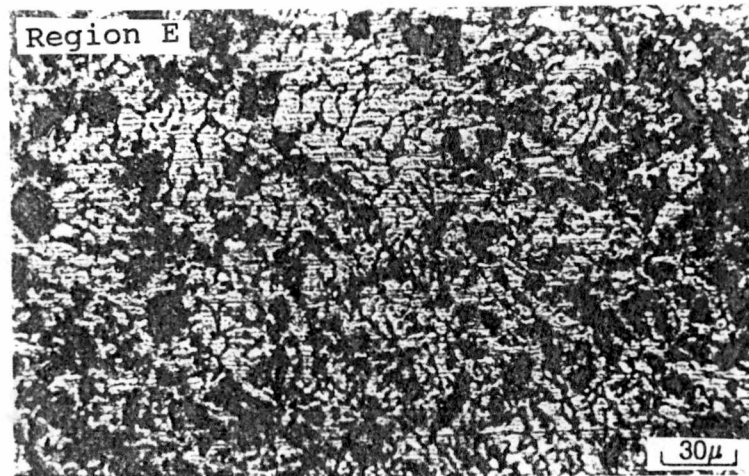
Figure 10. Microstructure of A356 Aluminum after laser processing, showing (a) central weld region showing fine dendritic structure (b) weld region and base structure.



(a)

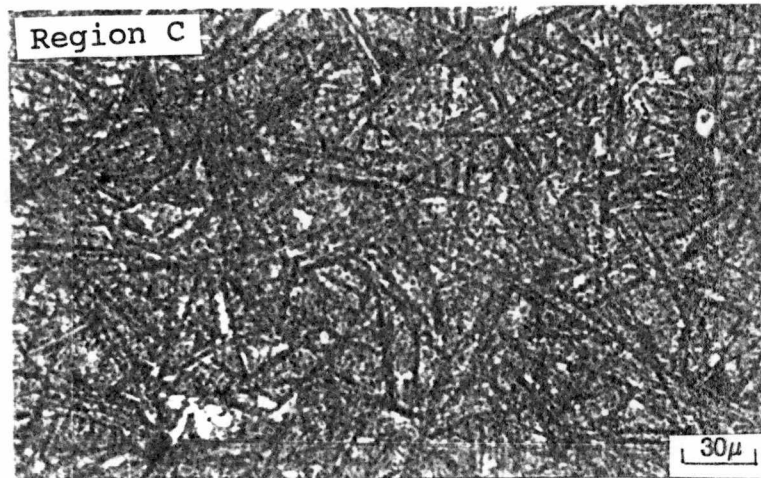


(b)

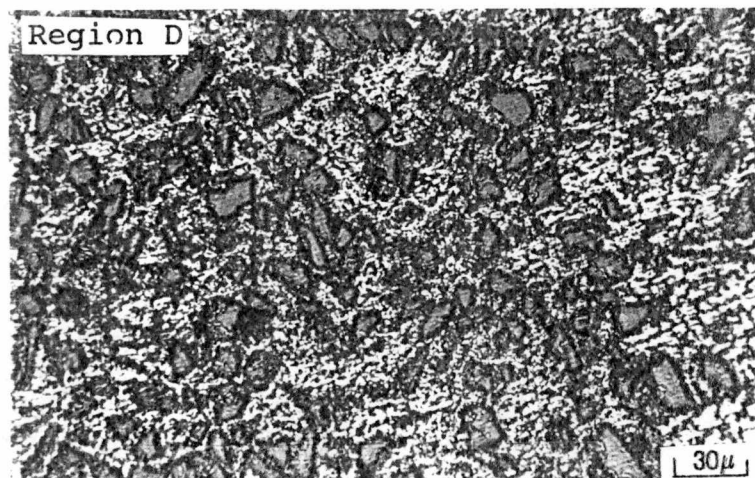


(c)

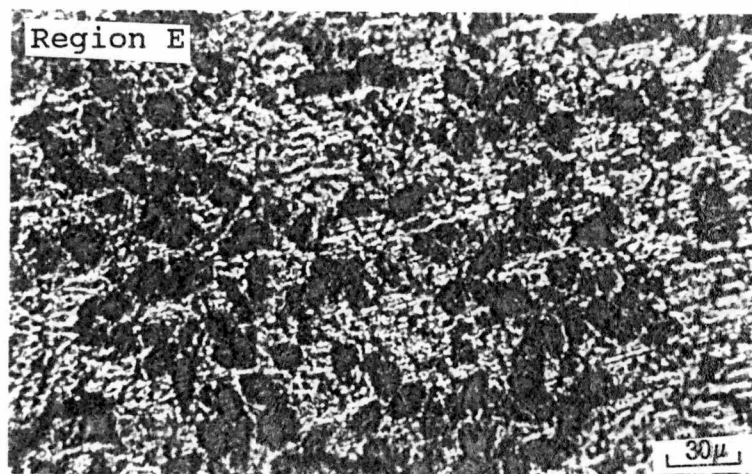
Figure 11. Microstructure of Al-10%SiC_(p) MMC after laser processing, showing (a) central weld region with Al₄C₃ plates (b) area of redistribution of SiC particles (c) partially melted zone



(a)



(b)



(c)

Figure 12. Microstructure of Al-20%SiC_(p) MMC after laser processing, showing (a) central weld region with Al₄C₃ plates (b) area of redistribution of SiC particles (c) partially melted zone

(B) RESULTS FROM WELD AREA AND ALUMINUM CARBIDE AREA MEASUREMENTS

Low-magnification (10X) photographs of the weld cross sections were taken and the weld profiles were determined from these photographs. Weld areas were also determined from these photographs by the use of a calibrated mesh. It was observed that increased incident power resulted in larger weld areas. In addition, as input power was increased, the weld changed from a conduction limited weld to a keyhole weld.

Figure 13 shows the effect of input laser power on the weld area for A356 Al, Al-10%SiC MMC and Al-20%SiC MMC. The A356 Al shows very small weld areas for input powers upto 1800 Watts. These welds were found to be conduction limited welds. At 2000 Watts, however, the weld area increases dramatically as the weld transitions from a conduction weld to a keyhole weld. At 2200 Watts input power, the weld is fully penetrated, and the weld area is close to that of the two composites at that power level. In the case of the Al-10%SiC MMC, the weld area at low input powers is larger than that for A356 Al but smaller than for the Al-20%SiC MMC. A356 Al and both MMC's, exhibit a jump at the point of full penetration. In the case of Al-10%SiC MMC, full penetration occurs between 1400 Watts and 1600 Watts, while in the case of Al-20%SiC MMC, it occurs between 1200 Watts and 1400 Watts. At higher powers (above 1800 Watts), however, the Al-10%SiC MMC exhibits a larger weld

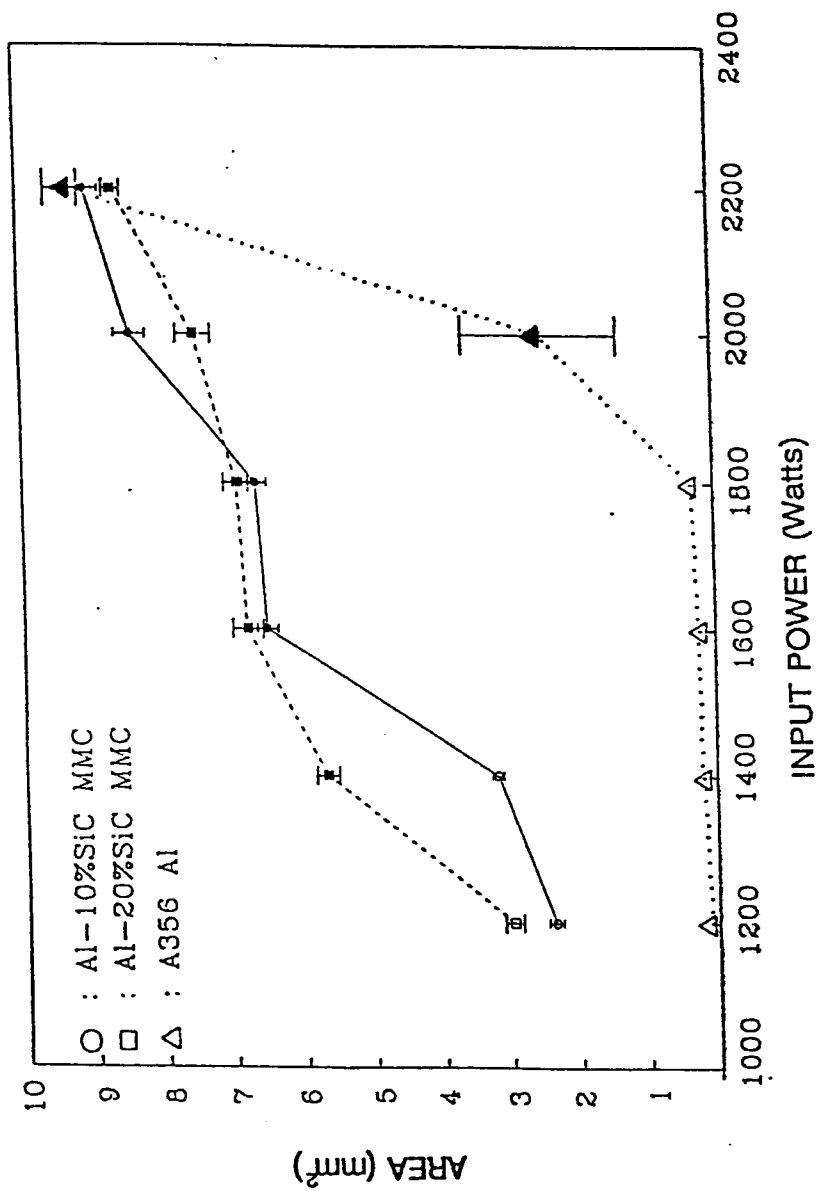


Figure 13. Effect of input laser power on the measured weld cross section areas for Al-10%SiC MMC and Al-20%SiC MMC and A356 Al. (Filled squares/triangles/circles represent full penetration)

area than the Al-20%SiC MMC. The error bars in the figure represent the maximum and the minimum measured weld areas.

The area of the aluminum carbide region is the area of the Region C represented in Figure 9. Measurement of this area was done with the help of a series of high magnification (50 X) photographs put together to reconstruct the weld region. The aluminum carbide area in these photographs was measured by using a calibrated mesh and then converted into actual area values.

Figure 14 shows the effect of input power on the aluminum carbide area within the weld cross section. The Al-20%SiC MMC has a higher area of aluminum carbide than the Al-10%SiC MMC for lower input powers. Both composites exhibit a sudden jump in Al_4C_3 area at full penetration. At higher powers, the aluminum carbide area in the Al-20%SiC MMC sample levels off and remains essentially constant. The Al_4C_3 area in Al-10%SiC MMC, however, increases with increase in power. The error bars correspond to the maximum and minimum measured Al_4C_3 areas.

Figure 15 shows the effect of input power on the ratio of the Al_4C_3 area to weld area. The Al-10%SiC MMC shows a higher area fraction of Al_4C_3 than the Al-20%SiC MMC within the power range used in the present investigation. In the figure, the error bars represent the maximum and minimum area ratios.

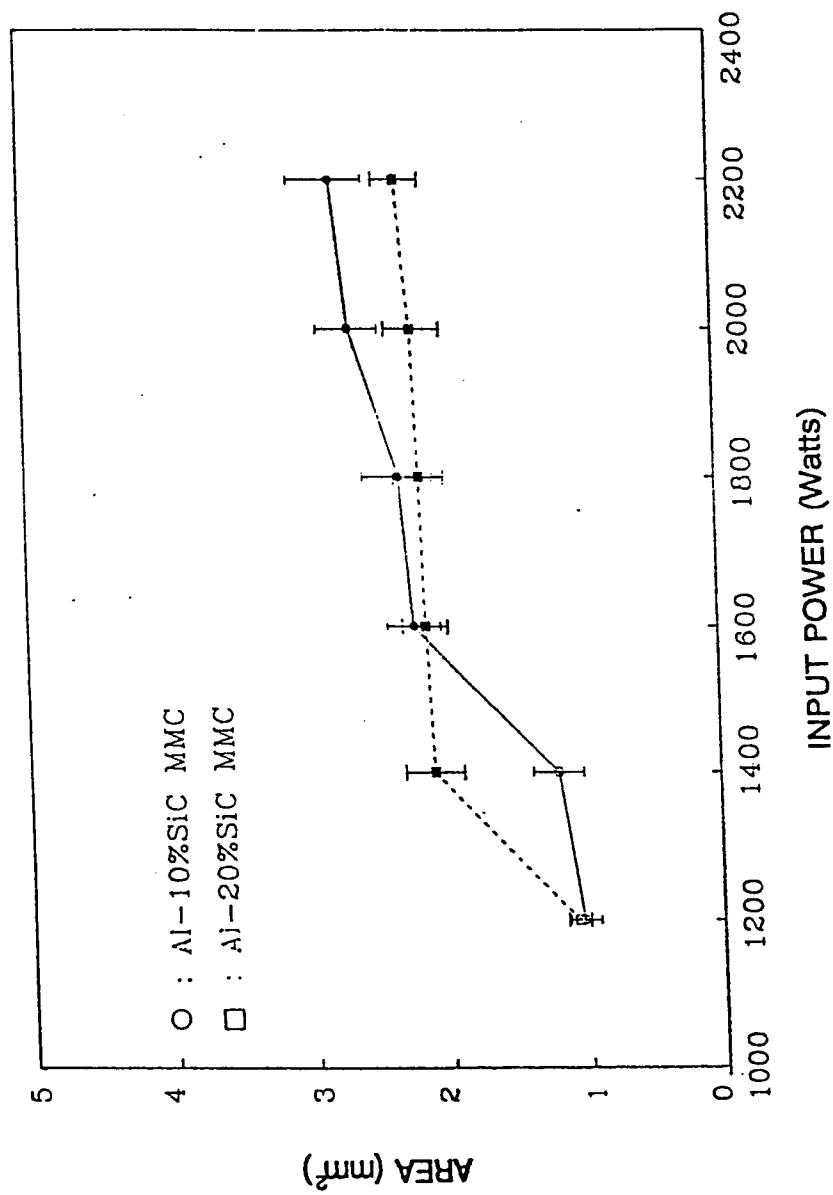


Figure 14. Effect of input laser power on the measured Al_4C_3 cross section areas for Al-10%SiC MMC and Al-20%SiC MMC. (Filled squares/circles represent full penetration)

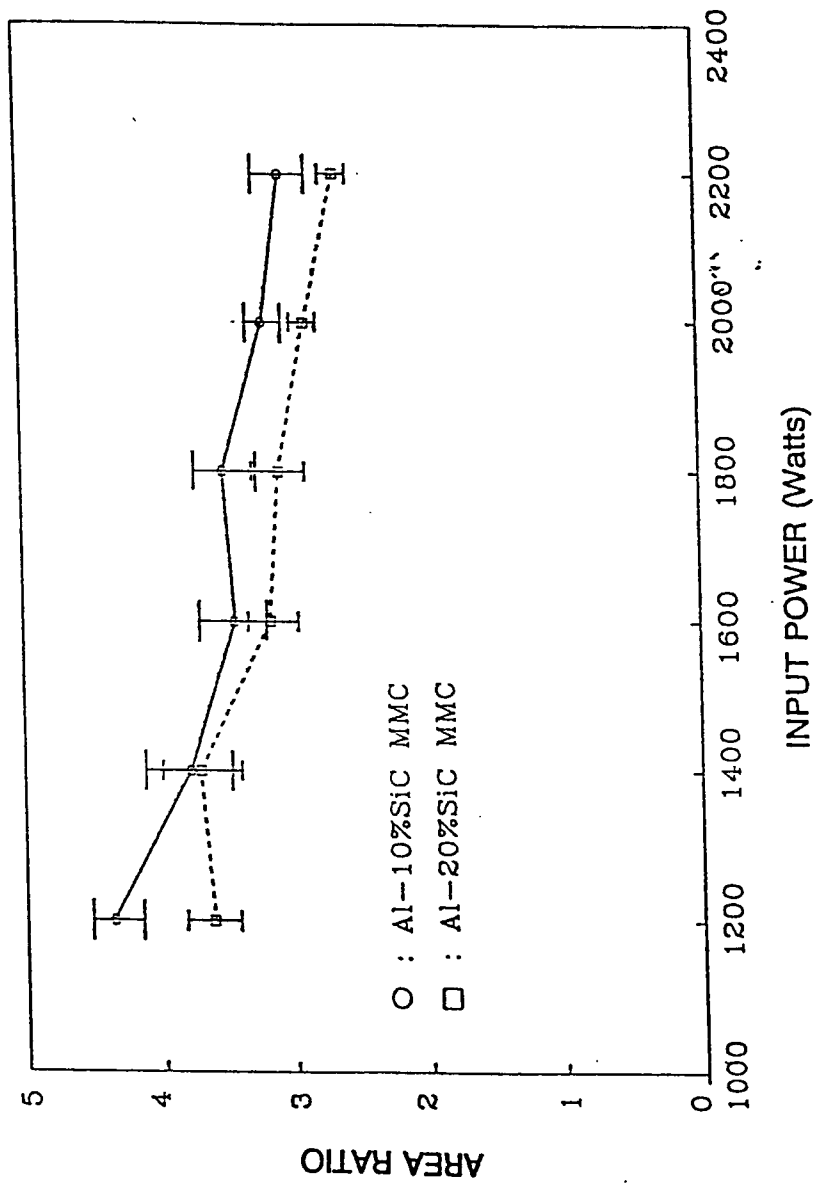


Figure 15. Effect of input laser power on the Al_4C_3 area: weld area ratios for Al-10%SiC MMC and Al-20%SiC MMC.

(C) RESULTS FROM TEMPERATURE-TIME MEASUREMENT EXPERIMENT

The temperature-time data collected by the high speed temperature measurement system during laser processing of the MMC's was reduced and plotted. It was observed that the peak temperature of the thermocouples decreased with their distance from the weld centerline. These temperature-time plots were used later in order to validate the predictions of the analytical code. A typical resulting temperature-time curve is illustrated in Figure 16. The temperature-time curves obtained during the laser processing experiment are illustrated in Appendix 4.

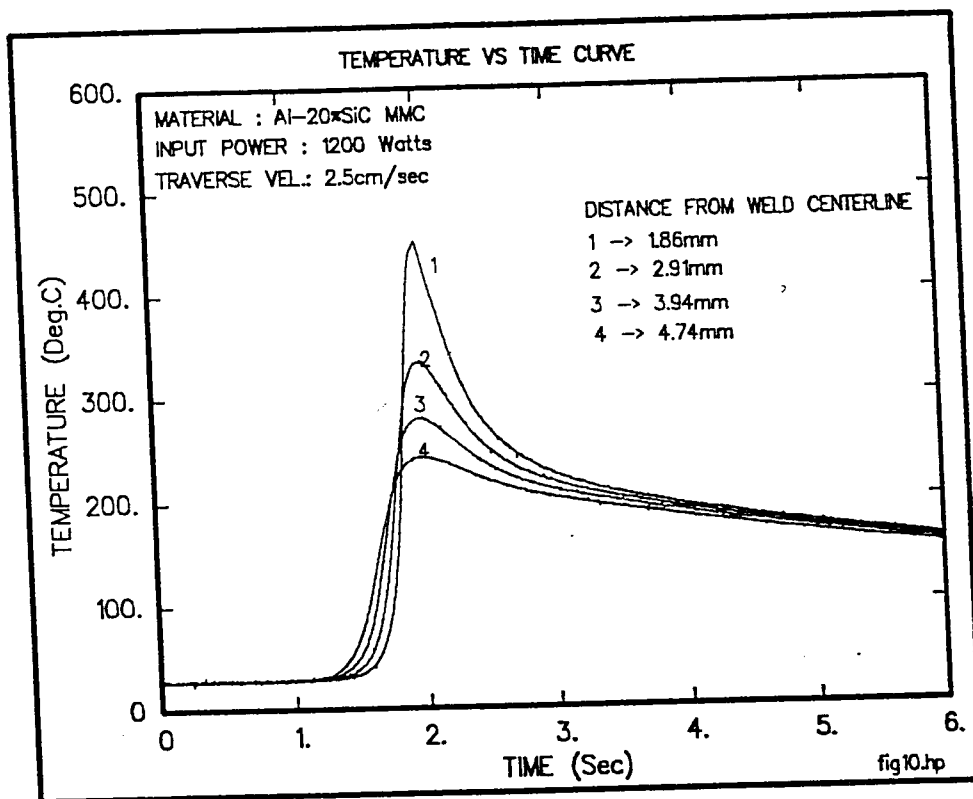


Figure 16. Typical measured temperature-time plot.

CHAPTER 6

ANALYTICAL MODEL DEVELOPMENT

(A) DERIVATION OF THE MODEL

The analytical model developed for this research is based on Rosenthal's solution to a moving line source problem (21). Initially, the point source solution is derived and it is then extended into the line source solution. The heat source is a laser beam which is assumed to be stationary while the sample is moved relative to the beam in the positive X-direction. The coordinate system is stationary with its origin at the center of the weld pool (where the laser beam is incident on the sample) as illustrated in Figure 17.

Heat flow in the sample which is assumed to be a semi-infinite plate is described by the energy equation,

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 2\lambda \frac{\partial T}{\partial t} \quad (1)$$

where

$$\frac{1}{2\lambda} = \frac{k}{\rho C_p} = \text{thermal diffusivity} \left(\frac{\text{cm}^2}{\text{sec}} \right)$$

If heat energy is initially concentrated at a point, equation (1) describes how the energy will be spread throughout the material by the process of diffusion. The heat equation assumes that thermal properties of the material are

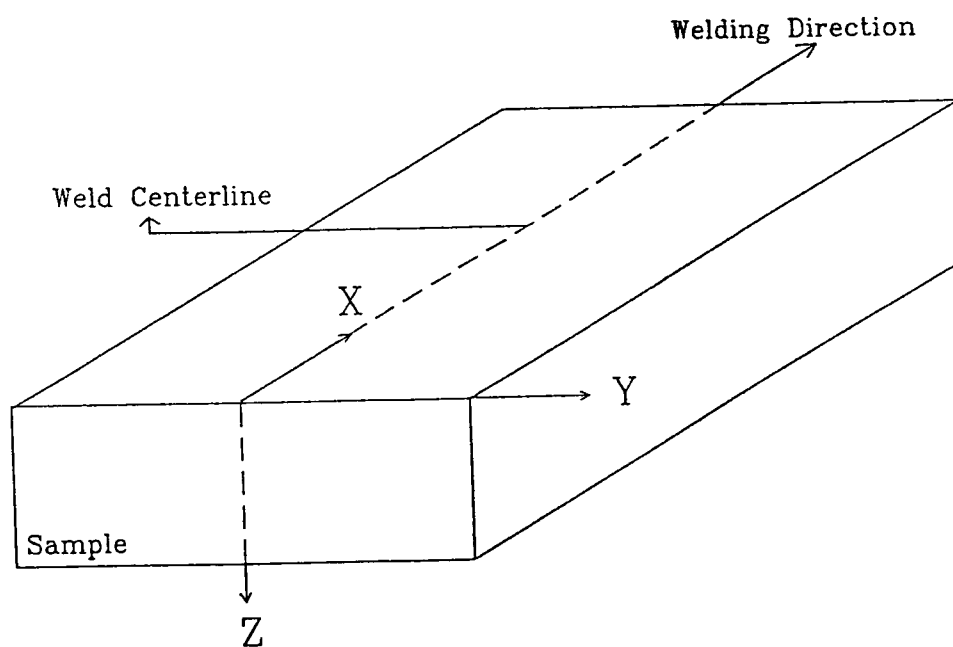


Figure 17. The coordinate system used in the analytical model.

constant and independent of temperature and that there are no sources present.

In order to account for the quasi-stationary state, the origin is transferred to the moving source via the coordinate transformation,

$$\xi = x - vt$$

where x = direction of welding

Equation (1) becomes,

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = -2\lambda v \frac{\partial T}{\partial \xi} + 2\lambda \frac{\partial T}{\partial t} \quad (2)$$

Assuming a quasi-stationary state requires that, $\partial T / \partial t = 0$ and equation (2) becomes

$$\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = -2\lambda v \frac{\partial T}{\partial \xi} \quad (3)$$

This equation has a solution of the form

$$T = T_o + e^{-\lambda v \xi} \psi(\xi, y, z)$$

Upon substitution, the governing equation becomes

$$\frac{\partial^2 \psi}{\partial \xi^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} = (\lambda v)^2 \psi \quad (4)$$

Now, in cylindrical coordinates, $r^2 = y^2 + z^2$

Equation (4) can be rewritten to become,

$$\frac{\partial^2 \psi}{\partial \xi^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial r^2} = (\lambda v)^2 \psi \quad (5)$$

This equation has a solution of the form,

$$\psi = C \frac{e^{-\lambda v R}}{R} \quad (6)$$

where

$$R = \sqrt{\xi^2 + r^2},$$

$$C = \frac{Q_p}{2\pi k},$$

and Q_p = total power input in Watts,

The temperature field is therefore

$$T - T_o = \frac{Q_p}{2\pi k} e^{-\lambda v \xi} \frac{e^{-\lambda v R}}{R} \quad (7)$$

Equation (7) is the point source solution obtained by Rosenthal (21). Now the point source solution is extended into a line source solution in the following manner. The line source is considered as a series of point sources placed along the depth of the material, i.e. along the z-axis of the sample. If q represents the heat input per unit depth, then the heat input over a depth $\Delta z'$ will be $q\Delta z'$. Hence the temperature rise $\Delta(T-T_o)$ at a point at a distance R' from such a source will be

$$\Delta (T - T_o) = \frac{q \Delta z'}{4\pi k} e^{-\lambda v \xi} \frac{e^{-\lambda v R'}}{R'} \quad (8)$$

The line source solution is obtained by integrating over a series of point sources, i.e.,

$$T - T_o = \int \frac{q dz'}{4\pi k} e^{-\lambda v \xi} \frac{e^{-\lambda v R'}}{R'} \quad (9)$$

where

$$R' = \sqrt{\xi^2 + y^2 + (z - z')^2}$$

The laser beam is assumed to be a line source of heat. The distribution of energy along this line source is, however, neither constant nor linear. Mazumder et al (20) assumed that the laser beam energy absorption by the vapor and the plasma reduced exponentially with depth and that it followed Beer Lambert's Law, i.e., $q = q_s e^{-\beta z}$.

In order to account for convection effects, the present model assumes that laser energy absorption by the plasma follows a Modified Beer Lambert's Law which is expressed below as

$$q = q_0 e^{-\beta^* z}$$

Substituting for q in the line source equation yields

$$T - T_o = \frac{q_o}{2\pi k} e^{-\lambda v \xi} \int_0^g e^{-\beta^* z'} \frac{e^{-\lambda v R'}}{R'} dz' \quad (10)$$

Expanding the exponential in β^* using a Fourier Cosine series,

$$e^{-\beta^* z} = a_o + \sum_1^{\infty} a_n \cos \frac{n\pi z}{g}$$

Hence the temperature field is given by

$$T - T_o = \frac{q_o}{2\pi k} e^{-\lambda v \xi} \int_0^{\infty} \left(a_o + \sum_1^{\infty} a_n \cos \left(\frac{n\pi z}{g} \right) \right) \frac{e^{-\lambda v R'}}{R'} dz' \quad (11)$$

Using an approximation that

$$\int_0^{\infty} \frac{e^{-\lambda v R'}}{R'} \cos \frac{n\pi z'}{g} dz' = K_o \left[r' \sqrt{(\lambda v)^2 + \left(\frac{n\pi}{g} \right)^2} \right] \cos \frac{n\pi z}{g}, \quad (12)$$

the solution (11) takes the form,

$$T - T_o = \frac{q_o}{2\pi k} e^{-\lambda v \xi} \left[a_o K_o(\lambda v r') + \sum_1^{\infty} a_n K_o \left(r' \sqrt{(\lambda v)^2 + \left(\frac{n\pi}{g} \right)^2} \right) \cos \frac{n\pi z}{g} \right] \quad (13)$$

where

$$r' = \sqrt{\xi^2 + y^2}$$

The term q_o must still be addressed. This term describes the heat input per unit length into the sample and is defined below as a function of the total heat input αQ_o , and β^* ,

$$\int_0^g q(z) = \alpha Q_o = \int_0^g q_o e^{-\beta^* z} dz'$$

Hence

$$q_o = \frac{\alpha Q_o}{\int_0^g e^{-\beta^* z'} dz'} \quad (14)$$

Substituting this result into equation (13) obtains the final temperature distribution equation.

$$T - T_o = \frac{\alpha Q_o}{2\pi k \int_0^g e^{-\beta^* z'} dz'} e^{-\lambda v t} [a_o K_o(\lambda v r') + \sum_1^{\infty} a_n K_o \left(r' \sqrt{(\lambda v)^2 + \left(\frac{n\pi}{g} \right)^2} \right) \cos \frac{n\pi z}{g}] \quad (15)$$

where

$$a_o = \frac{1}{g} \int_0^g e^{-\beta^* z'} dz'$$

and

$$a_n = \frac{2}{g} \int_0^g e^{-\beta^* z'} \cos \left(\frac{n\pi z'}{g} \right) dz'$$

(B) SOLUTION OF THE CODE

(i) Calculation of weld profiles

The analytical code was written to solve equation (15). First the temperature fields across a cross section of the material were calculated. The input parameters included the input power, absorption coefficients and absorption efficiency. The traverse velocity, fusion temperature criterion and the material properties were input through an input data file. The value of the x-coordinate and the time t were kept constant. For a given value of z , (starting at the surface, $z = 0$), the value of y was increased progressively in steps, and temperatures calculated, until the fusion temperature criterion of 900 K (627°C) was satisfied. These particular y and z coordinates were saved in a data file and the temperature fields were then calculated for the next increment in z . Upon plotting the above data file, the weld profiles for various conditions of input power were obtained.

(ii) Calculation of thermocouple temperatures

During the laser welding experiment, thermocouples had been placed on the surface of the MMC samples at known distances from the designated weld centerline and their temperature had been measured by the high speed temperature measurement system. The computer code developed in this section was verified by comparing the temperatures at various

input power conditions calculated by the model to the actual temperatures measured by the thermocouples during laser welding. In these runs the value of the z coordinate was $z = 0$, since the thermocouples were spot welded on the surface of the work-piece. The value of the x -coordinate was kept constant and temperature-time curves were calculated at y -coordinate positions that represented the distance of the thermocouples from the weld centerline.

(iii) Calculation of cooling rates

In order to calculate the cooling rate in the weld region, it was necessary to vary time, t , as well as the y and z coordinates. Starting at the surface, ($z = 0$), the temperature-time curves were calculated for successive values of y . A total of 360 temperature-time data points were calculated in a total time of 6 seconds, yielding a time step of 0.0166 seconds between readings. This time step was hard-wired into the code. The cooling rate at each data point was calculated by dividing the difference between successive temperature values by the time step. When the cooling rate reached the input value called the critical cooling rate, (discussed in Chapter 7, Section D) the y and z coordinate values were stored in a data file and cooling rate calculations were then made for the next increment of z . The selected critical cooling rate was included in the input file, and could be varied. The plot of the data file yielded the

region inside the fusion zone that experienced cooling rates and temperatures greater than the threshold cooling rate conditions. These were the areas in which Al_4C_3 was predicted to form. The above predicted areas were later compared to the actual Al_4C_3 areas measured in the laser treated composites.

The codes developed in order to perform the above-mentioned calculations have been listed in Appendices 5 and 6.

CHAPTER 7

COMPUTATION RESULTS AND COMPARISON WITH THE EXPERIMENTAL RESULTS

(A) THE EFFECT OF INPUT VARIABLES ON THE WELD PROFILE

The analytical model described in the previous section computed temperature profiles and cooling rates based upon the effect of input power, absorption efficiency α and the combined coefficient of absorption β^* . This model was used in order to estimate the critical conditions for the formation of Al_4C_3 .

The absorption efficiency α determines the total amount of incident radiation absorbed by the material within the keyhole. The absorbed energy is distributed along the thickness of the sample in the manner dictated largely by the absorption coefficient, β_0 . However, penetration effects lead to a change in the shape of the bottom of the weld, since, in full penetration welding, the plasma emerging through the bottom of the keyhole radiates heat to the bottom of the weld, resulting in the widening of the weld at the bottom. Since Beer Lambert's Law dictates an exponentially decreasing cross section, a modified, depth dependent absorption coefficient, β_1 was introduced in order to account for the shape of the bottom of the weld cross-section.

Figure 18 shows the effect of α on the weld profile for a typical case. It is seen that for a given incident power, an increase in α results in higher absorbed power into the material and hence larger weld areas. Any change in the value of α results in changes in area as well as top and bottom bead widths and penetration depths of the welds.

The effect of β^* is a combination of the effects of β_0 and β_1 . The factor β_0 affects the heat distribution and hence the weld profile through the entire thickness of the material. Figure 19 illustrates the effect of β_0 on the weld shape for a selected case. It is observed that an increase in the value of β_0 results in the increased curvature of the weld profile. Figure 20 illustrates the effect of β_1 on the weld profile for a selected case. β_1 is observed to primarily affect the heat distribution at the bottom of the weld profile since it is the coefficient of the z^2 term in the Modified Beer Lambert's Law, and this term contributes significantly to the heat input into the material only at the bottom of the weld.

It should be noted that the governing equations in the analytical model were not non-dimensionalized. The effect of β_1 on the heat distribution is small as compared to that of β_0 since the thickness of the sample is 0.25 cm. In order to use this model in samples with higher thicknesses, (greater than 1 cm), the equations will be required to be non-dimensionalized.

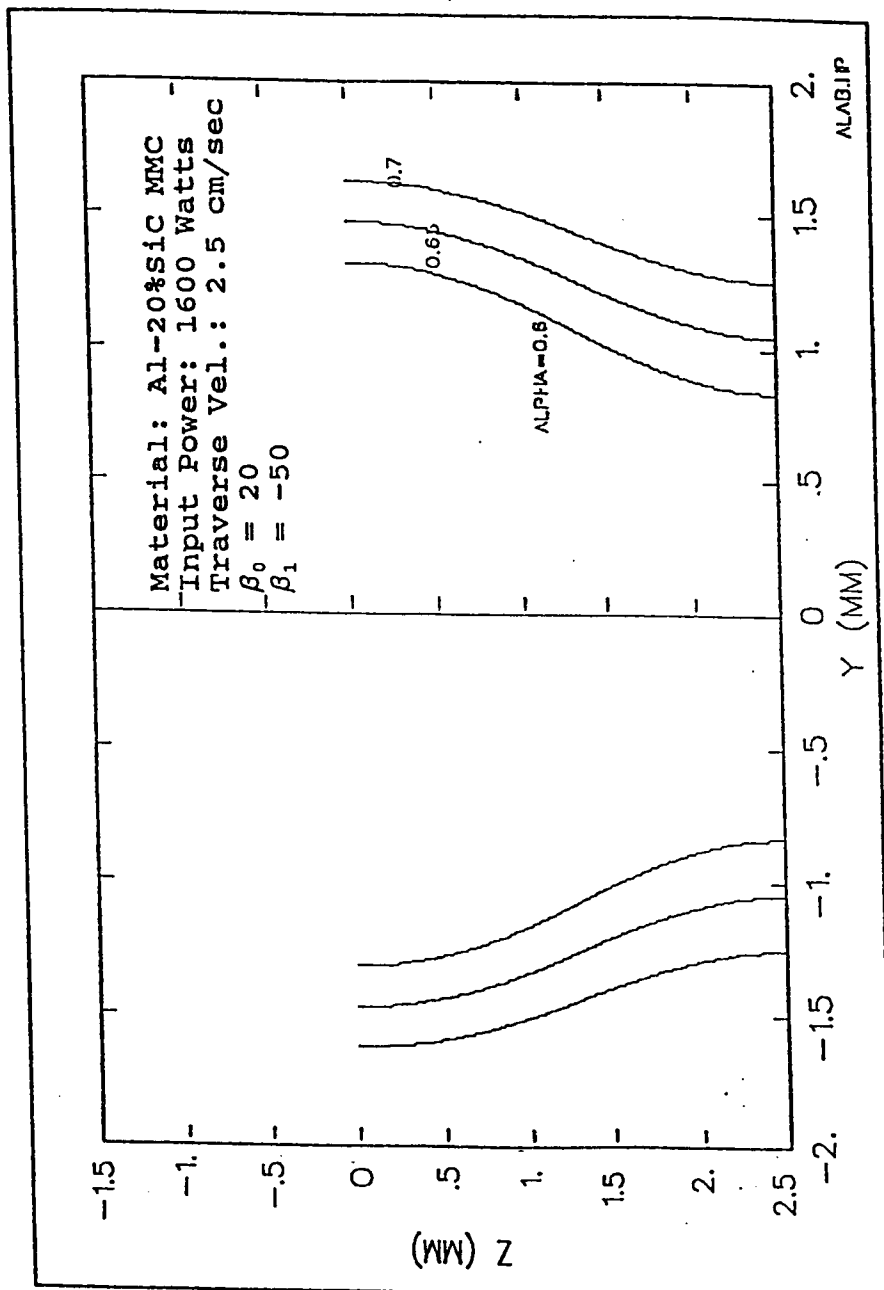


Figure 18. Effect of absorption efficiency α on the weld profile.

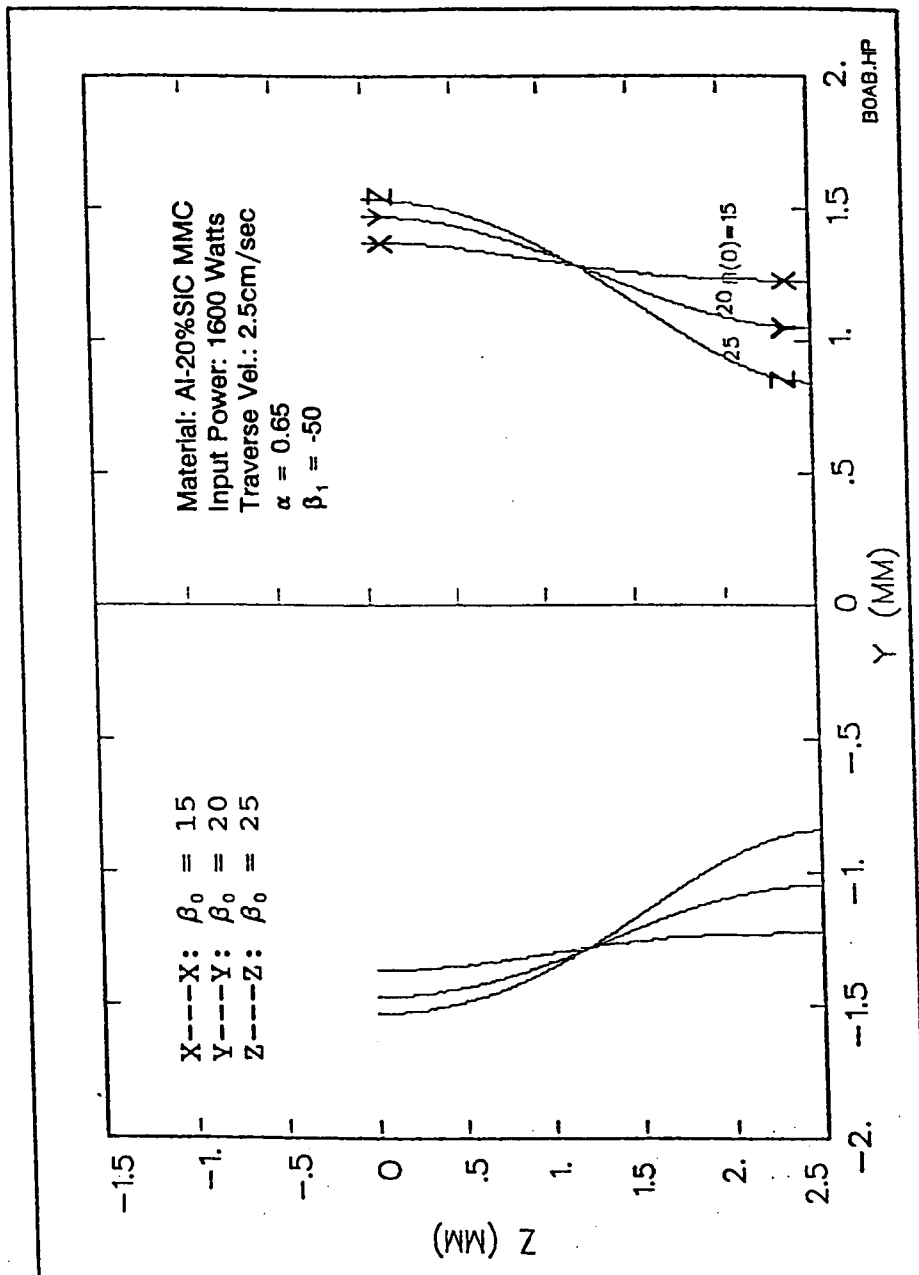


Figure 19. The effect of changes in absorption coefficient β_0 on the weld profile.

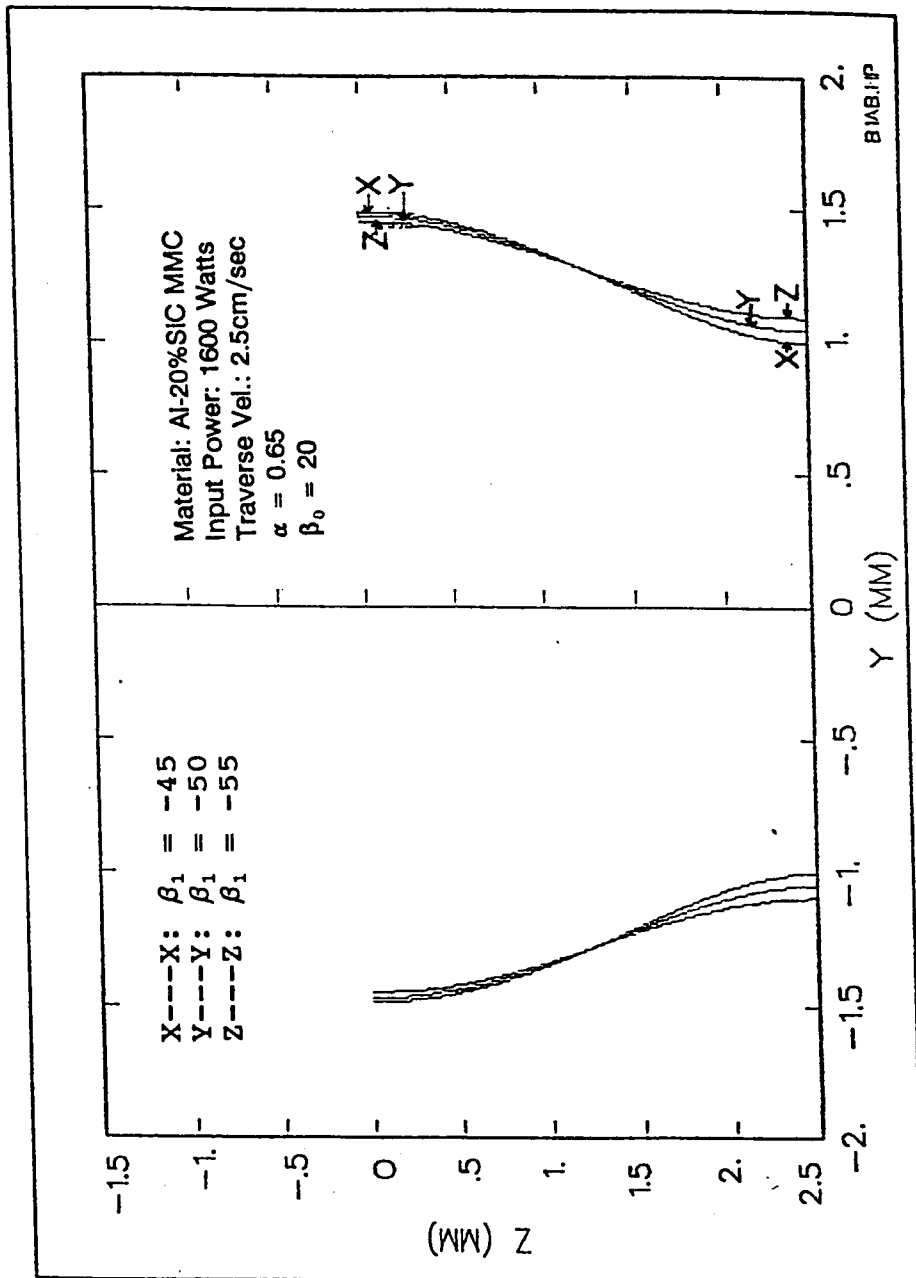


Figure 20. The effect of changes in modified absorption coefficient β_1 on the weld profile.

(B) CALCULATION OF WELD PROFILES AND COMPARISON WITH ACTUAL EXPERIMENTS

The model was first applied in order to duplicate the weld profiles of Al-20%SiC MMC and the Al-10%SiC MMC by varying the absorption efficiency α and the absorption coefficient parameters β_0 and β_1 for different input power conditions. The temperature fields produced during in the weld region were calculated by the model. The 900 K (627°C) isotherms represented the weld profiles. Once the weld profiles were obtained, the validity of the results was checked by comparing the peak temperatures from the temperature-time curves generated for each material at each input power condition, with the experimentally measured peak temperatures.

No information on the value of absorption coefficient for these materials was available in the literature. However, Mazumder et al (20) had calculated the value of 7 cm^{-1} for the absorption coefficient of steel. He also found that this absorption coefficient remained constant for that material for all input laser energies. Hence, β_0 for each of the MMC's was kept constant for all input power conditions while running the code. Starting from this baseline value for β_0 and using a reasonable value for the absorption efficiency, the β_0 value that yielded a weld profile close to that of the experimental weld profile was determined. The actual value for the

absorption efficiency α was then determined by determining the value of α that yielded a top bead width similar to that of the actual laser processed sample. It was found that, for values of $\beta_0 = 15 \text{ cm}^{-1}$ and $\beta_0 = 20 \text{ cm}^{-1}$ for Al-10%SiC MMC and Al-20%SiC MMC respectively, the computed weld profiles roughly matched the experimentally determined weld profiles. The values of α that yielded weld top bead widths close to the experimentally determined top bead widths ranged from 0.51 to 0.63 for Al-10%SiC MMC and from 0.54 to 0.68 for Al-20%SiC MMC. The match between the profiles was rough since the change in the shape of the bottom of the weld was not taken into account. This problem was addressed by the β_1 term in the Modified Beer Lambert's Law. With the introduction of the β_1 term into the calculations, the calculated weld profiles matched the experimentally determined profiles more closely. The actual and calculated weld profiles were matched by taking into account the top bead width, the bottom bead width and the shape of the weld region. Two regimes were observed in the values of β_1 , one before and one after full penetration. Higher values of β_1 resulted in weld shapes with narrow bottoms. These were used in order to generate weld profiles before full penetration. Lower values of β_1 resulted in weld profiles with widened bottoms, and these values were used in full penetration cases. A flow chart of the procedure used for determining the variables α , β_0 and β_1 is shown in Figure 21. The values of α , β_0 and β_1 that were used in order to

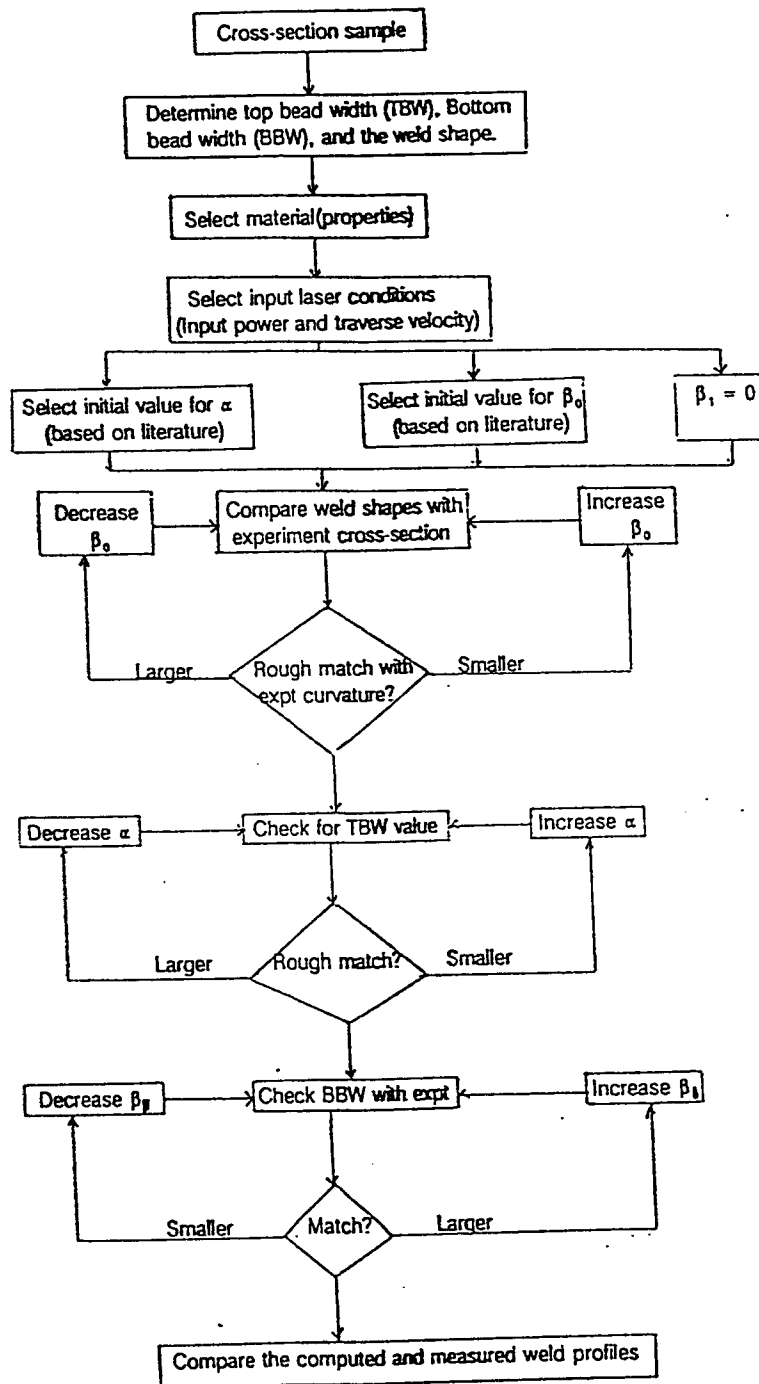


Figure 21. Flow chart of the procedure used in determining the values of α , β_0 and β_1 in the code.

match weld profiles were subsequently used in order to predict temperatures and cooling rates throughout the weld cross-section and these have been illustrated in Table III. The actual and computed weld profiles for the two MMCs are illustrated in Figures 22 and 23 respectively.

In the case of A356 Al, it was observed that the welds, for the lower power conditions between 1000 Watts and 1800 Watts, obeyed the point source solution, (equation 7 in the analytical model derivation) resulting in the formation of conduction welds. However, at power levels above 2000 Watts, the line source solution was obeyed by A356 Al and deep penetration keyhole welds were produced. The values of α , β_0 and β_1 for A356 Al for various input powers are listed in Table III.

(C) CALCULATION OF THERMOCOUPLE TEMPERATURES AND COMPARISON WITH ACTUAL EXPERIMENTS

The peak thermocouple temperatures recorded during the experiments were compared with those calculated by the analytical model. The comparison between the peak temperatures at the thermocouple locations for Al-20%SiC MMC and Al-10%SiC MMC's are illustrated in Figures 24 and 25 respectively. It was observed that the peak temperatures in the Al-20%MMC's, in general, gave a better comparison with the experimental values than that for Al-10%SiC MMC. This could

TABLE III: VALUES OF α , β_0 AND β_1 USED IN ORDER TO MATCH THE OBSERVED WELD PROFILES.

MATERIAL: A356 Al-20%SiC MMC

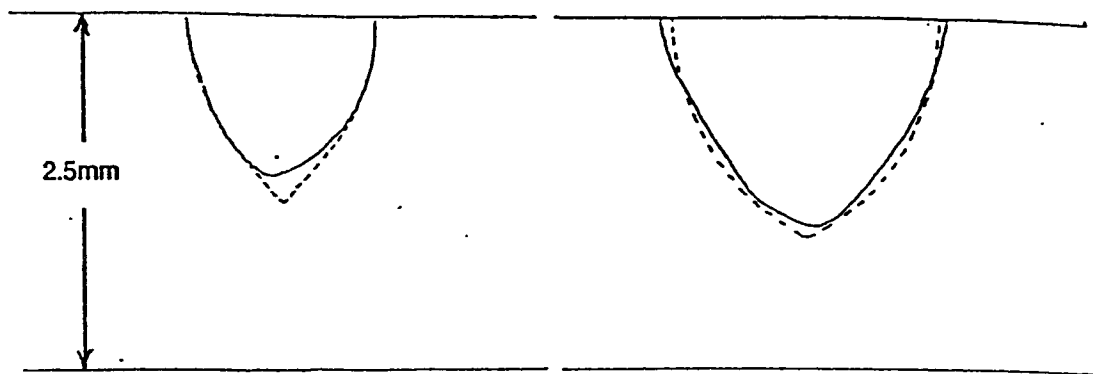
POWER	1000W	1200W	1400W	1600W	1800W	2000W	2200W
α	0.68	0.66	0.67	0.65	0.60	0.55	0.54
β_0	20	20	20	20	20	20	20
β_1	10	10	-50	-50	-50	-50	-50

MATERIAL: A356 Al-10%SiC MMC

POWER	1000W	1200W	1400W	1600W	1800W	2000W	2200W
α	0.51	0.58	0.59	0.63	0.59	0.58	0.55
β_0	15	15	15	15	15	15	15
β_1	60	60	60	15	15	15	15

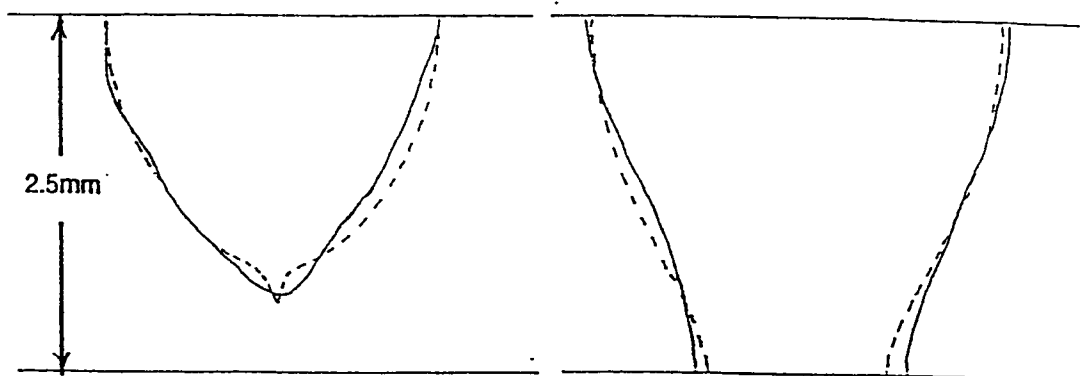
MATERIAL: A356 Al:

POWER	1000W	1200W	1400W	1600W	1800W	2000W	2200W
α	0.26	0.27	0.27	0.27	0.27	0.41	0.56
β_0	na	na	na	na	na	10	10
β_1	na	na	na	na	na	40	-20



(i) 1000 Watts

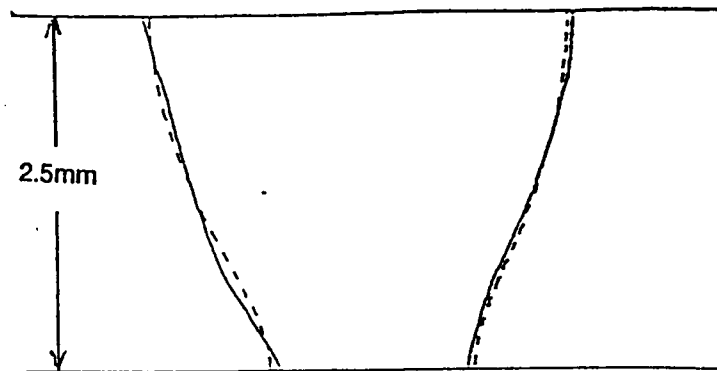
(ii) 1200 Watts



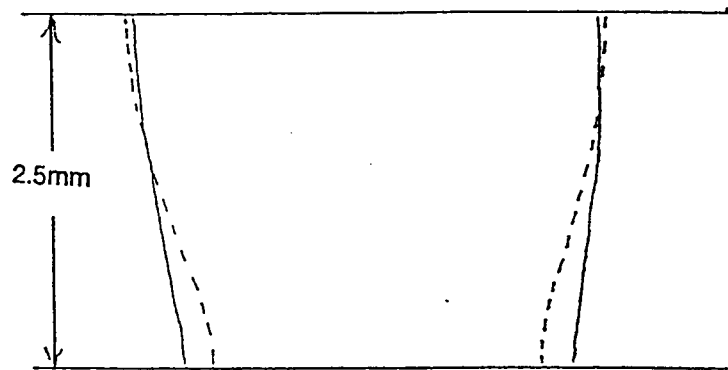
(iii) 1400 Watts

(iv) 1600 Watts

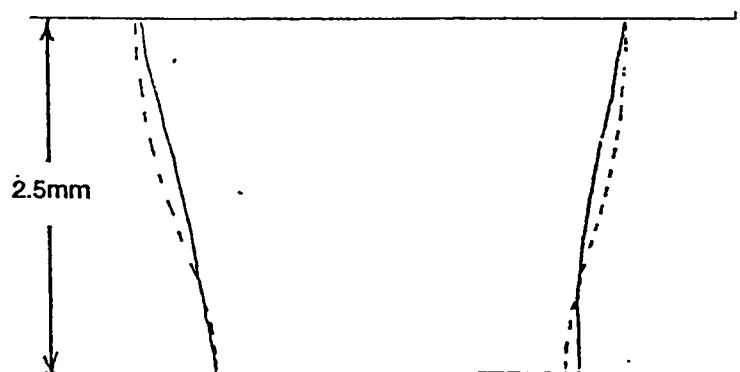
Figure 22. Comparison between the actual and computed weld profiles. Dashed and full lines represent the calculated and actual weld profile respectively. (Material: Al-20%SiC MMC)



(v) 1800 Watts

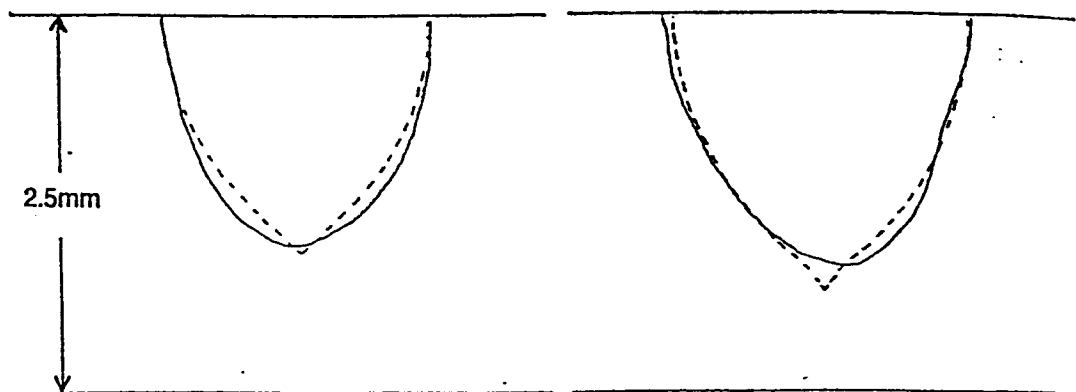


(vi) 2000 Watts



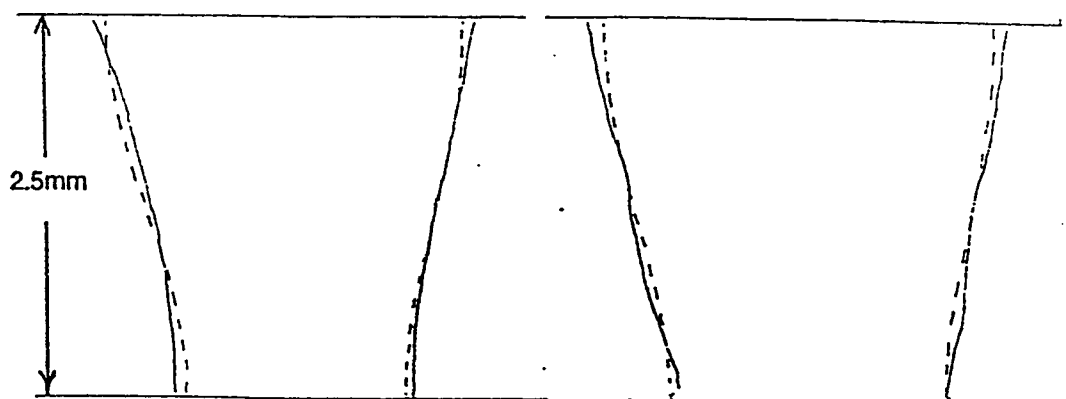
(vii) 2200 Watts

Figure 22. (continued)



(i) 1000 Watts

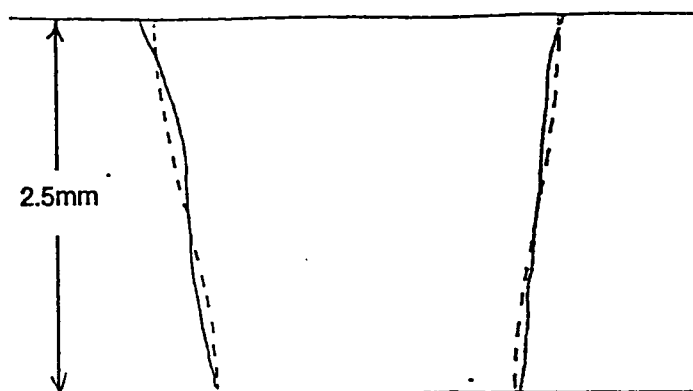
(ii) 1200 Watts



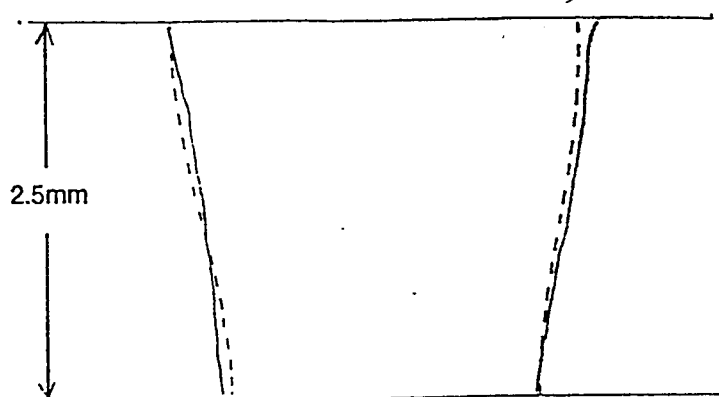
(iii) 1400 Watts

(iv) 1600 Watts

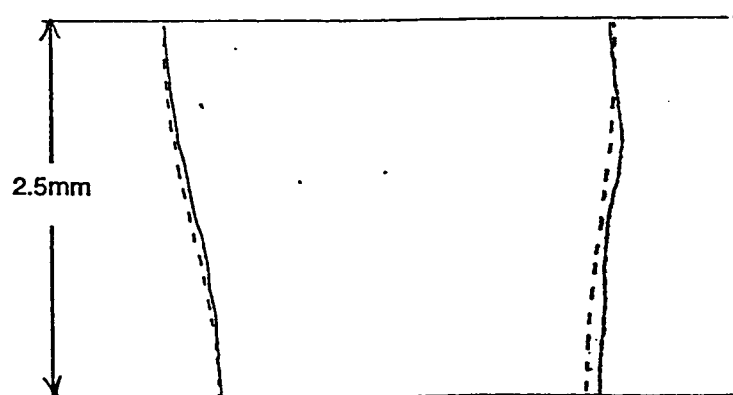
Figure 23. Comparison between the actual and computed weld profiles. Dashed and full lines represent the calculated and actual weld profile respectively. (Material: Al-10%SiC MMC)



(v) 1800 Watts

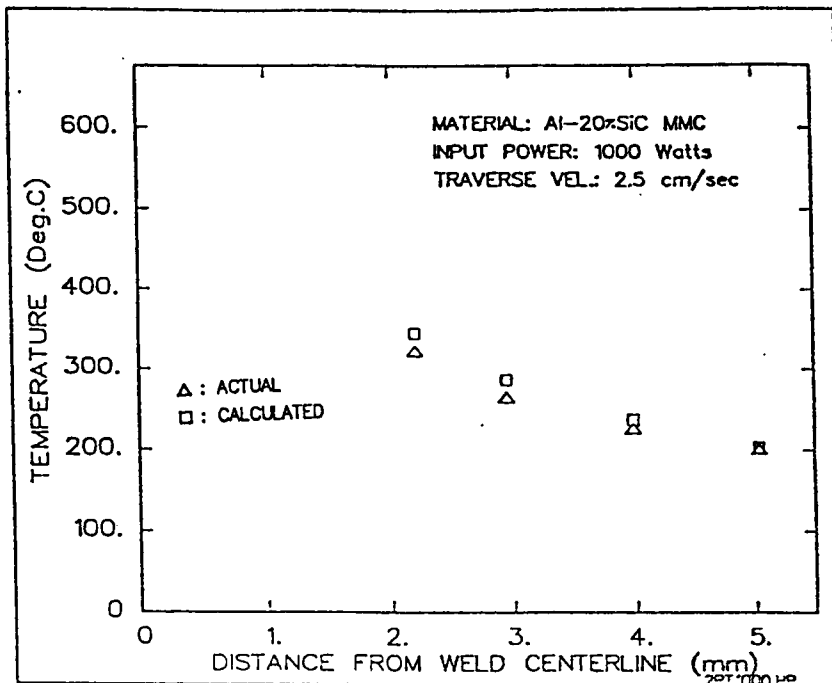


(vi) 2000 Watts

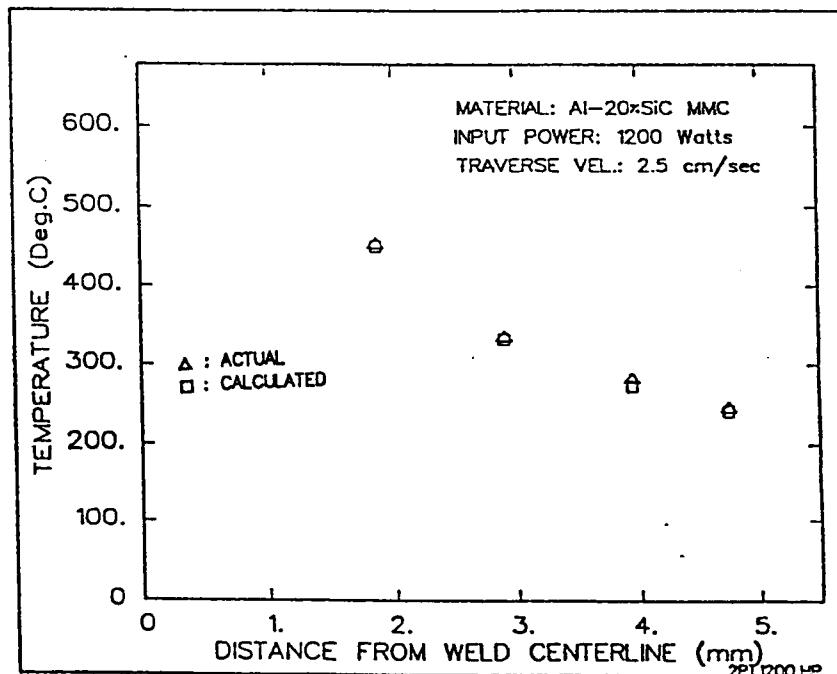


(vii) 2200 Watts

Figure 23. (continued)

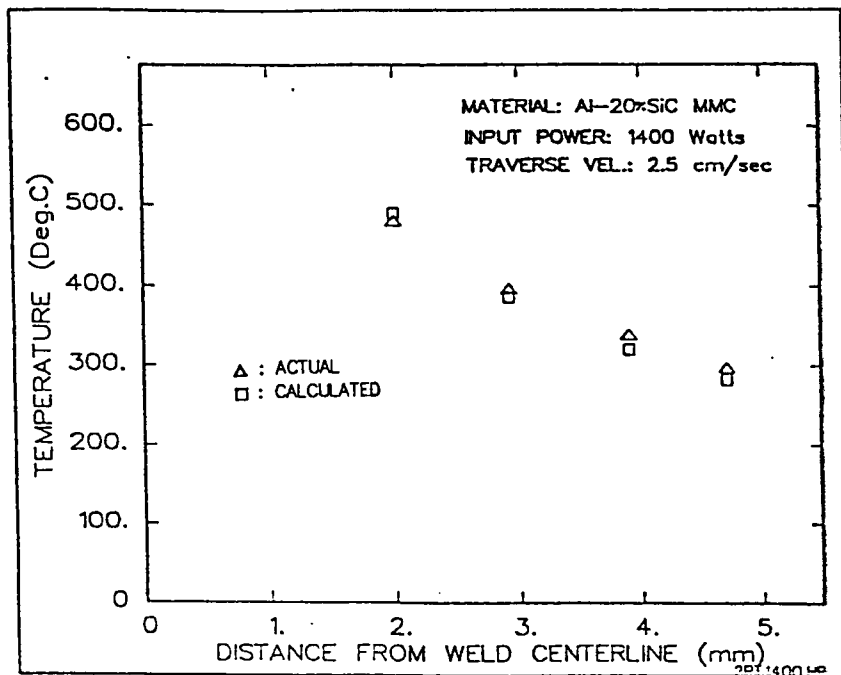


(i) Power: 1000 Watts

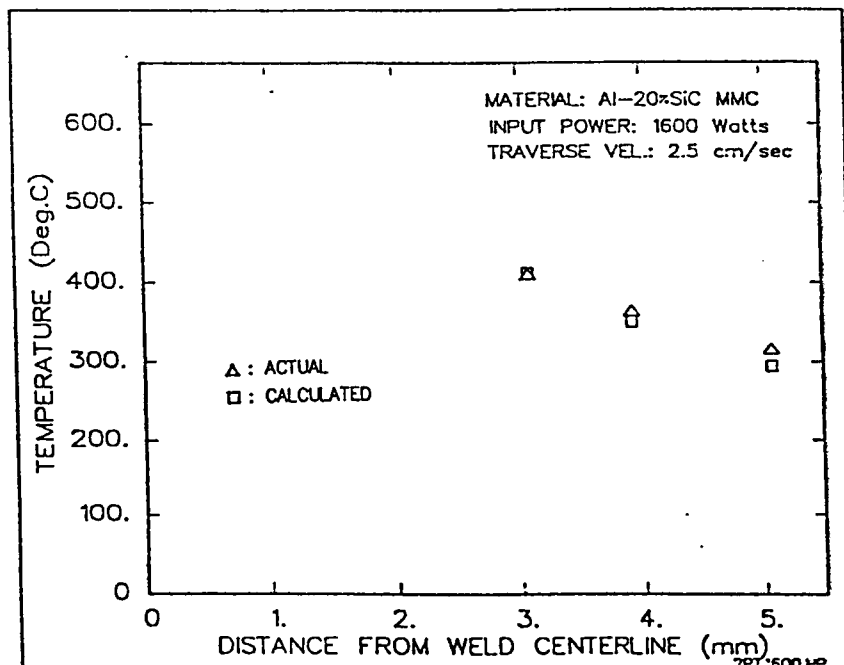


(ii) Power: 1200 Watts

Figure 24. Comparison between actual and calculated peak temperatures. (Al-20%SiC MMC)

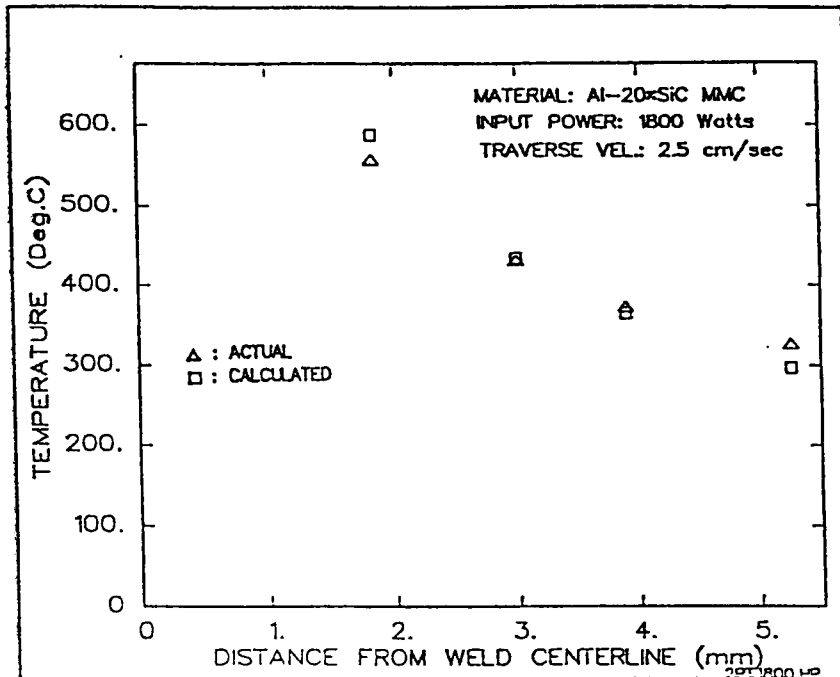


(iii) Power: 1400 Watts

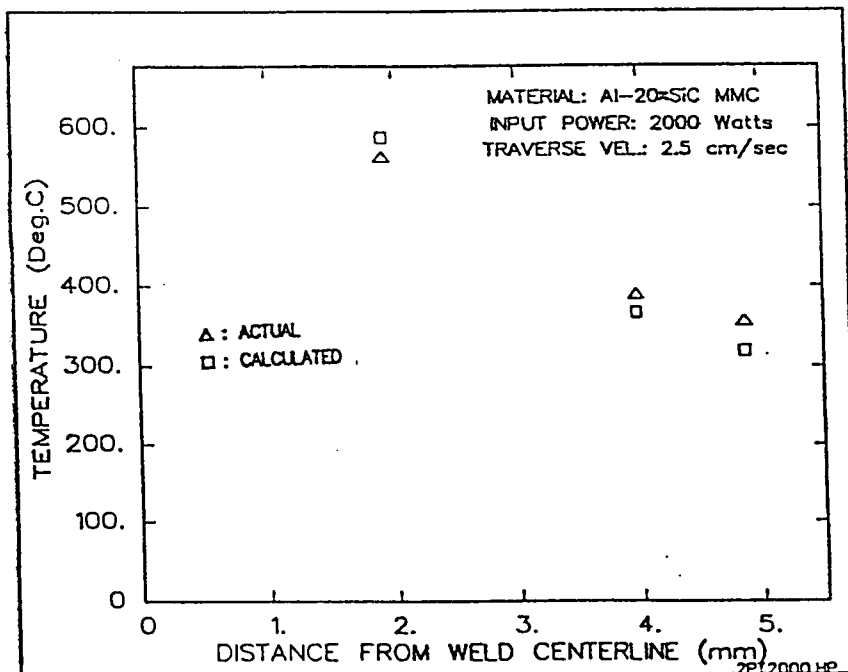


(iv) Power: 1600 Watts

Figure 24. (continued)

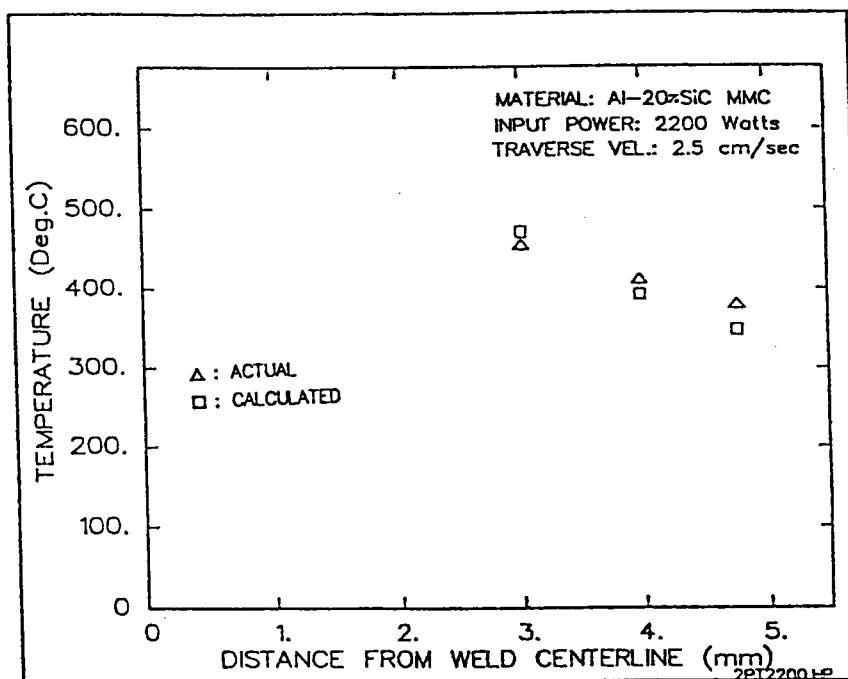


(v) Power: 1800 Watts



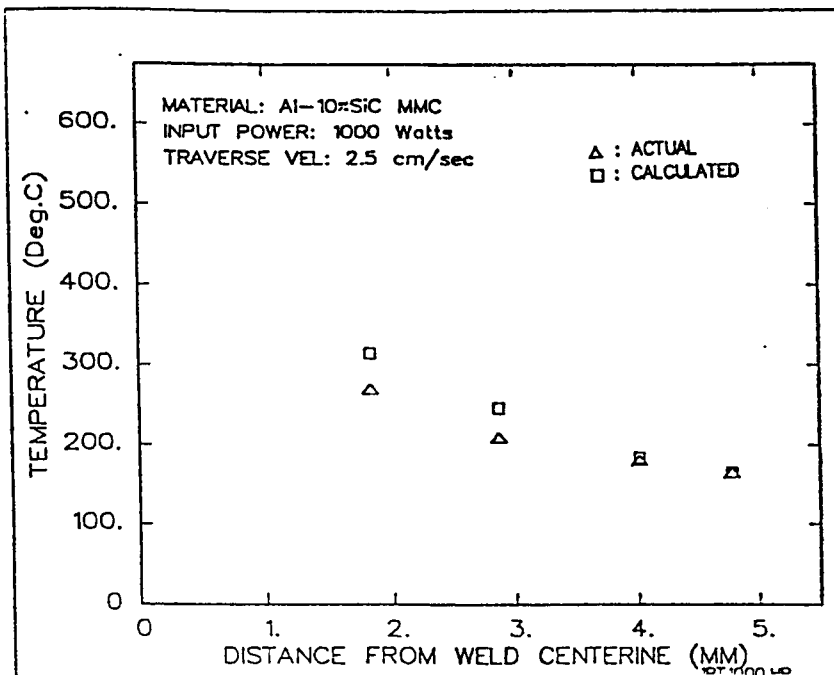
(vi) Power: 2000 Watts

Figure 24. (continued)

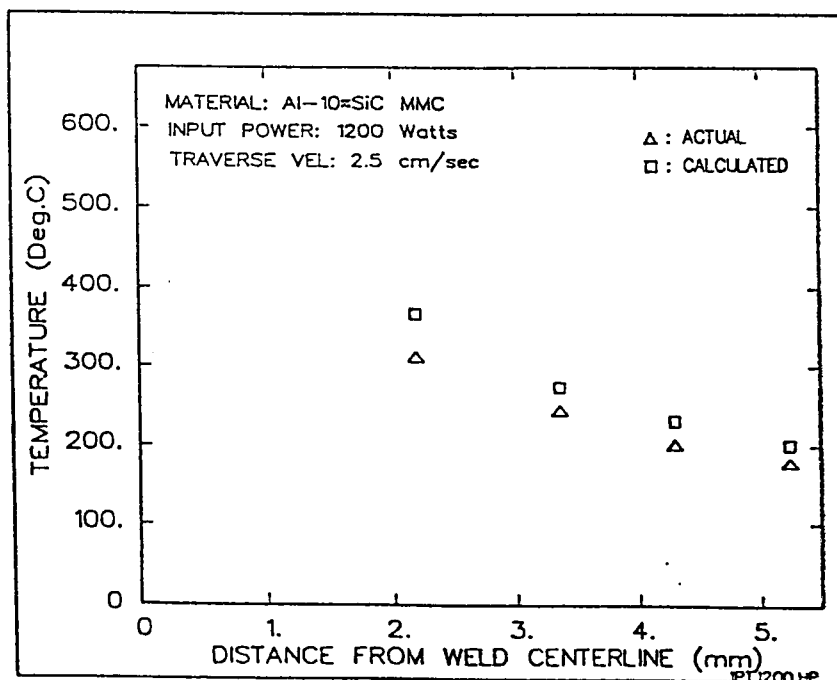


(vii) Power: 2200 Watts.

Figure 24. (continued)

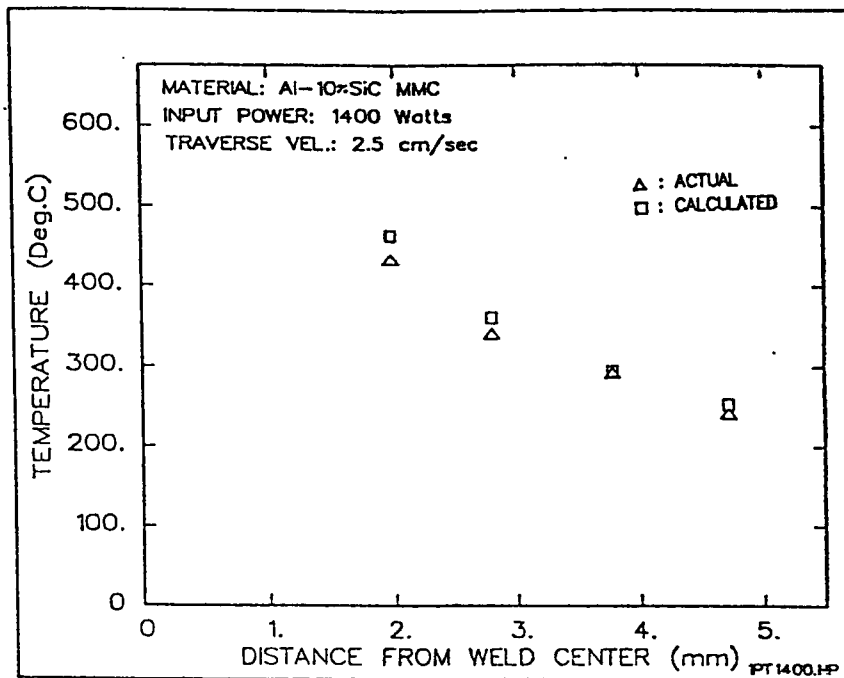


(i) Power: 1000 Watts

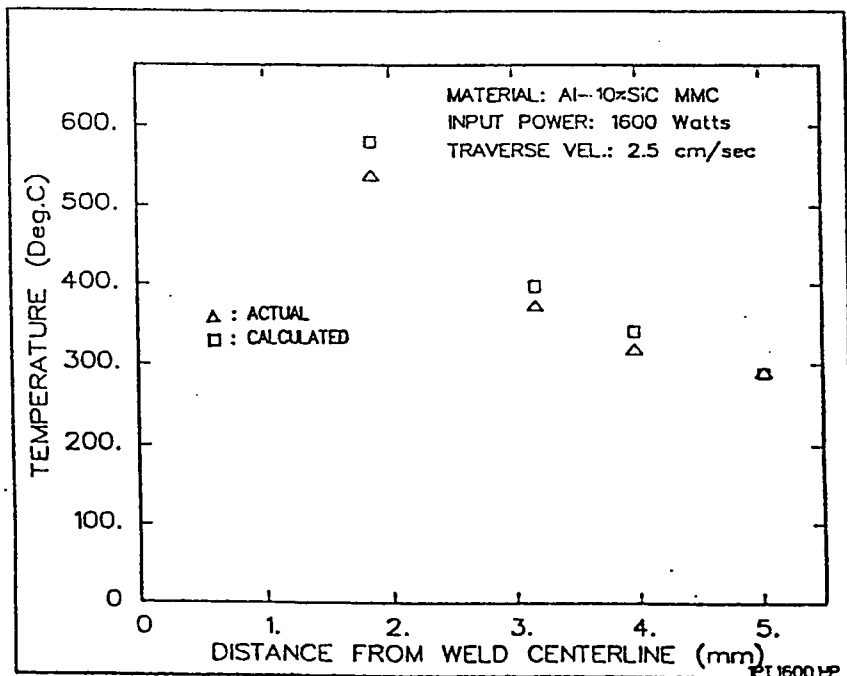


(ii) Power: 1200 Watts

Figure 25. Comparison between actual and calculated peak temperatures. (Al-10%SiC MMC)

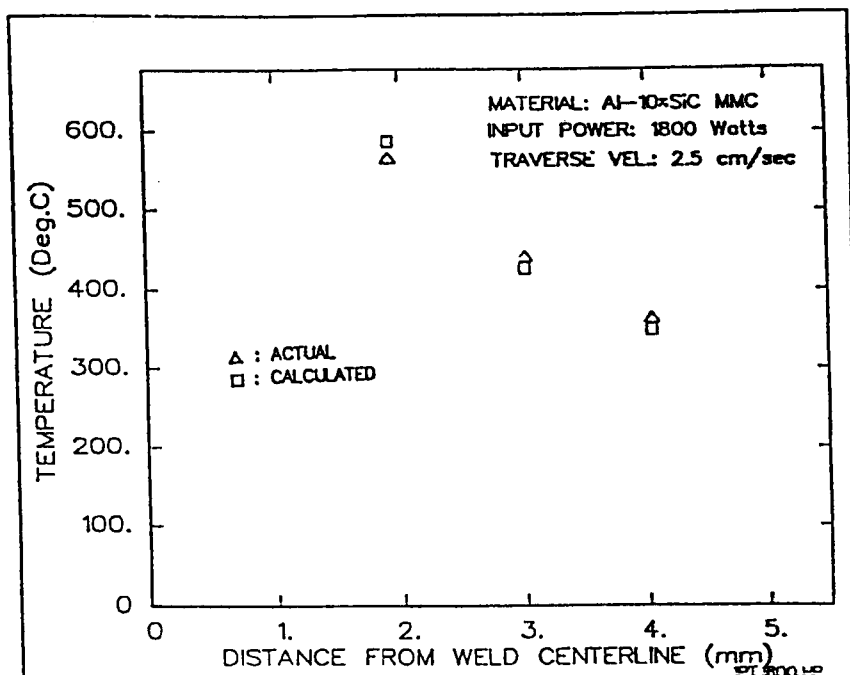


(iii) Power: 1400 Watts

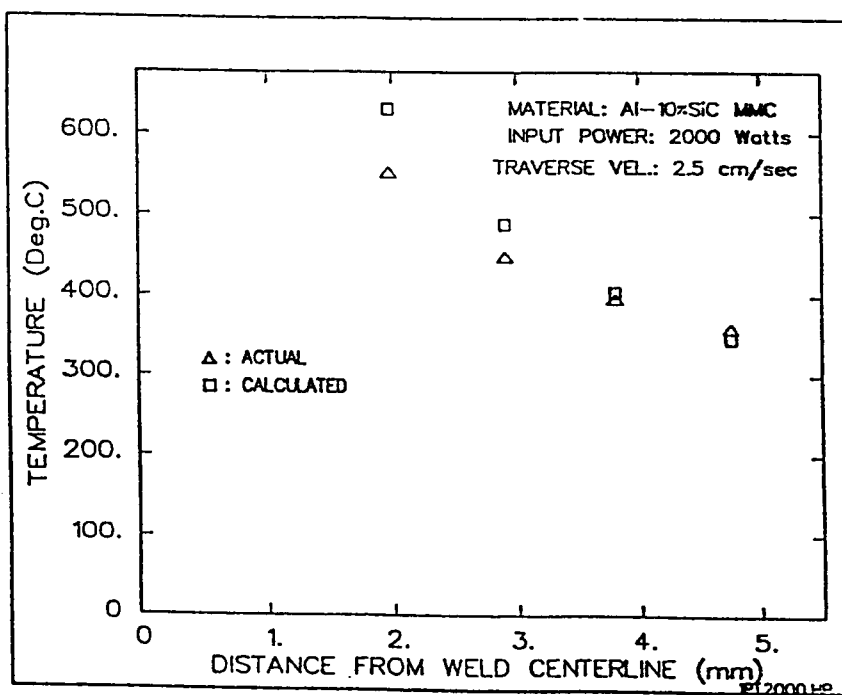


(iv) Power: 1600 Watts

Figure 25. (continued)

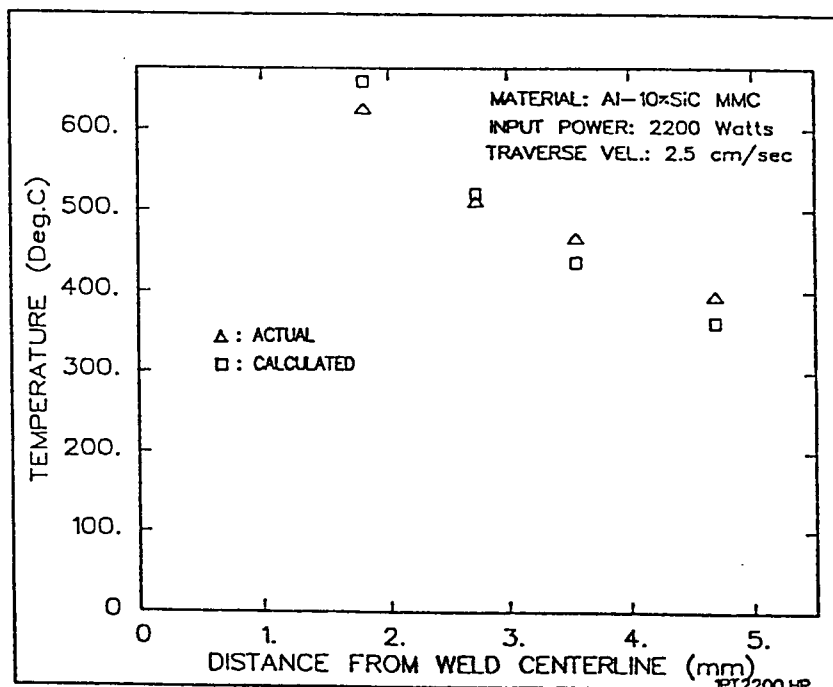


(v) Power: 1800 Watts



(vi) Power: 2000 watts

Figure 25. (continued)



(vii) Power: 2200 Watts.

Figure 25. (continued)

be the result of several factors such as the large inhomogeneity in the microstructure of Al-10%SiC compared to that in Al-20%SiC and improper contact between the thermocouple bead and the substrate material. It is also observed in plots in Figures 24 and 25 that some of the peak temperature points are missing. These were the points at which the thermocouple was damaged due to the intense heat from the plasma plume.

(D) CALCULATION OF ALUMINUM CARBIDE AREAS FOR Al-20%SiC MMC AND COMPARISON WITH ACTUAL EXPERIMENTS

It was now possible to get a reasonable estimate for the thermal fields that were produced inside the weld during the laser processing of the composites at various power levels. There are two factors that could affect the formation of aluminum carbide phase during laser processing, temperature and cooling rate. In order to study the importance of temperature on the formation of Al_4C_3 , the analytical code was solved using the values of α , β_0 and β_1 as calculated in Table III for various input threshold temperatures. The areas predicted by the code were compared with the actual Al_4C_3 areas. It was found that the temperature criterion alone did not compare well with the experimental results. Hence cooling rate was determined to be the governing factor in the formation of Al_4C_3 . Iseki et al (16) calculated that for a_{Si}

= 0.1, the free energy change for the formation of Al_4C_3 from the reaction between Al and SiC becomes negative at temperatures above 1100 K (827°C/sec). Hence this temperature was used in the analytical code as the minimum temperature for the formation of Al_4C_3 .

Using the model with the input conditions listed in Table III, the area of aluminum carbide formed was initially computed for varying threshold cooling rates for Al-20%SiC MMC. On comparing the results with the actual aluminum carbide area formed, it was found that at a threshold cooling rate of 12000 K/sec (12000°C/sec) the calculated aluminum carbide areas compared well with the experimentally determined aluminum carbide areas for the input power conditions used in this research. The comparison between actual and calculated aluminum carbide areas formed for Al-20%SiC MMC is illustrated in Figure 26.

(E) APPLICATION OF COOLING RATE CRITERION TO PREDICT ALUMINUM CARBIDE AREAS IN Al-10%SiC MMC

Having established the critical cooling rate criterion for Al-20%SiC, the same criterion of 12000 K/sec (12000°C/sec) was then utilized in order to predict the aluminum carbide area in the Al-10%SiC MMC for varying input powers and using the parameters listed in Table III. The actual, measured aluminum carbide areas and areas predicted by the code for the

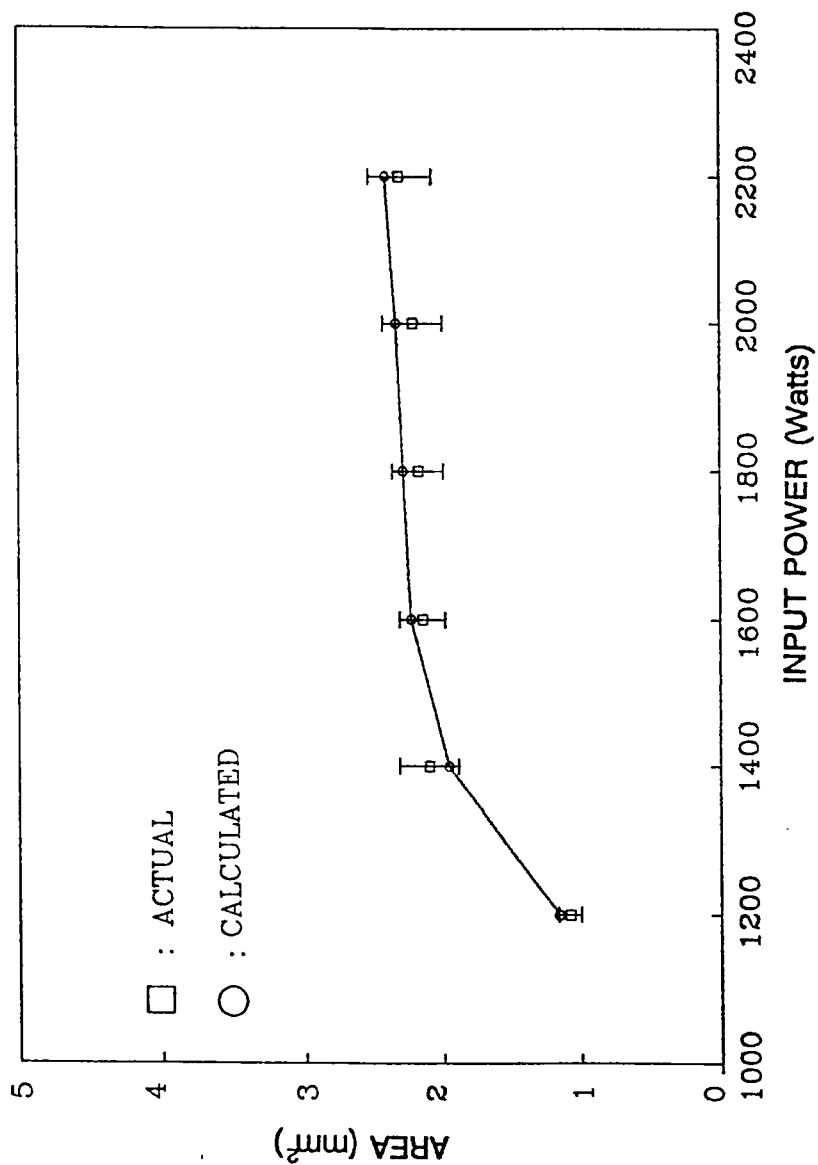


Figure 26. Comparison between the measured and computed Al₄C₃ areas. (Material: Al-20%SiC MMC)

Al-10%SiC MMC were found to be similar. This is illustrated in Figure 27.

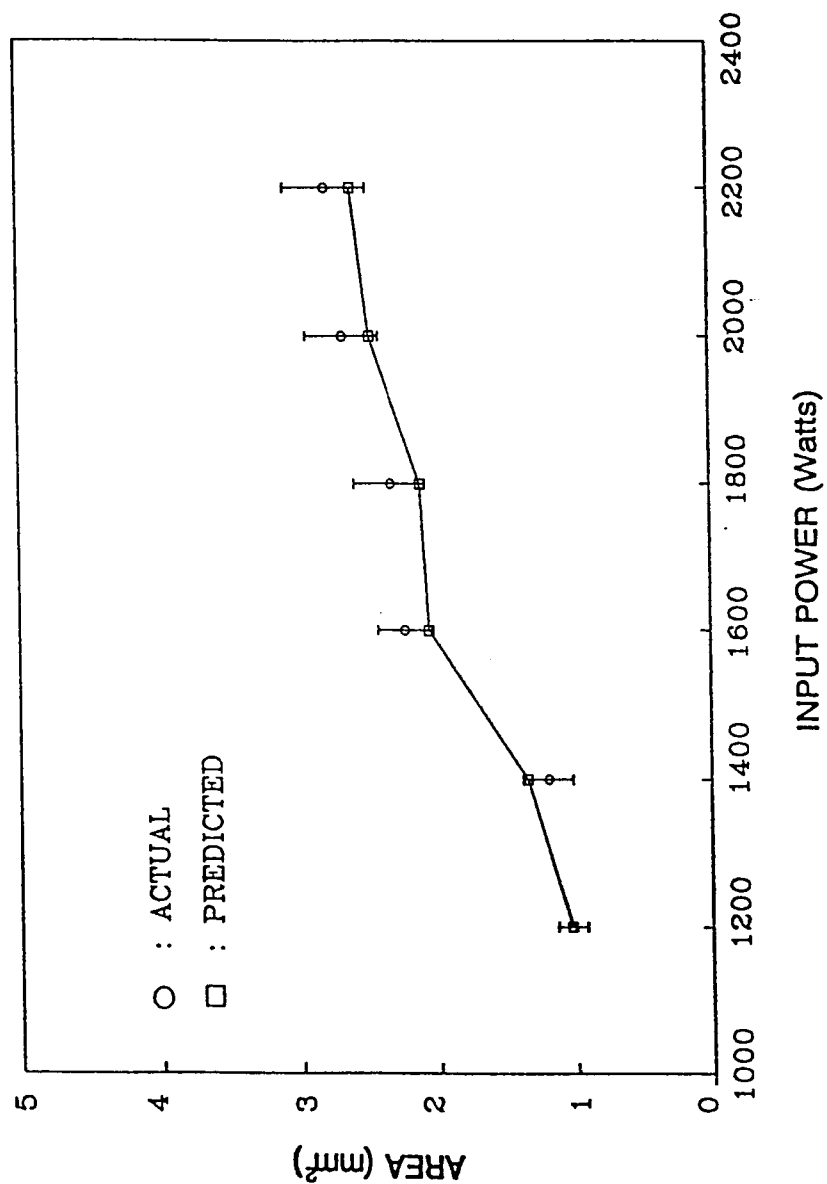


Figure 27. Comparison between the measured and predicted Al_4C_3 areas. (Material: Al-10%SiC MMC)

CHAPTER 8

DISCUSSION

The formation mechanism of the Al_4C_3 during laser processing is illustrated in Figure 28. It shows a SiC particle that has been attacked by the matrix aluminum. The Al_4C_3 phase has been nucleated and needles of Al_4C_3 have started to emerge from the SiC particle. This contrasts completely with the observations made by Iseki et al (16) under equilibrium conditions in which a thin reaction layer made up of fine Al_4C_3 particles was formed. The vast difference in the morphology and the amount of Al_4C_3 formed in this process as compared to conventional near equilibrium processes leads to the conclusion that during the non-equilibrium processing of these materials, the mechanism for the formation of Al_4C_3 is altered.

Very limited information is available about the behavior of the Al-Si-C system at high temperatures involved in laser processing. Slavinsky et al (23) observed that above 2000°C carbon dissolves in aluminum to form Al_4C_3 and then separates out from aluminum during slow cooling. Also, according to Kannikeshwaran and Lin (14), the kinetics of the formation of Al_4C_3 involves the dissociation of SiC and the subsequent attack of Al by C. Hence it can be concluded that, at the high temperatures involved in laser processing, SiC is

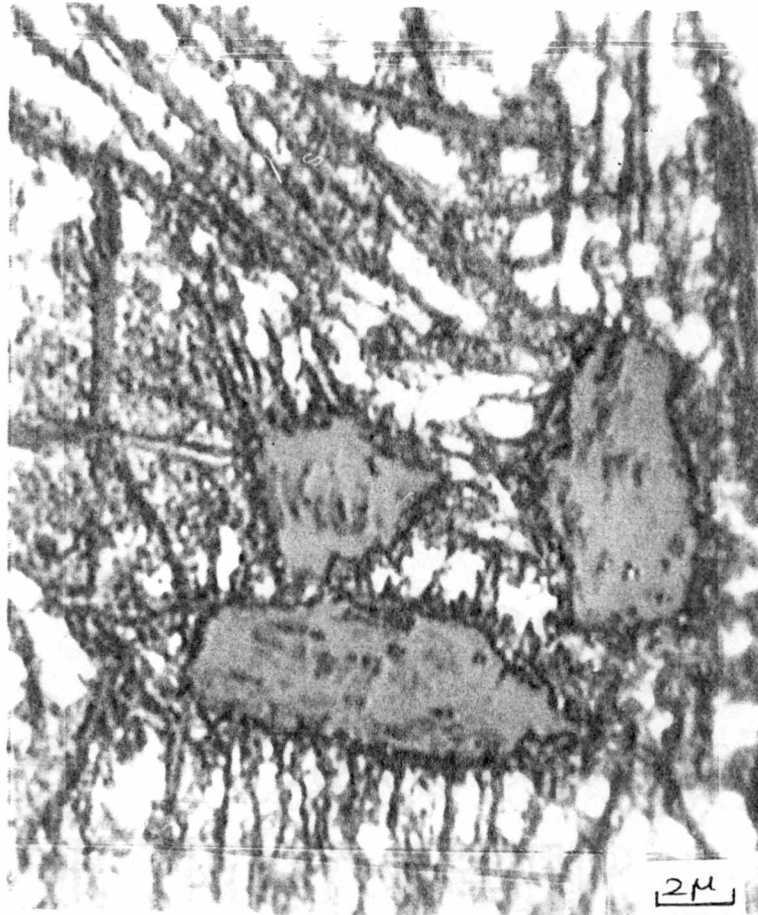


Figure 28. Micrograph showing Al₄C₃ needles being nucleated at the surface of a SiC particle.

dissociated and there exists a homogeneous solution of Al, C and Si in the central weld region which experiences the highest temperature. If this mixture was cooled slowly under equilibrium conditions, C would be rejected from the solution due to the low solubility (<0.05 weight% between $1300 - 1500^{\circ}\text{C}$) of C in Al. This carbon would then diffuse towards the free Si and the resulting structure would contain recrystallized SiC, Al and a trace amount of Al_4C_3 . During laser processing, however, the rapid solidification process and the high cooling rates associated with it, limit the diffusion process (24). As a result, a large fraction of the Al_4C_3 that was formed at high temperatures may be retained on rapid cooling. The high cooling rates can produce large undercoolings below the liquidus temperature (25). Under such conditions, solubility and activity limits of C in molten Al may increase, thereby favoring the formation of Al_4C_3 even at lower temperatures.

The rapid cooling may also result in the formation of several Al-Si-C non-equilibrium phases. Preliminary x-ray diffraction and analytical microscopy studies identified Al_4C_3 and $\text{Al}_4\text{Si}_2\text{C}_5$ in laser processed MMC's (11).

In the experiments, the aluminum carbide area in the laser processed Al-20%SiC MMC was observed to remain constant after an initial increase with power (Figure 14). This phenomenon could be explained by the studies conducted by Lloyd (26). He studied the reaction rates of the Al-SiC

system by x-ray diffraction analysis. He observed that the Al-SiC reaction rate, i.e. the rate of formation of Al_4C_3 , in Al-SiC MMC's was extremely high initially, and this rate later dropped off to a steady level. He performed thermodynamic calculations to predict the Si level required in the matrix in order to prevent the formation of Al_4C_3 . He found that the required Si level increased linearly with temperature. The formation of Al_4C_3 is, however, accompanied by an increase in the amount of Si in the area adjacent to the Al_4C_3 plates. When this Si content exceeds the level required to prevent Al_4C_3 , the reaction between Al and SiC will not proceed. The Al-20%SiC MMC contains larger amounts of SiC than the Al-10%SiC MMC. Hence, when the MMC's are laser treated, the amount of Si increases much faster in the Al-20%SiC than the Al-10%SiC MMC's. The saturation of Al_4C_3 formation in the Al-20%SiC MMC hence occurs much faster than in the Al-10%SiC MMC. In the regime of power conditions used in this study, the saturation of only Al-20%SiC was observed. At higher regimes of input power, the Al-10%SiC MMC is also expected to saturate in Al_4C_3 area.

Iseki et al (16) studied the thermodynamics of the reaction between aluminum and SiC. They calculated the change in free energy with temperature for this reaction for various activities of Si. It was observed that for a system with activity of Si, $a_{\text{Si}} = 0.1$, the free energy of formation of Al_4C_3 due to the reaction between Al and SiC became negative

at temperatures above 1100 K (827°C/sec). Since a_{Si} for A356 Aluminum was 0.1, the value of 1100 K (827°C) was used as the minimum temperature for the formation of Al_4C_3 in the code.

CHAPTER 9

RESULTS SUMMARY

A356 Aluminum, A356 Al-10%SiC and A356 Al-20%SiC metal matrix composites were laser processed under various input power conditions. The laser processed A356 Al showed a fusion zone with a fine dendritic structure. The high temperatures and the high cooling rates associated with laser material interactions resulted in the formation of fine, needle shaped aluminum carbide phase within the fusion region of the MMC's. The formation of aluminum carbide occurred in a regime of silicon concentration in which equilibrium thermodynamics predicted that no aluminum carbide would form.

The weld area increased with increase in input laser power in A356 Al and in both the Al-SiC MMC's. All three materials exhibited a large increase in weld area after full penetration was achieved. In the regime of input laser power conditions used in this research, the Al-10%SiC MMC showed an increase in aluminum carbide area but a decrease in the aluminum carbide area to weld area ratio, with increase in input power. In Al-20%SiC MMC, the aluminum carbide area stabilized after an initial increase with power. The aluminum carbide area to weld area ratio of Al-20%SiC MMC also decreased with increase in power.

An analytical computer code was developed in order to obtain weld profiles and thermocouple temperatures comparable to those obtained in the composites during laser welding. The code was then used to determine the conditions for and the extent of formation of the aluminum carbide phase in the Al-20%SiC MMC's. The minimum temperature for the formation of aluminum carbide in the weld was determined from the literature to be 1100 K (827°C). Once the critical cooling rate for the formation of aluminum carbide during laser processing was determined to be 12000 K/sec (12000°C/sec), this condition for cooling rate was used to predict aluminum carbide areas in Al-10%SiC MMC's. The predicted aluminum carbide areas compared well with the actual measured aluminum carbide areas.

The results of the experiment as well as the code emphasized the deviation of the laser welding process from equilibrium processes.

CHAPTER 10

CONCLUSIONS

- (1) Cooling rate was the primary thermal condition that influenced the formation of aluminum carbide during the laser processing of Al-SiC metal matrix composites.
- (2) The critical cooling rate for the formation of aluminum carbide during laser processing of both Al-10%SiC and Al-20%SiC metal matrix composites was 12000 K/sec (12000°C/sec).
- (3) The area of aluminum carbide stabilized with power and the aluminum carbide area to weld area ratio decreased with power. This fact, coupled with the small weld areas produced during laser welding leads to the conclusion that the extent of aluminum carbide formation can be controlled to a large extent by using the laser welding technique.

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LIST OF REFERENCES

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APPENDIXES

APPENDIX 1

CONFIGURATION TABLE FOR THE TEMPERATURE MEASUREMENT SYSTEM

CONFIGURATION TABLE FOR THE TEMPERATURE MEASUREMENT SYSTEM

SLOT TABLE-

SLOT 1: AMM2, Range: 10.B, Filt: 100 KHz, DIFF
SLOT 2: NONE
SLOT 3: AIM7
SLOT 4: NONE
SLOT 5: NONE
SLOT 6: NONE
SLOT 7: NONE
SLOT 8: NONE
SLOT 9: DIO1, Port: A) IN B) IN C)OUT D)OUT
SLOT 10: NONE

CHANNEL NAMES-

SLOT 1-

SLOT1CH0: AMM2, SL 1, CH 0, 16 BIT, LOCx1,
GLOx1, A FP 7.2
SLOT1CH1: AMM2, SL 1, CH 1, 16 BIT, LOCx1,
GLOx1, A FP 7.2
SLOT1CH2: AMM2, SL 1, CH 2, 16 BIT, LOCx1,
GLOx1, A FP 7.2
SLOT1CH3: AMM2, SL 1, CH 3, 16 BIT, LOCx1,
GLOx1, A FP 7.2
SLOT1CH4: AMM2, SL 1, CH 4, 16 BIT, LOCx1,
GLOx1, A FP 7.2

APPENDIX 2

BASIC SOFT500 PROGRAM TO SET SAMPLING PARAMETERS

BASIC SOFT500 PROGRAM TO SET SAMPLING PARAMETERS

```

40 CLS
50 CALL INIT 150 CALL IONAME'("SLOT9CH0",9,0)
60 '
70 ' SET UP PARAMETER NAMES FOR ANIN COMMAND
80 ARRAY$ = "STORE%"
90 'enter # of samples
100 SN! =2000!
110 IONL$ = "SLOT1CH0,SLOT1CH1,SLOT1CH2,SLOT1CH3,SLOT1CH4"
120 TION$ = "SLOT9CH0"
130 '
140 ' WAIT FOR EXTERNAL TRIGGER. LOOK FOR IT 5 TIMES PER
    INTERRUPT
150 CALL DIGINTRIG'(TION$,"ON","ST","TASK2")
160 '
170 'SETUP THERMOCOUPLE INPUT
180 'sintv - single ground trigger interval
190 'SINTV%=MULTIPLE OF 10 MICROSECONDS IN BETWEEN READINGS
200 SINTV% = 300
210 BFN$ = "TASK1"
220 PRINT "READY TO BEGIN DATA COLLECTION"
230 CALL ANINQ'(ARRAY$,SN!,IONL$,SINTV%,"WST")
240 PRINT "STOP"
250 'SAVE DATA VALUES FROM ARRAY TO HARD DISK
260 PRINT "SAVING DATA ON HARD DISK...PLEASE WAIT"
270 FOR CHAN% = 1 TO 5
280 CHN = CHAN% - 1
290 CH$ = STR$(CHN)
300 IF CHN<10 THEN CHN$ = "CHN.00"+RIGHT$(CH$,1)
310 IF CHN=>10 THEN CHN$ = "CHN.0"+RIGHT$(CH$,2)
320 OPEN CHN$ FOR OUTPUT AS #1
330 WRITE #1, SN!
340 VALUE = 0!
350 FOR DEP! = 1 TO SN!
360 CALL ARGETVAL'("STORE%",DEP!,CHAN%,VALUE,0)
370 WRITE #1,DEP!,VALUE
380 NEXT DEP!
390 CLOSE #1
400 NEXT CHAN%
410 '
420 PRINT "PRESS q TO QUIT; r to repeat "
430 PRINT "If you want to convert this data to temperature,"
440 PRINT "get out of SOFT500 by typing < > 'SYSTEM' < > "
450 PRINT "and then type 'j2' < >, SINTV% = 300"
460 A$ = INKEY$ : IF A$ = "" THEN 610
470 IF A$ = "r" THEN GOTO 50
480 END

```

APPENDIX 3

PROGRAM TO CONVERT VOLTAGE INTO TEMPERATURE

PROGRAM TO CONVERT VOLTAGE INTO TEMPERATURE

```

PROGRAM MILLITEMP
INTEGER GAIN,SINTV
REAL t,a0,a1,a2,a3,a4,a5,a6,a7,a8,x
a0 = 0.226584602
a1 = 24152.109
a2 = 67233.4248
a3 = 2210340.682
a4 = -860963914.9
a5 = 4.83506e10
a6 = -1.18452e12
a7 = 1.3869e13
a8 = -6.33708e13
GAIN = 100
WRITE(*,*) 'ENTER SINTV%'
READ(*,*) SINTV
TTIME = (SINTV )/100000.
OPEN(11,FILE='CHN.000')
READ (11,*) N
OPEN (1,FILE = 'OP1')
WRITE(1,*) N
DO 10 I = 1,N
READ (11,*) TIME,XX
X = XX/(GAIN)
T1 = a0 + a1*X + a2*X*X + a3*(X**3) + a4*(X**4)
T2 = a5*(X**5) + a6*(X**6) + a7*(X**7) + a8*(X**8)
T = T1 + T2
WRITE(1,*) TIME*TTIME,T
IF (I.EQ.N) THEN
    CLOSE(11)
    CLOSE(1)
    GOTO 100
ENDIF
10 CONTINUE
100 CONTINUE
open(12,file='chn.001')
READ (12,*) N
OPEN (2,FILE = 'OP2')
WRITE(2,*) N
DO 20 II = 1,N
READ (12,*) TIME,xx
x = xx/(gain)
t1 = a0 + a1*x + a2*x*x + a3*(x**3) + a4*(x**4)
t2 = a5*(x**5) + a6*(x**6) + a7*(x**7) + a8*(x**8)
t = t1 + t2
WRITE(2,*) time*ttime,t
IF (II.EQ.N) THEN
    CLOSE(12)
    CLOSE(2)

```

```

        GOTO 200
    ENDIF
20    CONTINUE
200    CONTINUE
        open(13,file='chn.002')
        READ (13,*) N
        OPEN (3,FILE = 'OP3')
        WRITE(3,*) N
        DO 30 III = 1,N
        READ (13,*) TIME,xx
        x = xx/(gain)
        t1 = a0 + a1*x + a2*x*x + a3*(x**3) + a4*(x**4)
        t2 = a5*(x**5) + a6*(x**6) + a7*(x**7) + a8*(x**8)
        t = t1 + t2
        WRITE(3,*) time*tttime,t
        IF (III.EQ.N) THEN
            CLOSE(13)
            CLOSE(3)
            GOTO 300
        ENDIF
30    CONTINUE
300    CONTINUE
        open(14,file='chn.003')
        READ (14,*) N
        OPEN (4,FILE = 'OP4')
        WRITE(4,*) N
        DO 40 IIII = 1,N
        READ (14,*) TIME,xx
        x = xx/(gain)
        t1 = a0 + a1*x + a2*x*x + a3*(x**3) + a4*(x**4)
        t2 = a5*(x**5) + a6*(x**6) + a7*(x**7) + a8*(x**8)
        t = t1 + t2
        WRITE(4,*) time*tttime,t
        IF (IIII.EQ.N) THEN
            CLOSE(14)
            CLOSE(4)
            GOTO 400
        ENDIF
40    CONTINUE
400    CONTINUE
C
C
        open(15,file='chn.004')
        READ (15,*) N
        OPEN (5,FILE = 'OP5')
        WRITE(5,*) N
        DO 50 IIIII = 1,N
        READ (15,*) TIME,xx
        x = xx/(gain)
        t1 = a0 + a1*x + a2*x*x + a3*(x**3) + a4*(x**4)
        t2 = a5*(x**5) + a6*(x**6) + a7*(x**7) + a8*(x**8)
        t = t1 + t2

```

```

WRITE(5,*) time*tttime,t
IF (IIIII.EQ.N) THEN
  CLOSE(15)
  CLOSE(5)
  GOTO 500
ENDIF
50  CONTINUE
500 CONTINUE
write(*,*) 'FINISHED CONVERSION. YOUR TEMP VS TIME'
write(*,*) 'FILES ARE CALLED OP1,OP2,OP3,OP4 AND OP5'
END

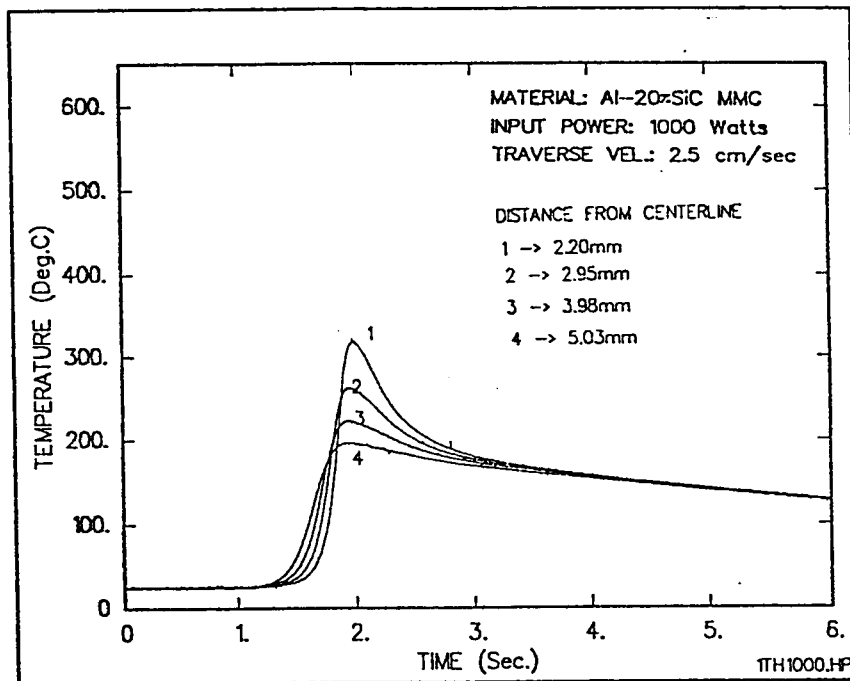
```

APPENDIX 4

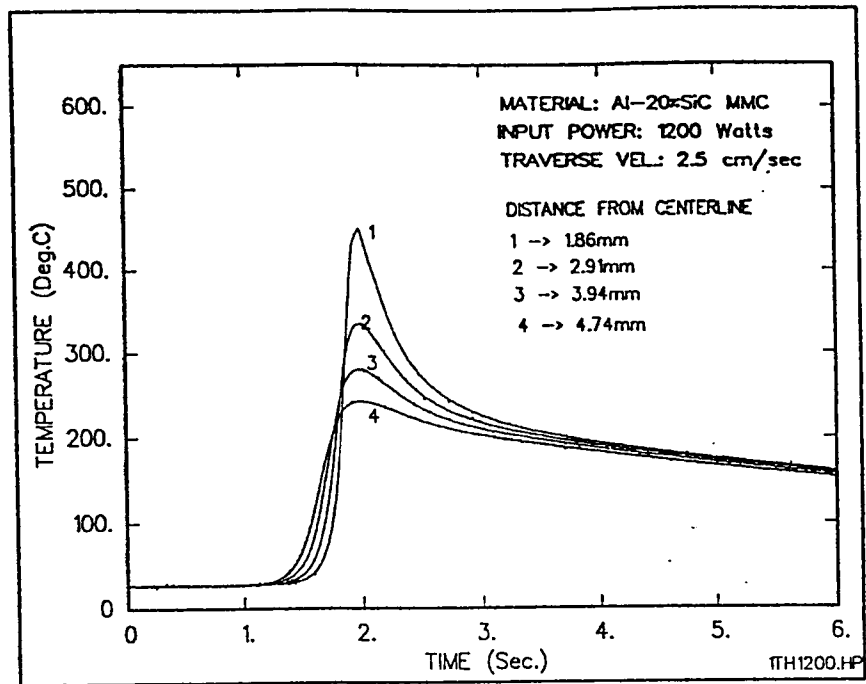
EXPERIMENTALLY MEASURED TEMPERATURE-TIME CURVES

EXPERIMENTALLY MEASURED TEMPERATURE-TIME CURVES

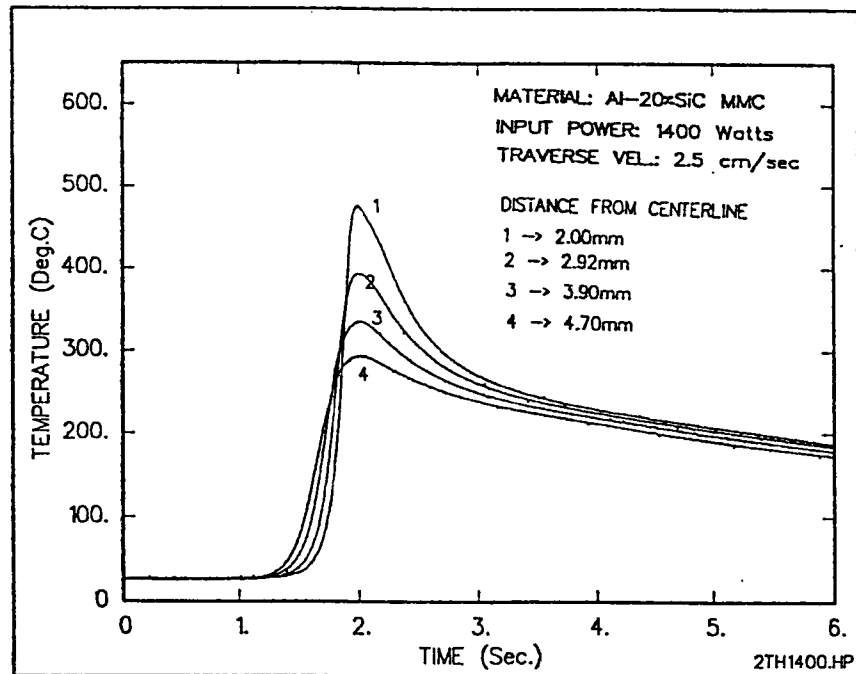
(A) Al-20%SiC MMC:



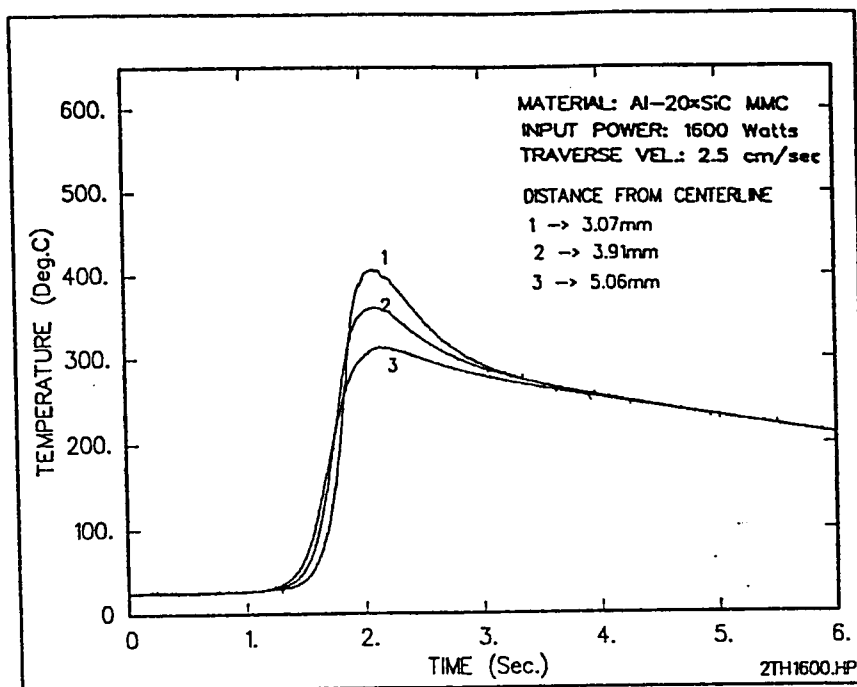
(a) Power = 1000 Watts



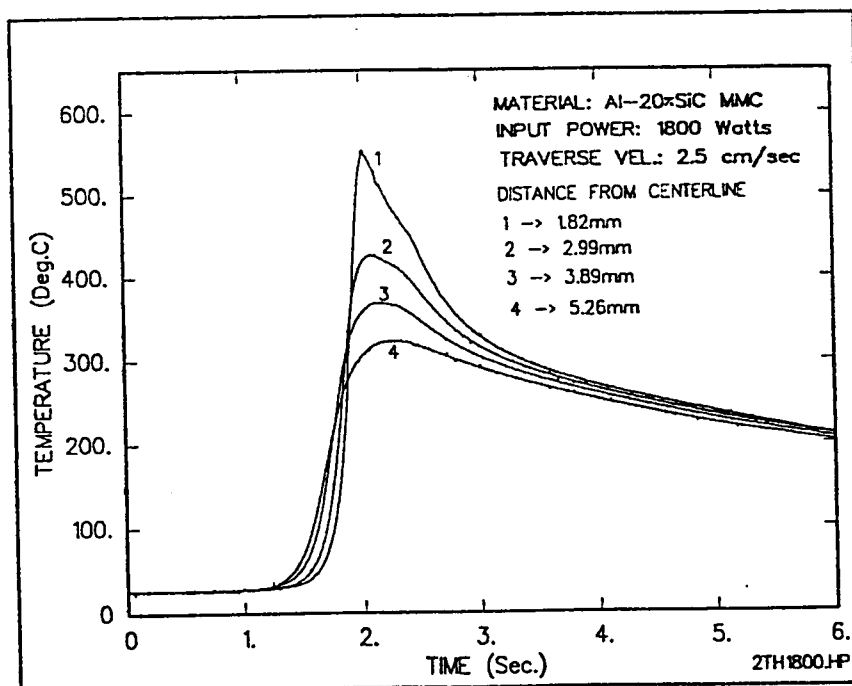
(b) Power = 1200 Watts



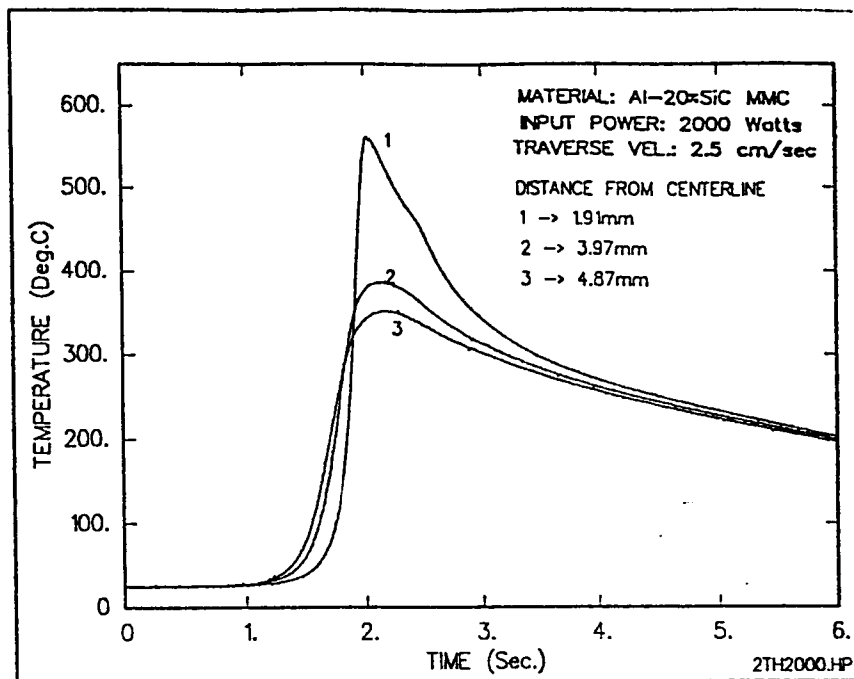
(c) Power = 1400 Watts



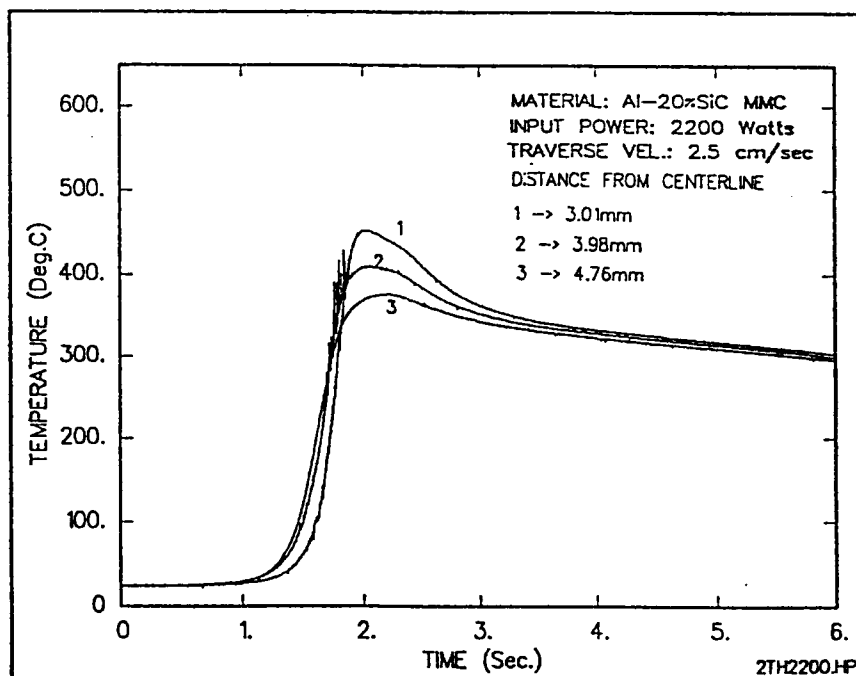
(d) Power = 1600 Watts



(e) Power = 1800 Watts

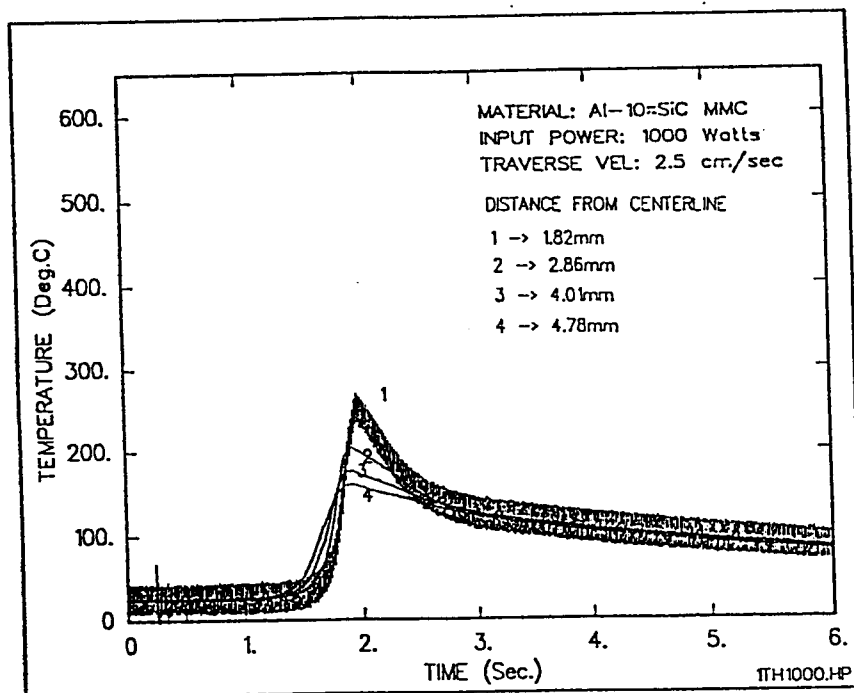


(f) Power = 2000 Watts

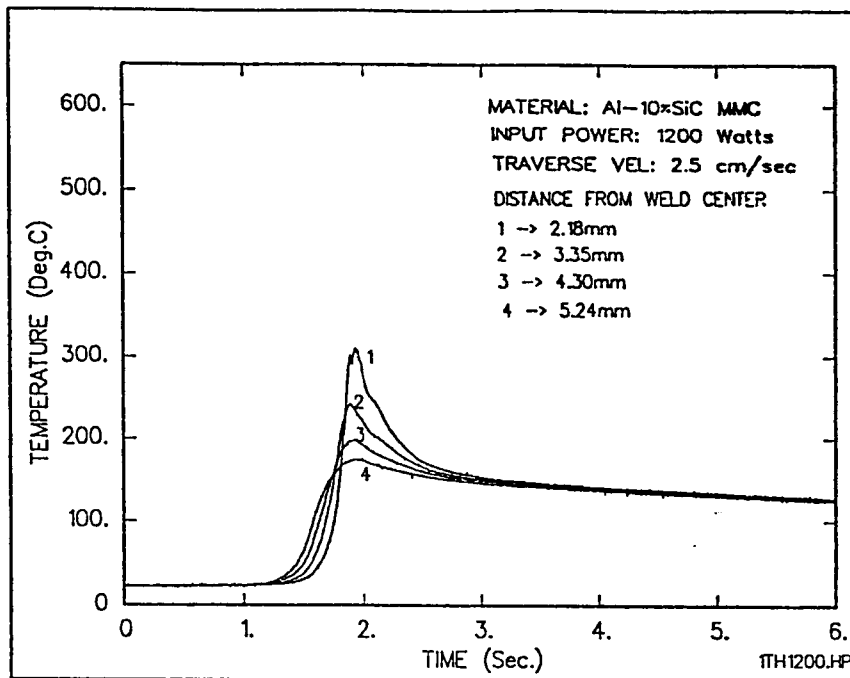


(g) Power = 2200 Watts

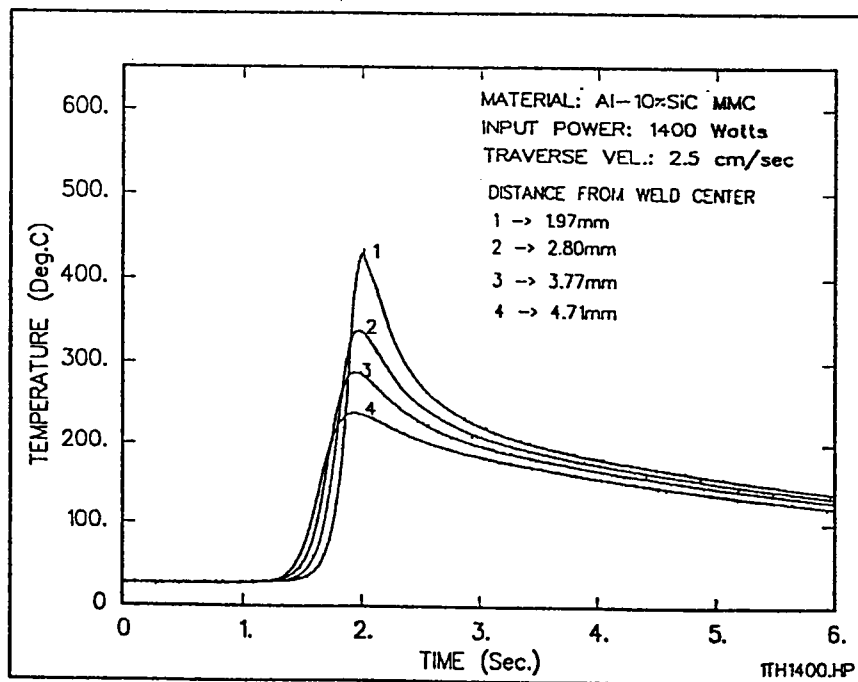
(B) Al-10%SiC MMC:



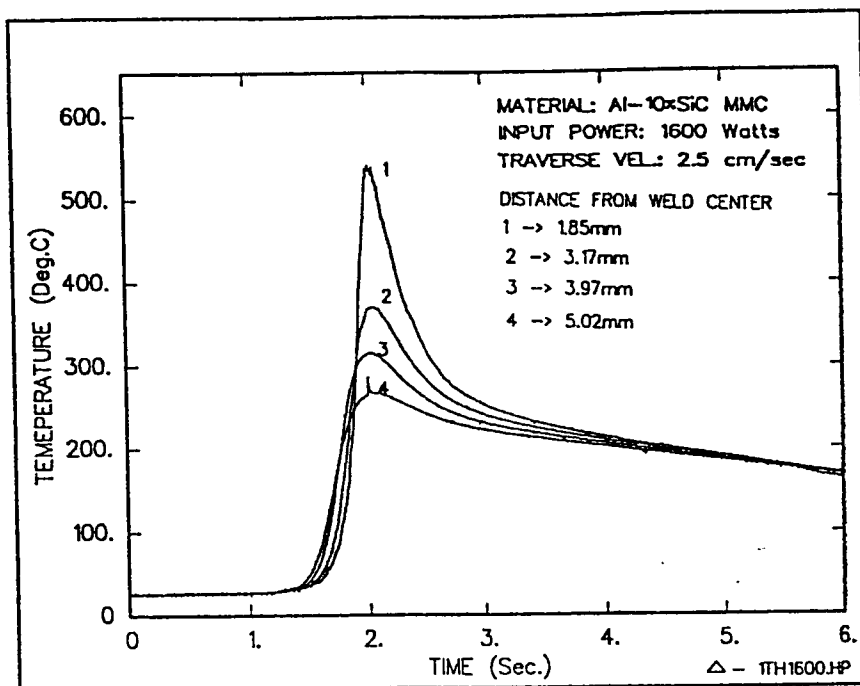
(a) Power = 1000 Watts



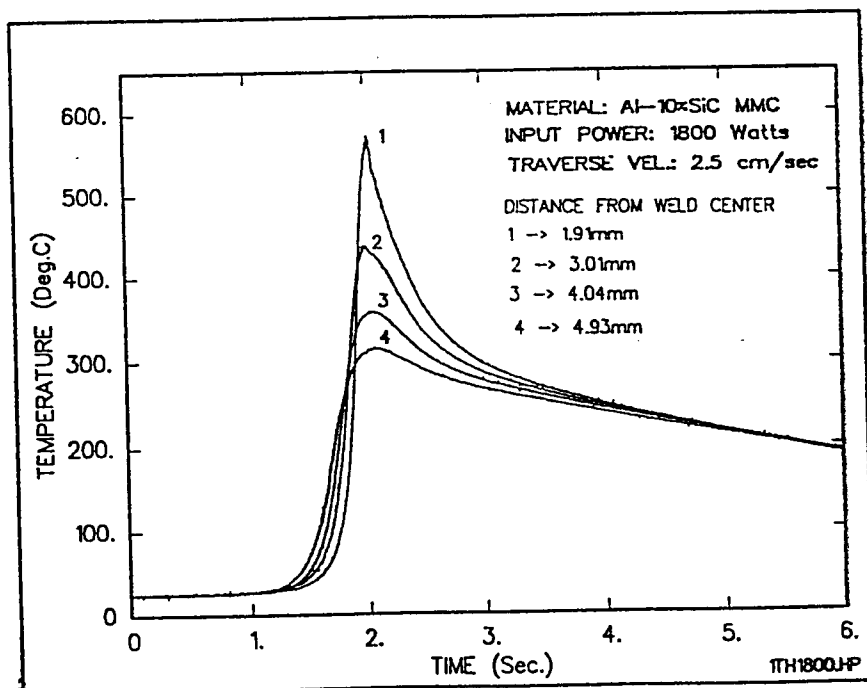
(b) Power = 1200 Watts



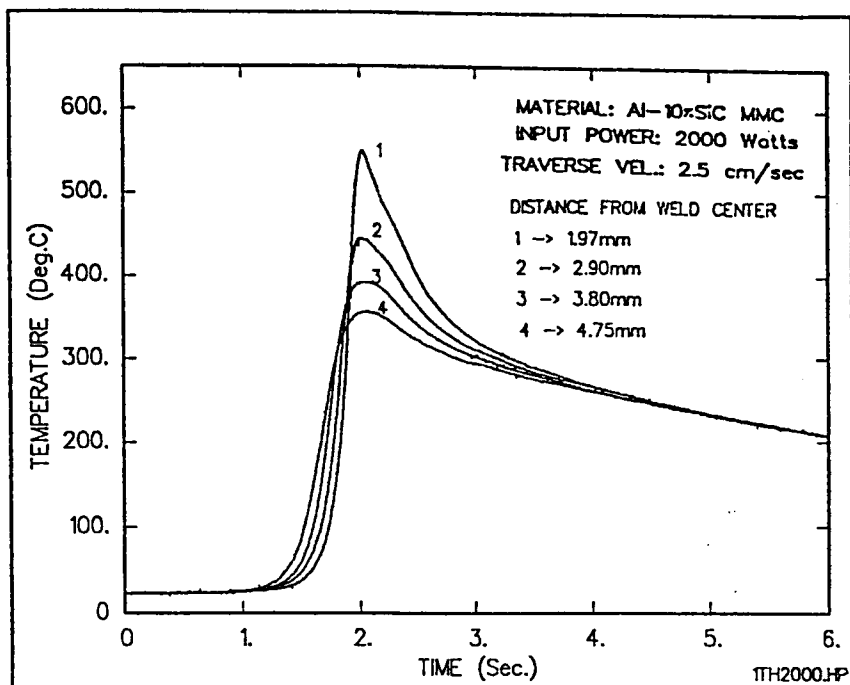
(c) Power = 1400 Watts



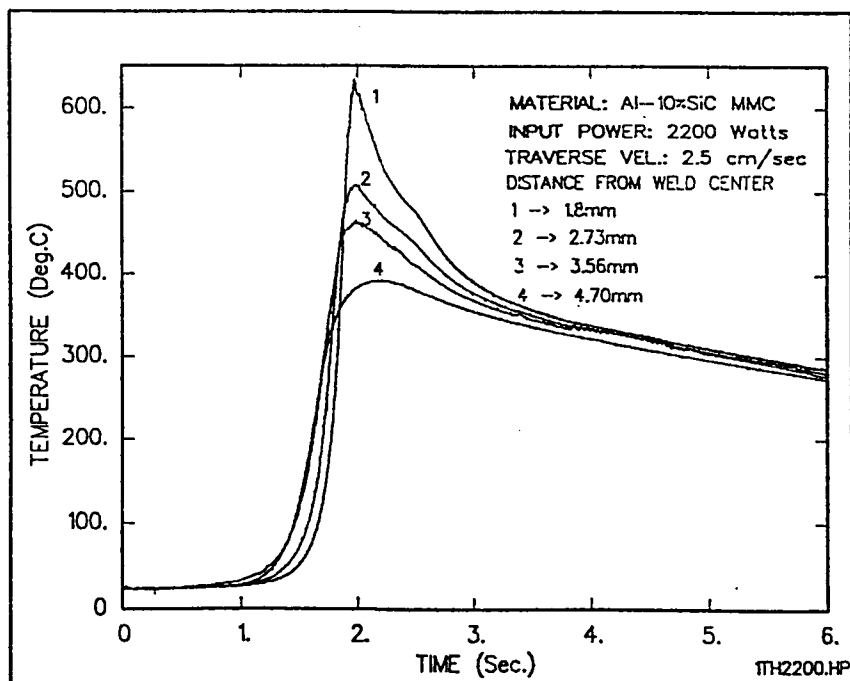
(d) Power = 1600 Watts



(e) Power = 1800 Watts



(f) Power = 2000 Watts



(g) Power = 2200 Watts

APPENDIX 5

COMPUTER CODE FOR THE WELD PROFILE AND THE ALUMINUM CARBIDE AREA CALCULATION

```
C *****
C
C                                     PROGRAM COMP.FOR
C                                     BY   SANTOSH GOPINATHAN
C
C THIS CODE FIRST CALCULATES THE WELD PROFILES GENERATED
C DURING THE LASER PROCESSING OF METAL MATRIX COMPOSITES
C USING THE MATERIAL PROPERTIES PROVIDED AND THE INPUT
C VALUES OF POWER, ABSORPTION EFFICIENCY, ABSORPTION
C COEFF., TRAVERSE VELOCITY AND THE CONVERGENCE TOL. FOR
C SOLIDIFICATION TEMPERATURE. NEXT THE CODE CALCULATES
C THE EXTENT OF ALUMINUM CARBIDE AREA IN THE WELD BY
C CALCULATING THE COOLING RATES AND TEMPERATURE AND THEN
C COMPARING THEM WITH THE PRESCRIBED TOLERANCES.
C
C *****
C
C      include 'fgraph.fi'
C      call graphicsmode()
C
C *****
C
C      CALL SUBROUTINE CONDEFF1 IN ORDER TO CALCULATE THE
C WELD PROFILE BASED ON THE ISOTHERM OF 900 DEG.K WHICH
C IS THE SOLIDIFICATION TEMPERATURE FOR A356 ALUMINUM
C
C *****
C
C      call CONDEFF1(mmm,Qo,alpha)
C
C *****
C
C      CALL SUBROUTINE CONDEFF2 IN ORDER TO CALCULATE THE
C EXTENT OF ALUMINUM CARBIDE FORMATION BASED ON A
C PRESCRIBED COOLING RATE AND A THRESHOLD TEMPERATURE.
C
C *****
C
C      call CONDEFF2(mmm,Qo,alpha)
C      call endprogram()
C      end
C
```

C DEFINE THE COORDINATE SYSTEM FOR THE GRAPHICS MODE
C

```
integer*2 FUNCTION newx(xcoord)
integer*2 xcoord,maxx,maxy
real*4 tempx
common maxx,maxy
tempx = maxx/1000.0
tempx = xcoord*tempx +0.5
newx = tempx
end
```

C
C

```
integer*2 FUNCTION newy(ycoord)
integer*2 ycoord,maxx,maxy
real*4 tempy
common maxx,maxy
tempy = maxy/1000.0
tempy = ycoord*tempy +0.5
newy = tempy
end
```

C
C
C

SET UP THE GRAPHICS MODE

```
SUBROUTINE graphicsmode()
include 'fgraph.fd'
integer*2        dummy,maxx,maxy
record/videoconfig/myscreen
common  maxx,maxy
```

C
C
C

FIND THE GRAPHICS ADAPTER

```
call getvideoconfig(myscreen)
select case (myscreen.adapter)
  case($cga)
    dummy = setvideomode ($hresbw)
  case($ocga)
    dummy = setvideomode ($orescolor)
  case($ega,$oega)
    if (myscreen.monitor.eq.$mono) then
      dummy = setvideomode ($eresnocolor)
    else
      dummy = setvideomode ($erescolor)
    endif
  case($vga,$ovga,$mcga)
    dummy = setvideomode ($vres16color)
  case($hgc)
    dummy = setvideomode ($hercmono)
  case default
    dummy = 0
end select
if (dummy.eq.0) STOP 'error:cannot set graphics mode'
```

C

```

C      DETERMINE THE MAX AND MIN DIMENSIONS
C
      call getvideoconfig(myscreen)
      maxx = myscreen.numxpixels - 1
      maxy = myscreen.numypixels - 1
      end

C *****
C
C      CALLING SUBROUTINE CONDEFF1
C *****
C
C      SUBROUTINE CONDEFF1(mmm,Qo,alpha)
C
C      INCLUDE 'FGRAPH.FD'
      REAL X,XX,Y,Z,QQ,Qo,LA,PI,temp,tol,TRZ,H,g
      INTEGER COUNT,NRN,AA,MMM,OO
      DIMENSION FZ(999),FY(999),an(10)
      external f1,f2,NEWX,NEWY
      INTEGER*2 DUMMY,NEWX,NEWY,LOCX,LOCY,K
      common/f1c/b0,b1,g
      common/f2c/n,pi
      character*7 ystrin, zstrin, ustrin,vstrin
      character*10 astrin,bstrin,cstrin,dstrin,estrin,fstrin
      record /xycoord/ xy

C *****
C      VARIABLES: SYMBOLS AND VALUES
C *****
C
C      Qo = SURFACE HEAT INPUT
C      CY = THERMAL CONDUCTIVITY
C      CY OF A356Al = 1.51 W/cm K; SiC = 3.04 W/cm K
C      SPHT = SPECIFIC HEAT
C      SPHT OF A356Al = 0.9623 J/gm K; SiC = 0.598 J/gm K
C      DENSITY OF A356Al = 2.685 gm/cc; SiC = 3.22 gm/cc
C      LA = (DENSITY*SPHT)/(2*CY)
C      1/(2*LA) = THERMAL DIFFUSIVITY (cm2/sec)
C      V = VELOCITY OF TRAVERSE (cm/sec)
C      TT = TIME(SECS)
C      G = THICKNESS (.25cm)
C      XX = X - V*TT
C      RP = (XX**2 + Y**2)**.5
C      TEMP = LOWEST TEMPERATURE AT WHICH LIQUID PHASE OCCURS
C              IN THE ALLOY SYSTEM(°K)
C      TT = TIME ALONG THE WELD AT WHICH THE TEMPERATURE
C              FIELD HAS BEEN DEVELOPED (SECS)
C      X = DISTANCE ALONG THE WELD AT WHICH THE TEMPERATURE
C              FIELD HAS BEEN DEVELOPED (CMS)
C *****

```

C

```

TEMP = 900.0
PI = 22.0/7.0
TT = .4
X = 1.0

```

```

WRITE(*,*) '*****'
WRITE(*,*) 'THIS CODE RUNS AN ANALYTICAL MODEL FOR'
WRITE(*,*) 'LASER WELDING OF THE TWO MATERIALS LISTED'
WRITE(*,*) 'BELOW. THE OUTPUT OF THIS CODE IS THE'
WRITE(*,*) 'WELD POOL SHAPE IN THE MATERIAL'
WRITE(*,*) '*****'
WRITE(*,*) ' '
WRITE(*,*) ' '

```

C
C
C

```

USER INPUT:

```

```

WRITE(*,*) 'MATERIAL : A356 10 Sic? (1)'
WRITE(*,*) '           : A356 20 Sic? (2)'
READ (*,*) MMM
WRITE(*,*) ' '
WRITE(*,*) ' NOTE: THE PROPERTIES USED IN THIS CODE'
WRITE(*,*) ' FOR Al-10% Sic MMC AND Al-20Sic MMC '
WRITE(*,*) ' ARE LISTED IN DATA FILES, PT1.DAT'
WRITE(*,*) ' AND "PT2.DAT" RESPECTIVELY. PLEASE'
WRITE(*,*) ' ACCESS THESE FILES IF YOU NEED TO CHANGE'
WRITE(*,*) ' THE PROPERTIES'
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) 'DO YOU WANT A LISTING OF THE PROPERTIES?'
WRITE(*,*) '1 = YES, 0 = NO'
READ (*,*) OO
WRITE(*,*) ' '

```

C
C
C
C

```

PT1.DAT = FILE IN WHICH A356 Al -10%SIC PROPERTIES
          ARE STORED.

```

```

IF (MMM.EQ.1) THEN
OPEN (4,FILE = 'PT1.DAT')
READ (4,*) CY,SPHT,DENSITY,V,G,NRN,X,T0,TOL,TOL1
IF (OO.EQ.1) THEN
WRITE(*,*) 'PROPERTIES OF A356 ALUMINUM - 10% Sic '
WRITE(*,*) ' '
GOTO 211
ELSE
GOTO 212
ENDIF
ENDIF

```

C

```

C      PT2.DAT = FILE IN WHICH A356 Al -20%SiC PROPERTIES
C      ARE STORED.
C
      IF (MMM.EQ.2) THEN
      OPEN (5,FILE = 'PT2.DAT')
      READ (5,*) CY,SPHT,DENSITY,V,G,NRN,X,TO,TOL,TOL1
      IF (OO.EQ.1) THEN
        WRITE(*,*) 'PROPERTIES OF A356 ALUMINUM - 20% SiC '
        WRITE(*,*) ' '
        GOTO 211
      ELSE
        GOTO 212
      ENDIF
    ENDIF

C
C
211    CONTINUE
      WRITE(*,*) '*****'
      WRITE(*,*) 'THERMAL CONDUCTIVITY (W/cm°K) = ',CY
      WRITE(*,*) ' '
      WRITE(*,*) 'SPECIFIC HEAT (J/gm°K) = ',SPHT
      WRITE(*,*) ' '
      WRITE(*,*) 'DENSITY (gm/cc) = ',DENSITY
      WRITE(*,*) ' '
      WRITE(*,*) 'TRAVERSE VELOCITY (cm/sec) = ',V
      WRITE(*,*) ' '
      WRITE(*,*) 'SAMPLE THICKNESS (cm) = ',G
      WRITE(*,*) ' '
      WRITE(*,*) 'NUMBER OF ITERATIONS = ',NRN
      WRITE(*,*) ' '
      WRITE(*,*) 'DATA TAKEN AT X (cm) = ',X
      WRITE(*,*) ' '
      WRITE(*,*) 'AMBIENT TEMPERATURE (°K) = ',TO
      WRITE(*,*) ' '
      WRITE(*,*) 'TEMPERATURE TOLERANCE (°K) = ',TOL
      WRITE(*,*) ' '
      WRITE(*,*) 'CRITICAL COOLING RATE (°K/sec) = ',TOL1
      WRITE(*,*) '*****'

C
212    CONTINUE
      format(F6.3)
      format(f7.2)
      format(f6.3)

C
      WRITE(*,*) 'ENTER INPUT POWER IN WATTS '
      READ(*,*) Qo
      write(bstrin,2) Qo
      WRITE(*,*) ' '
      WRITE(*,*) 'ENTER ABSORPTION EFFICIENCY ALPHA AS A '
      WRITE(*,*) 'FRACTION'
      READ(*,*) alpha
      write(dstrin,3) alpha

```

```

C      WRITE(*,*) '      '
      write(*,*) 'ENTER ABSORPTION COEFFICIENT B0 (1/CM) '
      read (*,*) B0
      write(estrin,2) B0

C      WRITE(*,*) '      '
      write(*,*) 'ENTER B1 (1/(CM**2)) '
      read (*,*) B1
      write(fstrin,2) B1

C      WRITE(*,*) '      '
      write(*,*) 'WANT TO LIST ALL TEMPERATURES?'
      write(*,*) '1 = YES, 0 = NO'
      read (*,*) AA
      WRITE(*,*) '      '
      write(cstrin,3) v

C
C      CALCULATE THE THERMAL DIFFUSIVITY
C
      LA = (DENSITY*SPHT)/(2.0*CY)
      diff = 1/(2*la)
C      write(*,*) 'thermal diffusivity in cm^X2^X/sec = ',diff
C
C
      COUNT = 0
      II = 0
      YMAX=0
      ZMAX=0
      OPEN(1,FILE='ONE')
      OPEN(2,FILE='TWO')
      OPEN(6,FILE='six')
C      OPEN(7,FILE='sev')
      call clearscreen ($gclearscreen)
      dummy2 = setbkcolor($blue)

C
      WRITE(*,*) '----- THE WELD PROFILE -----'
      dummy1 = setcolor(8)
      dummy1 = rectangle($gfillinterior,390,26,626,120)
      dummy1 = setcolor(1)
      dummy1 = rectangle($gfillinterior,400,22,636,116)
      dummy1 = setcolor(4)
      dummy1 = rectangle($gborder,400,22,636,116)
      dummy1 = setcolor(15)
      WRITE(*,*) '      '
      WRITE(*,*) '      '
      WRITE(*,*) '      '
      WRITE(*,*) '      '
      WRITE(*,*) '      '
      WRITE(*,*) '      '
      WRITE(*,*) '      '
      WRITE(*,*) '      '

```

```

WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
WRITE(*,*) ' '
C
C   DRAW THE AXES AND THE WELD CENTERLINE
C
DO 303 K = 0,999,9
LOCX = NEWX(K)
LOCY = 125
DUMMY = SETPIXEL(LOCX,LOCY)
WRITE (6,*) K,locx,locy
303 CONTINUE
DO 304 K = 0,999,9
LOCX = NEWX(K)
LOCY = 125 + NEWY(INT2(0.25*1500))
DUMMY = SETPIXEL(LOCX,LOCY)
WRITE (6,*) K,locx,locy
304 CONTINUE
DO 305 K = 250,650,9
LOCX = 319
LOCY = NEWY(K)
DUMMY = SETPIXEL(LOCX,LOCY)
305 CONTINUE
LY = 125
Z = 0
XX = X - V*TT
C
C
C   EXPRESSION FOR COEFFICIENT A0
C
den = dcadre(f1,0,g,1e-2,1e-3,err,ier)
a0 = den/g
Qoo = (alpha*Qo)/den
QQ = (Qoo*EXP(-LA*V*XX))/(2*PI*CY)
C
C   EXPRESSION FOR COEFFICIENT A0
C
DO 31 N=1,NRN
den = dcadre(f2,0,g,1e-2,1e-3,err,ier)
an(n) = 2*den/g
31 continue
C
110 CONTINUE

```

```

      Y = 0.0
C      H = INCREMENT IN Y DIRECTION(CMS)
C
      H = 0.0025
C      STOP IF Z = THICKNESS G
C
      IF (Z.GT.G) THEN
        GOTO 999
      ENDIF
111  continue
C
C      *****
C      CALCULATION OF THE COEFFICIENTS AND INDIVIDUAL TERMS
C      IN THE FINAL TEMPERATURE EQUATION.
C      *****
C
      XX = X - V*TT
C
C
C      W1 = ARGUMENT FOR THE FIRST BESSEL FUNCTION
C
      RP = (XX**2 + Y**2)**.5
      W1 = LA * V * RP
C
C      SUMMATION OF THE BESSEL FUNCTION SERIES AND FOR THE
C      SERIES FOR AN.
C
      DD = 0
      DO 30 N=1,NRN
C      W2 = ARGUMENT FOR SECOND BESSEL FUNCTION
      W2 = RP*((LA*LA*V*V)+(N*PI/G)**2)**.5
      S = N*PI/G
      D = AN(N) * BESSK0(W2) * COS(S*Z)
      D = D + DD
      DD = D
30  CONTINUE
C
C      *****
C      FINAL EQN
C      *****
C
      TRZ = T0 + (QQ * A0 * BESSK0(W1)) + (QQ * DD)
C
      If (AA.eq.1) then
        write (*,*) trz,y,z
      endif
C
      IF ((TRZ+TOL).LT.TEMP) THEN
C        WRITE(*,*) 'Z=',Z
        Z = Z + 0.0025
        goto 110
      ENDIF

```

```

C      IF ((TRZ-TEMP).LE.100) THEN
          H = 0.001
        ELSE
          H = 0.0025
        ENDIF

C
C 998  continue
C
C      COMPARING VALUES FOR TOLERANCE
C
      IF (ABS(TRZ-TEMP).LE.TOL) THEN
        COUNT = COUNT + 1
        II = II + 1
        FY(II) = Y
        FZ(II) = Z
        IF (YMAX.LT.FY(II)) THEN
          YMAX = FY(II)
        ENDIF
        IF (ZMAX.LT.FZ(II)) THEN
          ZMAX = FZ(II)
        ENDIF
      write(ystrin,1) fy(ii)*10
      call settextposition(3,52,xy)
      call outtext( ' Y = '// ystrin //'mm ')
      write(zstrin,1) fz(ii)*10
      call settextposition(4,52,xy)
      call outtext( ' Z = '// zstrin //'mm ')
      LOCX1 = 319 + NEWX(INT2(FY(II-1)*1500))
      LOCY1 = 125 + NEWY(INT2(FZ(II-1)*1500))
      LOCX = 319 + NEWX(INT2(FY(II)*1500))
      LOCY = 125 + NEWY(INT2(FZ(II)*1500))
C      IF (LOCY.LE.LY) THEN
        DUMMYA = SETPIXEL(LOCX,LOCY)
        dummy = setcolor (4)
        if(count.eq.1) then
          dummy = rectangle($gfillinterior,locx1,ly,319,locy)
        endif
        dummy =rectangle($gfillinterior,locx1,locy1,319,locy)
        LOCX2 = 319 + NEWX(INT2(-FY(II-1)*1500))
        LOCY2 = 125 + NEWY(INT2(FZ(II-1)*1500))
        LOCX = 319 + NEWX(INT2(-FY(II)*1500))
        LOCY = 125 + NEWY(INT2(FZ(II)*1500))
        DUMMYA = SETPIXEL(LOCX,LOCY)
        dummy = setcolor(4)
        if(count.eq.1) then
          dummy = rectangle($gfillinterior,locx2,ly,319,locy)
        endif
        dummy =rectangle($gfillinterior,locx2,locy2,319,locy)
C      ENDIF
      Z = Z + 0.0005
      goto 110

```

```

ELSE
  Y = Y + H
  GOTO 111
ENDIF

C
999  CONTINUE
C
C      *****
C      OUTPUT
C      *****
555  continue
C
C
dummy1 = setcolor(8)
dummy1 = rectangle($gfillinterior,44,311,415,474)
dummy1 = setcolor(1)
dummy1 = rectangle($gfillinterior,54,307,425,470)
dummy1 = setcolor(4)
dummy1 = rectangle($gborder,54,307,425,470)
IF (MMM.EQ.1) THEN
C      write(astrin,*) 'Al-10%SiC MMC'
      astrin = 'Al-10%SiC MMC'
ENDIF
IF (MMM.EQ.2) THEN
C      write(astrin,*) 'Al-20%SiC MMC'
      astrin = 'Al-20%SiC'
ENDIF
dummy = settextcolor(14)
call settextposition(21,8,xy)
call outtext (' MATERIAL : ' //astrin// ' ')
call settextposition(22,8,xy)
call outtext(' INPUT LASER POWER: ' //bstrin// ' WATTS')
call settextposition(23,8,xy)
call outtext(' TRAVERSE VELOCITY: ' //cstrin// ' CM/S')
call settextposition(24,8,xy)
call outtext(' ALPHA : ' //dstrin// ' ')
call settextposition(25,8,xy)
call outtext(' B0 : ' //estrin// ' ')
call settextposition(26,8,xy)
call outtext(' B1 : ' //fstrin// ' ')
C
      WRITE(1,*) COUNT
      WRITE(2,*) COUNT
      DO 300 K = 1,COUNT
      WRITE (1,*) FY(K),0.25-FZ(K)
      WRITE (2,*) -FY(K),0.25-FZ(K)
300  CONTINUE
C
write(ustrin,1) ymax*20
call settextposition(27,9,xy)
call outtext(' TOP BEAD WIDTH      = '//ustrin//'mm ')
write(vstrin,1) zmax*10

```

```

call settextposition(28,9,xy)
call outtext( 'PENETRATION DEPTH = '// vstrin //'mm ')
call settextposition(6,53,xy)
dummy = settextcolor(2)
call outtext(' Press "ENTER" to continue ')
read(*,*)          ! Wait for ENTER to be pressed
CLOSE(1)
CLOSE(2)
CLOSE(3)
close(4)
close(5)
close(6)
END

```

C
C
C
C
C

```

*****
CALL SUBROUTINE CONDEFF2
*****

```

```

SUBROUTINE CONDEFF2(mmm,Qo,alpha)
INCLUDE 'FGRAPH.FD'
REAL X,XX,Y,Z,QQ,Qo,LA,PI,temp,tol,TRZ,TRI,H,g
INTEGER COUNT,NRN,MMM
DIMENSION an(10)
external f1,f2,NEWX,NEWY
INTEGER*2 NEWX,NEWY,LOCX,LOCY,LOCX1
INTEGER*2 DUMMY,DUMMY1,DUMMY2,DUMMYA,DUMMYB
common/f1c/b0,b1,g
common/f2c/n,pi
character*7 ystrin, zstrin, ustrin,vstrin
record /xycoord/ xy
TEMP = 900.0

```

C

```

PI = 22.0/7.0

```

C

```

call settextposition(6,53,xy)
dummy = settextcolor(2)
call outtext(' DOING PART II OF THE CODE ')

```

C

212

```

CONTINUE
format(F6.3)
format(f7.2)
format(f6.3)

```

1

2

3

C

C

```

IF (MMM.EQ.1) THEN
OPEN (4,FILE = 'PT1.DAT')
READ (4,*) CY,SPHT,DENSITY,V,G,NRN,X,TO,TOL,TOL1
ENDIF

```

C

C

```

IF (MMM.EQ.2) THEN
OPEN (5,FILE = 'PT2.DAT')

```

```

      READ (5,*) CY,SPHT,DENSITY,V,G,NRN,X,T0,TOL,TOL1
      ENDIF
      LA = (DENSITY*SPHT)/(2.0*CY)
C      diff = 1/(2*la)
C
      H = .001
      COUNT = 0
      II = 0
      YMAX=0
      ZMAX=0
      TRI = 0
C      tti = 0
C      OPEN(1,FILE='ONE')
C      OPEN(2,FILE='TWO')
      OPEN(6,FILE='six')
      OPEN(7,FILE='sev')
      OPEN(8,FILE='ATE')
      Z = 0.0
      locyb = 126
C
701  CONTINUE
C      EXPRESSION FOR COEFFICIENT A0
C
      den = dcadre(f1,0,g,1e-2,1e-3,err,ier)
      a0 = den/g
      Qoo = (alpha*Qo)/den
C
C      EXPRESSION FOR COEFFICIENT AN
C
      DO 31 N=1,NRN
      den = dcadre(f2,0,g,1e-2,1e-3,err,ier)
      an(n) = 2*den/g
31  continue
C
      IF (Z.GT.G) THEN
      GOTO 999
      ENDIF
      Y = 0
C
700  continue
      fgmax = 0
      fg = 0
      tti = 0
      write(ystrin,1) y*10
      call setttextposition(3,52,xy)
      call outtext( ' Y = '// ystrin //'mm ')
      write(zstrin,1) z*10
      call setttextposition(4,52,xy)
      call outtext( ' Z = '// zstrin //'mm ')
      DO 55 i = 0,360
      XX = X - V*i/180.
      RP = (XX**2 + Y**2)**.5

```

```

      if (rp.eq.0) then
        xx = x - v*(i+.05)/180
      endif
      tti = tt
      tt = i/180.
      QQ = (Qoo*EXP(-LA*V*XX))/(2*PI*CY)
C
110      CONTINUE
C
C      *****
C      CALCULATION OF THE COEFFICIENTS AND INDIVIDUAL TERMS
C      IN THE FINAL TEMPERATURE EQUATION.
C      *****
C
C      W1 = ARGUMENT FOR THE FIRST BESSEL FUNCTION
C
      RP = (XX**2 + Y**2)**.5
      W1 = LA * V * RP
C
C      SUMMATION OF THE BESSEL FUNCTION SERIES AND FOR THE
C      SERIES FOR AN.
C
      DD = 0
      DO 30 N=1,NRN
C      W2 = ARGUMENT FOR SECOND BESSEL FUNCTION
      W2 = RP*((LA*LA*V*V)+(N*PI/G)**2)**.5
      S = N*PI/G
      D = AN(n) * BESSK0(W2) * COS(S*Z)
      D = D + DD
      DD = D
30      CONTINUE
C
C      *****
C      FINAL EQN
C      *****
C
      TRI = TRZ
C
C
      TRZ = T0 + (QQ * A0 * BESSK0(W1)) + (QQ * DD)
C
      if (tt.gt.0) then
        FG = (TRZ - TRI)/(TT - tti)
        write(*,*) fg,tt,y,z
      endif
      IF ((FG.GT.TOL1).AND.(TRZ.GT.1373)) THEN
        GOTO 7
      ENDIF
      IF (ABS(FG).GT.ABS(FGMAX)) THEN
        FGMAX = FG

```

```

ELSE
  if (tt.gt.0) then
    GOTO 7
  endif
ENDIF
55 continue
7 CONTINUE
IF ((FG.GT.TOL1).AND.(TRZ.GT.1373)) THEN
  if (y.gt.ymax) then
    ymax = y
  endif
  Y = Y + H
  GOTO 700
ELSE
  IF (Y.GT.(2*H)) THEN
    WRITE(6,*) Y-H,0.25-Z
    write(7,*) -(Y-H),0.25-z
    WRITE(8,*) TRZ-273,fg,0.25-Z
    C    WRITE(*,*) TRZ,fg,Z
        LOCX1 = 319 - NEWX(INT2((Y-H)*1500))
        LOCX = 319 + NEWX(INT2((Y-H)*1500))
        LOCY = 125 + NEWY(INT2((Z)*1500))
        dummy = setcolor (15)
        DUMMYA = SETPIXEL(LOCX,LOCY)
        DUMMYB = SETPIXEL(LOCX1,LOCY)
        locyb = locy
      ENDIF
      Z = Z + H
      zmax = z-h
      GOTO 701
    ENDIF
  C
  C 999 CONTINUE
  C
  C *****
  C OUTPUT
  C *****
  C
  C
  write(ustrin,1) ymax*20
  call settextposition(27,9,xy)
  call outtext('AL4C3 SURFACE WIDTH= '// ustrin //'mm ')
  write(vstrin,1) zmax*10
  call settextposition(28,9,xy)
  call outtext('AL4C3 DEPTH = '// vstrin //'mm ')
  call settextposition(6,53,xy)
  dummy = settextcolor(2)
  call outtext(' Press "ENTER" to continue ')
  read(*,*) ! Wait for ENTER to be pressed
  call clearscreen ($gclearscreen)
  dummy2 = setbkcolor($cyan)
  dummy1 = setcolor(8)

```

```

dummy1 = rectangle($gfillinterior,49,120,500,350)
dummy1 = setcolor(3)
dummy1 = rectangle($gfillinterior,54,115,505,345)
dummy1 = setcolor(1)
dummy1 = rectangle($gborder,54,115,505,345)
dummy1 = settextrcolor(4)
call settextrwindow(5,9,30,59)
CALL SETTEXTPOSITION(8,8,XY)
CALL OUTTEXT('THE WELD PROFILE IN THE Y-Z PLANE CAN')
CALL SETTEXTPOSITION(9,8,XY)
CALL OUTTEXT(' BE VIEWED BY PLOTTING THE PLT FILES ')
CALL SETTEXTPOSITION(10,8,XY)
CALL OUTTEXT(' "ONE" AND "TWO" ')
CALL SETTEXTPOSITION(11,8,XY)
CALL OUTTEXT('THE A14C3 AREA IN THE Y-Z PLANE CAN')
CALL SETTEXTPOSITION(9,8,XY)
CALL OUTTEXT(' BE VIEWED BY PLOTTING THE PLT FILES ')
CALL SETTEXTPOSITION(10,8,XY)
CALL OUTTEXT(' "SIX" AND "SEV" ')
dummy1 = settextrcolor(17)
CALL SETTEXTPOSITION(14,8,XY)
CALL OUTTEXT('press ENTER to EXIT this program ')

```

C
C

```

CLOSE(1)
CLOSE(2)
CLOSE(3)
CLOSE(4)
close(5)
close(6)
close(7)
END

```

C
C
C
C
C

```

*****
SUBROUTINE TO CALCULATE BESSEL FUNCTIONS
*****

```

```

FUNCTION BESSK0(X)
REAL*8 Y,P1,P2,P3,P4,P5,P6,P7,
* Q1,Q2,Q3,Q4,Q5,Q6,Q7
DATA P1,P2,P3,P4,P5,P6,P7/-0.57721566D0,0.42278420D0,
* 0.23069756D0,0.3488590D-1,0.262698D-2,0.10750D-3,
* 0.74D-5/
DATA Q1,Q2,Q3,Q4,Q5,Q6,Q7/1.25331414D0,-0.7832358D-1,
* 0.2189568D-1, -0.1062446D-1,0.587872D-2,
* -0.251540D-2, 0.53208D-3/
IF (X.LE.2.0) THEN
Y=X*X/4.0
BESSK0=(-LOG(X/2.0)*BESSI0(X))+(P1+Y*(P2+Y*(P3+
* Y*(P4+Y*(P5+Y*(P6+Y*P7))))))
ELSE
Y=(2.0/X)

```

```

      BESSK0=(EXP(-X)/SQRT(X))*(Q1+Y*(Q2+Y*(Q3+
*      Y*(Q4+Y*(Q5+Y*(Q6+Y*Q7))))))
      ENDIF
      RETURN
      END
      FUNCTION BESSIO(X)
      REAL*8 Y,P1,P2,P3,P4,P5,P6,P7,
*      Q1,Q2,Q3,Q4,Q5,Q6,Q7,Q8,Q9
      DATA P1,P2,P3,P4,P5,P6,P7/1.0D0,3.5156229D0,
*      3.0899424D0,1.2067492D 0, 0.2659732D0,0.360768D-1,
*      0.45813D-2/
      DATA Q1,Q2,Q3,Q4,Q5,Q6,Q7,Q8,Q9/0.39894228D0,
*      0.1328592D-1,0.225319D-2,-0.157565D-2,
*      0.916281D-2,-0.2057706D-1, 0.2635537D-1,
*      -0.1647633D-1, 0.392377D-2/
      IF (ABS(X).LT.3.75) THEN
        Y=(X/3.75)**2
        BESSIO=P1+Y*(P2+Y*(P3+Y*(P4+Y*(P5+Y*(P6+Y*P7))))
      ELSE
        AX=ABS(X)
        Y=3.75/AX
        BESSIO=(EXP(AX)/SQRT(AX))*(Q1+Y*(Q2+Y*(Q3+Y*(Q4
*      +Y*(Q5+Y*(Q6+Y*(Q7+Y*(Q8+Y*Q9))))))
      ENDIF
      RETURN
      END

```

C
C
C
C
C

```

*****
FUNCTION STATEMENTS
*****

```

```

function f1(z)
common/flc/b0,b1,g
f1 = exp(-(b0+b1*z)*z)
return
end
function f2(z)
common/flc/b0,b1,g
common/f2c/n,pi
f2 = (exp(-(b0+b1*z)*z))*cos(n*pi*z/g)
return
end

```

C
C
C
C
C
C

```

*****
*****
SUBROUTINES FROM THE IMSL ROUTINE TO EVALUATE INTEGRALS
*****

```

C
C
C

```

SUBROUTINE UERTST (IER,NAME)

```

```

      SPECIFICATIONS FOR ARGUMENTS

```

```

      INTEGER          IER

```

```

C      CHARACTER          NAME*(*)
C      INTEGER            SPECIFICATIONS FOR LOCAL VARIABLES
C      CHARACTER          I, IEQDF, IOUNIT, LEVEL, LEVOLD, NIN, NMTB
C      CHARACTER          IEQ, NAMEQ(6), NAMSET(6), NAMUPK(6)
C      DATA              NAMSET/'U','E','R','S','E','T'/
C      DATA              NAMEQ/6*' '/
C      DATA              LEVEL/4/, IEQDF/0/, IEQ/'='/
C
C      UNPACK NAME INTO NAMUPK
C      FIRST EXECUTABLE STATEMENT
C
C      CALL USPDK (NAME,6,NAMUPK,NMTB)
C      GET OUTPUT UNIT NUMBER
C      CALL UGETIO(1,NIN,IOUNIT)
C      CHECK IER
C
C      IF (IER.GT.999) GO TO 25
C      IF (IER.LT.-32) GO TO 55
C      IF (IER.LE.128) GO TO 5
C      IF (LEVEL.LT.1) GO TO 30
C
C      PRINT TERMINAL MESSAGE
C      IF (IEQDF.EQ.1) WRITE(IOUNIT,35) IER,NAMEQ,IEQ,NAMUPK
C      IF (IEQDF.EQ.0) WRITE(IOUNIT,35) IER,NAMUPK
C      GO TO 30
5  IF (IER.LE.64) GO TO 10
C      IF (LEVEL.LT.2) GO TO 30
C
C      PRINT WARNING WITH FIX MESSAGE
C      IF (IEQDF.EQ.1) WRITE(IOUNIT,40) IER,NAMEQ,IEQ,NAMUPK
C      IF (IEQDF.EQ.0) WRITE(IOUNIT,40) IER,NAMUPK
C      GO TO 30
10 IF (IER.LE.32) GO TO 15
C      PRINT WARNING MESSAGE
C      IF (LEVEL.LT.3) GO TO 30
C      IF (IEQDF.EQ.1) WRITE(IOUNIT,45) IER,NAMEQ,IEQ,NAMUPK
C      IF (IEQDF.EQ.0) WRITE(IOUNIT,45) IER,NAMUPK
C      GO TO 30
15 CONTINUE
C
C      CHECK FOR UERSET CALL
C      DO 20 I=1,6
C      IF (NAMUPK(I).NE.NAMSET(I)) GO TO 25
20 CONTINUE
C      LEVOLD = LEVEL
C      LEVEL = IER
C      IER = LEVOLD
C      IF (LEVEL.LT.0) LEVEL = 4
C      IF (LEVEL.GT.4) LEVEL = 4
C      GO TO 30
25 CONTINUE
C      IF (LEVEL.LT.4) GO TO 30
C      PRINT NON-DEFINED MESSAGE
C      IF (IEQDF.EQ.1) WRITE(IOUNIT,50) IER,NAMEQ,IEQ,NAMUPK
C      IF (IEQDF.EQ.0) WRITE(IOUNIT,50) IER,NAMUPK
30 IEQDF = 0

```

```

        RETURN
35  FORMAT(19H *** TERMINAL ERROR,10X,7H( IER = ,I3,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
40  FORMAT(27H *** WARNING WITH FIX ERROR,2X,7H( IER = ,I3,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
45  FORMAT(18H *** WARNING ERROR,11X,7H( IER = ,I3,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
50  FORMAT(20H *** UNDEFINED ERROR,9X,7H( IER = ,I5,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
C
C
C
C
C      SAVE P FOR P = R CASE
C      P IS THE PAGE NAMUPK
C      R IS THE ROUTINE NAMUPK
55  IEQDF = 1
    DO 60 I=1,6
60  NAMEQ(I) = NAMUPK(I)
65  RETURN
    END
C
C      SUBROUTINE UGETIO(IOPT,NIN,NOUT)
C
C      SPECIFICATIONS FOR ARGUMENTS
C      INTEGER      IOPT,NIN,NOUT
C      SPECIFICATIONS FOR LOCAL VARIABLES
C      INTEGER      NIND,NOUTD
C      DATA        NIND/5/,NOUTD/6/
C      FIRST EXECUTABLE STATEMENT
    IF (IOPT.EQ.3) GO TO 10
    IF (IOPT.EQ.2) GO TO 5
    IF (IOPT.NE.1) GO TO 9005
    NIN = NIND
    NOUT = NOUTD
    GO TO 9005
5   NIND = NIN
    GO TO 9005
10  NOUTD = NOUT
9005 RETURN
    END
C
C      SUBROUTINE USPKD  (PACKED,NCHARS,UNPAKD,NCHMTB)
C
C      SPECIFICATIONS FOR ARGUMENTS
C      INTEGER      NC,NCHARS,NCHMTB
C
C      CHARACTER      UNPAKD(1),IBLANK
C      CHARACTER*(1)  PACKED(1)
C      DATA          IBLANK /' '/
C
C      INITIALIZE NCHMTB
    NCHMTB = 0
C
C      RETURN IF NCHARS IS LE ZERO
    IF(NCHARS.LE.0) RETURN
C
C      SET NC=NUMBER OF CHARS TO BE DECODED

```

```

        NC = MIN0 (129,NCHARS)
        DO 5 I=1,NC
            UNPAKD(I) = PACKED(I)
    5 CONTINUE
150 FORMAT (129A1)
C
C                                CHECK UNPAKD ARRAY AND SET NCHMTB
C                                BASED ON TRAILING BLANKS FOUND
        DO 200 N = 1,NC
            NN = NC - N + 1
            IF(UNPAKD(NN) .NE. IBLANK) GO TO 210
200 CONTINUE
210 NCHMTB = NN
    RETURN
    end
C
C
C *****
C CALL SUBROUTINE ENDPROGRAM
C *****
C
    subroutine endprogram()
    include 'fgraph.fd'
    integer*2 dummy
    read(*,*)      ! Wait for ENTER to be pressed
    dummy = setvideomode($defaultmode)
    end

```

APPENDIX 6

COMPUTER CODE FOR THE CALCULATION OF THE THERMOCOUPLE TEMPERATURES

COMPUTER CODE FOR THE CALCULATION OF THE THERMOCOUPLE TEMPERATURES

```

C *****
C *                                     PROGRAM COMP2.FOR *
C *                                     BY  SANTOSH GOPINATHAN *
C * THIS CODE CALCULATES THE TEMP VS TIME FIELDS GENERATED *
C * DURING THE LASER PROCESSING OF METAL MATRIX COMPOSITES *
C * AT A MEASURED CROSS SECTIONAL DISTANCE FROM THE WELD *
C * CENTERLINE BY USING THE MATERIAL PROPERTIES PROVIDED *
C * AND VALUES OF POWER, ABSORPTION EFF., ABSORPTION COEFF.*
C * TRAVERSE VELOCITY THE CONVERGENCE TOLERANCE FOR *
C * SOLIDIFICATION TEMPERATURE AND THE CROSS SECTIONAL *
C * DISTANCE OF THE THERMOCOUPLE FROM THE WELD CENTERLINE *
C *****
C
      include 'fgraph.fi'
      call graphicsmode()
      call condeff1()
      call endprogram()
      end

C
      integer*2 FUNCTION newx(xcoord)
      integer*2 xcoord,maxx,maxy
      real*4 tempx
      common maxx,maxy
      tempx = maxx/1000.0
      tempx = xcoord*tempx +0.5
      newx = tempx
      end

C
      integer*2 FUNCTION newy(ycoord)
      integer*2 ycoord,maxx,maxy
      real*4 tempy
      common maxx,maxy
      tempy = maxy/1000.0
      tempy = ycoord*tempy +0.5
      newy = tempy
      end

      SUBROUTINE graphicsmode()
      include 'fgraph.fd'
      integer*2 dummy,maxx,maxy
      record/videoconfig/myscreen
      common maxx,maxy

```

```

C      find graphics mode
C
      call getvideoconfig(myscreen)
      select case (myscreen.adapter)
        case($cga)
          dummy = setvideomode ($hresbw)
        case($ocga)
          dummy = setvideomode ($orescolor)
        case($ega,$oega)
          if (myscreen.monitor.eq.$mono) then
            dummy = setvideomode ($eresnocolor)
          else
            dummy = setvideomode ($erescolor)
          endif
        case($vga,$ovga,$mcga)
          dummy = setvideomode ($vres16color)
        case($hgc)
          dummy = setvideomode ($hercmono)
        case default
          dummy = 0
      end select
      if (dummy.eq.0) STOP 'error:cannot set graphics mode'

C
C      determine max and min dimensions
C
      call getvideoconfig(myscreen)
      maxx = myscreen.numxpixels - 1
      maxy = myscreen.numypixels - 1
      end

C
      SUBROUTINE CONDEFF1()
C
      include 'fgraph.fd'
      REAL X,XX,Y,Z,QQ,Qo,LA,PI,temp,tol,TRZ,g,tt
      INTEGER COUNT,NRN,AA,MMM,OO
      DIMENSION FZ(999),FY(999),an(100)
      external f1,f2,NEWX,NEWY
      INTEGER*2 DUMMY,NEWX,NEWY,LOCX,LOCY,K
      common/f1c/b0,b1,g
      common/f2c/n,pi
      character*7 testrin,tistrin,rstrin,gstrin
      character*10 astrin,bstrin,cstrin,dstrin,estrin,fstrin
      record /xycoord/ xy
      9/27/91
      Qo = SURFACE HEAT INPUT
      CY = THERMAL CONDUCTIVITY
      CY OF A356Al = 1.51 W/cm K; SiC = 3.04 W/cm K
      SPHT = SPECIFIC HEAT
      SPHT OF A356Al = 0.9623 J/gm K; SiC = 0.598 J/gm K
      DENSITY OF A356Al = 2.685 gm/cc; SiC = 3.22 gm/cc
      LA = (DENSITY*SPHT)/(2*CY)
      1/(2*LA) = THERMAL DIFFUSIVITY (cm^X2^X/sec)

```

```

C      V = VELOCITY OF TRAVERSE (cm/sec)
C      TT = TIME(SECS)
C      G = THICKNESS (.25cm)
C      XX = X - V*TT
C      RP = (XX**2 + Y**2)**.5
C
C      TEMP = 900.0
C
C      TEMP = LOWEST TEMPERATURE AT WHICH LIQUID PHASE OCCURS
C              IN THE ALLOY SYSTEM(^Xo^XK)
C
C      PI = 22.0/7.0
C
C      TT = TIME ALONG THE WELD AT WHICH THE TEMPERATURE
C              FIELD HAS BEEN DEVELOPED (SECS)
C
C      X = DISTANCE ALONG THE WELD AT WHICH THE TEMPERATURE
C              FIELD HAS BEEN DEVELOPED (CMS)
C
C      WRITE(*,*) '*****'
C      WRITE(*,*) 'THIS CODE RUNS AN ANALYTICAL MODEL FOR'
C      WRITE(*,*) 'LASER WELDING OF THE TWO MATERIALS LISTED'
C      WRITE(*,*) 'BELOW.THE OUTPUT OF THIS CODE IS THE TEMP'
C      WRITE(*,*) 'VERSUS TIME PROFILE AT A GIVEN DISTANCE '
C      WRITE(*,*) 'FROM THE WELD CENTERLINE ON THE SURFACE OF'
C      WRITE(*,*) 'THE MATERIAL'
C      WRITE(*,*) '*****'
C      WRITE(*,*) ' '
C      WRITE(*,*) ' '
C
C      USER INPUT:
C
C      WRITE(*,*) 'MATERIAL : A356Al 10%SiC? (1)'
C      WRITE(*,*) '          : A356Al 20%SiC? (2)'
C      READ (*,*) MMM
C      WRITE(*,*) ' '
C      WRITE(*,*) 'NOTE:THE PROPERTIES USED IN THIS CODE FOR'
C      WRITE(*,*) ' Al-10SiC MMC AND Al-20SiC MMC ARE'
C      WRITE(*,*) ' LISTED IN DATA FILES PR1.DAT" AND'
C      WRITE(*,*) ' "PR2.DAT" RESPECTIVELY. PLEASE ACCESS'
C      WRITE(*,*) ' THESE FILES IF YOU NEED TO CHANGE THE'
C      WRITE(*,*) ' PROPERTIES'
C      WRITE(*,*) ' '
C      WRITE(*,*) ' '
C      WRITE(*,*) ' '
C      WRITE(*,*) ' '
C      WRITE(*,*) 'DO YOU WANT A LISTING OF THE PROPERTIES?'
C      WRITE(*,*) '1 = YES, 0 = NO'
C      READ (*,*) OO
C      WRITE(*,*) ' '

```

C
C
C
C

PR1.DAT = FILE IN WHICH A356 Al -10%SiC PROPERTIES
ARE STORED.

```

IF (MMM.EQ.1) THEN
OPEN (4,FILE = 'PR1.DAT')
READ (4,*) CY,SPHT,DENSITY,V,G,NRN,X,T0,TOL
  IF (OO.EQ.1) THEN
    WRITE(*,*) 'PROPERTIES OF A356 ALUMINUM - 10% SiC '
    WRITE(*,*) ' '
    GOTO 211
  ELSE
    GOTO 212
  ENDIF
ENDIF

```

C
C
C
C

PR2.DAT = FILE IN WHICH A356 Al -20%SiC PROPERTIES
ARE STORED.

```

IF (MMM.EQ.2) THEN
OPEN (5,FILE = 'PR2.DAT')
READ (5,*) CY,SPHT,DENSITY,V,G,NRN,X,T0,TOL
  IF (OO.EQ.1) THEN
    WRITE(*,*) 'PROPERTIES OF A356 ALUMINUM - 20% SiC '
    WRITE(*,*) ' '
    GOTO 211
  ELSE
    GOTO 212
  ENDIF
ENDIF

```

C
C

211

```

CONTINUE
WRITE(*,*) '*****'
WRITE(*,*) 'THERMAL CONDUCTIVITY (W/cm^Xo^XK) = ',CY
WRITE(*,*) ' '
WRITE(*,*) 'SPECIFIC HEAT (J/gm^Xo^XK) = ',SPHT
WRITE(*,*) ' '
WRITE(*,*) 'DENSITY (gm/cc) = ',DENSITY
WRITE(*,*) ' '
WRITE(*,*) 'TRAVERSE VELOCITY (cm/sec) = ',V
WRITE(*,*) ' '
WRITE(*,*) 'SAMPLE THICKNESS (cm) = ',G
WRITE(*,*) ' '
WRITE(*,*) 'NUMBER OF ITERATIONS = ',NRN
WRITE(*,*) ' '
WRITE(*,*) 'DATA TAKEN AT X (cm) = ',X
WRITE(*,*) ' '
WRITE(*,*) 'AMBIENT TEMPERATURE (^Xo^XK) = ',T0
WRITE(*,*) ' '
WRITE(*,*) 'TEMPERATURE TOLERANCE (^Xo^XK) = ',TOL
WRITE(*,*) '*****'

```

```

C
212    CONTINUE
2      format(F7.2)
3      format(F6.3)
C
      WRITE(*,*) ' '
      WRITE(*,*) 'ENTER INPUT POWER IN WATTS '
      READ(*,*) Qo
      write(bstrin,2) Qo
C
      WRITE(*,*) ' '
      WRITE(*,*) 'ENTER ALPHA AS A FRACTION'
      READ(*,*) alpha
      write(dstrin,3) alpha
C
      WRITE(*,*) ' '
      write(*,*) 'ENTER ABSORPTION COEFFICIENT B0 (1/CM)'
      read (*,*) B0
      write(estrin,2) B0
C      estrin = b0
C
      WRITE(*,*) ' '
      write(*,*) 'ENTER B1 (1/(CM**2))'
      read (*,*) B1
      write(fstrin,2) B1
C      fstrin = b1
C
      WRITE(*,*) ' '
      write(*,*) 'WANT TO LIST ALL TEMPERATURES?'
      write(*,*) '1 = YES, 0 = NO'
      read (*,*) AA
      WRITE(*,*) ' '
      WRITE(*,*) 'ENTER THE DISTANCE OF THE THERMOCOUPLE'
      WRITE(*,*) 'FROM THE WELD CENTERLINE (CM)'
      READ (*,*) y
      write(gstrin,3) y
      write(cstrin,3) v
C      gstrin = y
C      WRITE(*,*) ' '
C
      LA = (DENSITY*SPHT)/(2.0*CY)
      diff = 1/(2*la)
C      write(*,*) 'thermal diffusivity in cm2/sec = ',diff
C
      rst = 0
      COUNT = 0
      II = 0
      OPEN(1,FILE='UNO')
      open(2,file='beam.dat')
C
      call clearscreen ($gclearscreen)
      dummy2 = setbkcolor($red)

```



```

call outtext(' ALPHA : ' //dstrin//' ')
call settextposition(27,8,xy)
call outtext(' B0 : ' //estrin//' ')
call settextposition(28,8,xy)
call outtext(' B1 : ' //fstrin//' ')
call settextposition(29,8,xy)
call outtext('DIST FROM WELD CENTER:' //gstrin//' CM')
dummy = setcolor(15)
Z = 0
DO 303 K = 0,899
LOCX = NEWX(K)
LOCY = 300
DUMMY = SETPIXEL(LOCX,LOCY)
303 CONTINUE
DO 304 K = 150,650
LOCX = 80
LOCY = NEWY(K)
DUMMY = SETPIXEL(LOCX,LOCY)
304 CONTINUE
DO 555 i = 0,360
XX = X - V*i/60.
tt = i/60.
C EXPRESSION FOR COEFFICIENT A0
C
den = dcadre(f1,0,g,1e-2,1e-3,err,ier)
a0 = den/g
Qoo = (alpha*Qo)/den
QQ = (Qoo*EXP(-LA*V*XX))/(2*PI*CY)
C
C EXPRESSION FOR COEFFICIENT A0
C
DO 31 N=1,NRN
den = dcadre(f2,0,g,1e-2,1e-3,err,ier)
an(n) = 2*den/g
31 continue
C
110 CONTINUE
C
z = 0
C
111 continue
C
C *****
C CALCULATION OF THE COEFFICIENTS AND INDIVIDUAL TERMS
C IN THE FINAL TEMPERATURE EQUATION.
C *****
C
C
C W1 = ARGUMENT FOR THE FIRST BESSEL FUNCTION
C
RP = (XX**2 + Y**2)**.5
W1 = LA * V * RP

```

```

C
C      SUMMATION OF THE BESSEL FUNCTION SERIES AND FOR THE
C      SERIES FOR AN.
C
      DD = 0
      DO 30 N=1,NRN
C      W2 = ARGUMENT FOR SECOND BESSEL FUNCTION
      W2 = RP*((LA*LA*V*V)+(N*PI/G)**2)**.5
C      den = dcadre(f2,0,g,1e-2,1e-3,err,ier)
C      an  = 2*den/g
      S  = N*PI/G
      D = AN(n) * BESSK0(W2) * COS(S*Z)
      D = D + DD
      DD = D
30    CONTINUE
C
C      *****
C      FINAL EQN
C      *****

      TRZ = T0 + (QQ * A0 * BESSK0(W1)) + (QQ * DD)
C
      If (AA.eq.1) then
        write (*,*) trz,y,z
      endif
C
C
C
998   continue
C
C      COMPARING VALUES FOR TOLERANCE
C
      COUNT = COUNT + 1
      II = II + 1
      FY(II) = tt
      FZ(II) = trz-273
      if (rst.lt.fz(ii)) then
        rst = fz(ii)
        yst = fy(ii)
      endif
      write(testrin,1) fz(ii)
1     format(F6.2)
      dummy = settextrcolor(14)
      call settextrwindow(2,59,10,79)
      call settextrposition(2,59,xy)
      call outtext( ' TEMP = '// testrin //'Deg.C ')
      write(tistrin,1) fy(ii)
      call settextrposition(3,59,xy)
      call outtext( ' TIME = '// tistrin //'secs  ')
      LOCX = 100 + NEWX(INT2(FY(II)*100))
      LOCY = 300 - NEWY(INT2(FZ(II)*.5))
      DUMMY = SETPIXEL(LOCX,LOCY)

```

```

555      CONTINUE
C
C      LYST = 100 + NEWX(INT2(YST*100))
C      LRST = 300 - NEWY(INT2((RST-273)*.5))
      write(rstrin,1) rst
      call settextposition(4,56,xy)
      call outtext( ' TMAX = '// rstrin //'Deg.C ')
      dummy = settextcolor(2)
      call outtext(' Press "ENTER" to      continue ')
C      dummy = settextcolor(6)
C      *****
C      OUTPUT
C      *****
C
      WRITE(1,*) COUNT
      DO 301 K = 1,COUNT
      WRITE (1,*) FY(K),FZ(K)
      WRITE (2,*) FZ(K)
301      CONTINUE
      read(*,*)      ! Wait for ENTER to be pressed
      call clearscreen ($gclearscreen)
      dummy2 = setbkcolor($cyan)
      dummy1 = setcolor(8)
      dummy1 = rectangle($gfillinterior,49,120,500,350)
      dummy1 = setcolor(3)
      dummy1 = rectangle($gfillinterior,54,115,505,345)
      dummy1 = setcolor(1)
      dummy1 = rectangle($gborder,54,115,505,345)
      dummy1 = settextcolor(4)
      call settextwindow(5,9,30,59)
      CALL SETTEXTPOSITION(9,8,XY)
      CALL OUTTEXT('THE TEMP VS TIME PLOT IN THE Y-Z PLANE')
      CALL SETTEXTPOSITION(10,8,XY)
      CALL OUTTEXT('MAY BE VIEWED BY PLOTTING THE PLT FILE')
      CALL SETTEXTPOSITION(11,8,XY)
      CALL OUTTEXT('      "UNO"      ')
      dummy1 = settextcolor(17)
      CALL SETTEXTPOSITION(13,8,XY)
      CALL OUTTEXT('press ENTER to EXIT this program ')
      CLOSE(1)
      END
C
C      *****
C      SUBROUTINE TO CALCULATE BESSEL FUNCTIONS
C      *****
C
      FUNCTION BESSK0(X)
      REAL*8 Y,P1,P2,P3,P4,P5,P6,P7,
      *      Q1,Q2,Q3,Q4,Q5,Q6,Q7
      DATA P1,P2,P3,P4,P5,P6,P7/-0.57721566D0,0.42278420D0,
      *      0.23069756D0,0.3488590D-1,0.262698D-2,0.10750D-3,
      *      0.74D-5/

```

```

DATA Q1,Q2,Q3,Q4,Q5,Q6,Q7/1.25331414D0,-0.7832358D-1,
* 0.2189568D-1, -0.1062446D-1,0.587872D-2,
* -0.251540D-2, 0.53208D-3/
IF (X.LE.2.0) THEN
  Y=X*X/4.0
  BESSK0=(-LOG(X/2.0)*BESSIO(X))+(P1+Y*(P2+Y*(P3+
* Y*(P4+Y*(P5+Y*(P6+Y*P7))))))
ELSE
  Y=(2.0/X)
  BESSK0=(EXP(-X)/SQRT(X))*(Q1+Y*(Q2+Y*(Q3+
* Y*(Q4+Y*(Q5+Y*(Q6+Y*Q7))))))
ENDIF
RETURN
END
FUNCTION BESSIO(X)
REAL*8 Y,P1,P2,P3,P4,P5,P6,P7,
* Q1,Q2,Q3,Q4,Q5,Q6,Q7,Q8,Q9
DATA P1,P2,P3,P4,P5,P6,P7/1.0D0,3.5156229D0,
* 3.0899424D0,1.2067492D 0, 0.2659732D0,0.360768D-1,
* 0.45813D-2/
DATA Q1,Q2,Q3,Q4,Q5,Q6,Q7,Q8,Q9/0.39894228D0,
* 0.1328592D-1,0.225319D-2,-0.157565D-2,
* 0.916281D-2,-0.2057706D-1, 0.2635537D-1,
* -0.1647633D-1, 0.392377D-2/
IF (ABS(X).LT.3.75) THEN
  Y=(X/3.75)**2
  BESSIO=P1+Y*(P2+Y*(P3+Y*(P4+Y*(P5+Y*(P6+Y*P7))))
ELSE
  AX=ABS(X)
  Y=3.75/AX
  BESSIO=(EXP(AX)/SQRT(AX))*(Q1+Y*(Q2+Y*(Q3+Y*(Q4
* +Y*(Q5+Y*(Q6+Y*(Q7+Y*(Q8+Y*Q9))))))
ENDIF
RETURN
END

```

C
C
C
C
C

```

*****
FUNCTION STATEMENTS
*****

```

```

function f1(z)
common/flc/b0,b1,g
f1 = exp(-(b0+b1*z)*z)
return
end
function f2(z)
common/flc/b0,b1,g
common/f2c/n,pi
f2 = (exp(-(b0+b1*z)*z))*cos(n*pi*z/g)
return
end

```

```

C *****
C SUBROUTINES FROM THE IMSL ROUTINE TO EVALUATE INTEGRALS
C *****
C
C SUBROUTINE UERTST (IER,NAME)
C
C SPECIFICATIONS FOR ARGUMENTS
C INTEGER IER
C CHARACTER NAME*(*)
C
C SPECIFICATIONS FOR LOCAL VARIABLES
C INTEGER I, IEQDF, IOUNIT, LEVEL, LEVOLD, NIN, NMTB
C CHARACTER IEQ, NAMEQ(6), NAMSET(6), NAMUPK(6)
C DATA NAMSET/'U','E','R','S','E','T'/
C DATA NAMEQ/6*' '/
C DATA LEVEL/4/, IEQDF/0/, IEQ/'='/
C
C UNPACK NAME INTO NAMUPK
C FIRST EXECUTABLE STATEMENT
C
C CALL USPKD (NAME,6,NAMUPK,NMTB)
C GET OUTPUT UNIT NUMBER
C CALL UGETIO(1,NIN,IOUNIT)
C CHECK IER
C
C IF (IER.GT.999) GO TO 25
C IF (IER.LT.-32) GO TO 55
C IF (IER.LE.128) GO TO 5
C IF (LEVEL.LT.1) GO TO 30
C
C PRINT TERMINAL MESSAGE
C IF (IEQDF.EQ.1) WRITE(IOUNIT,35) IER,NAMEQ,IEQ,NAMUPK
C IF (IEQDF.EQ.0) WRITE(IOUNIT,35) IER,NAMUPK
C GO TO 30
5 IF (IER.LE.64) GO TO 10
C IF (LEVEL.LT.2) GO TO 30
C
C PRINT WARNING WITH FIX MESSAGE
C IF (IEQDF.EQ.1) WRITE(IOUNIT,40) IER,NAMEQ,IEQ,NAMUPK
C IF (IEQDF.EQ.0) WRITE(IOUNIT,40) IER,NAMUPK
C GO TO 30
10 IF (IER.LE.32) GO TO 15
C
C PRINT WARNING MESSAGE
C IF (LEVEL.LT.3) GO TO 30
C IF (IEQDF.EQ.1) WRITE(IOUNIT,45) IER,NAMEQ,IEQ,NAMUPK
C IF (IEQDF.EQ.0) WRITE(IOUNIT,45) IER,NAMUPK
C GO TO 30
15 CONTINUE
C
C CHECK FOR UERSET CALL
C
C DO 20 I=1,6
C IF (NAMUPK(I).NE.NAMSET(I)) GO TO 25
20 CONTINUE
C LEVOLD = LEVEL
C LEVEL = IER
C IER = LEVOLD

```

```

        IF (LEVEL.LT.0) LEVEL = 4
        IF (LEVEL.GT.4) LEVEL = 4
        GO TO 30
25 CONTINUE
        IF (LEVEL.LT.4) GO TO 30
C          PRINT NON-DEFINED MESSAGE
        IF (IEQDF.EQ.1) WRITE(IOUNIT,50) IER,NAMEQ,IEQ,NAMUPK
        IF (IEQDF.EQ.0) WRITE(IOUNIT,50) IER,NAMUPK
30 IEQDF = 0
    RETURN
35 FORMAT(19H *** TERMINAL ERROR,10X,7H( IER = ,I3,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
40 FORMAT(27H *** WARNING WITH FIX ERROR,2X,7H( IER = ,I3,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
45 FORMAT(18H *** WARNING ERROR,11X,7H( IER = ,I3,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
50 FORMAT(20H *** UNDEFINED ERROR,9X,7H( IER = ,I5,
1      20H) FROM IMSL ROUTINE ,6A1,A1,6A1)
C
C          SAVE P FOR P = R CASE
C          P IS THE PAGE NAMUPK
C          R IS THE ROUTINE NAMUPK
55 IEQDF = 1
    DO 60 I=1,6
60 NAMEQ(I) = NAMUPK(I)
65 RETURN
    END
C
    SUBROUTINE UGETIO(IOPT,NIN,NOUT)
C
C          SPECIFICATIONS FOR ARGUMENTS
C          INTEGER          IOPT,NIN,NOUT
C          SPECIFICATIONS FOR LOCAL VARIABLES
C          INTEGER          NIND,NOUTD
C          DATA            NIND/5/,NOUTD/6/
C          FIRST EXECUTABLE STATEMENT
        IF (IOPT.EQ.3) GO TO 10
        IF (IOPT.EQ.2) GO TO 5
        IF (IOPT.NE.1) GO TO 9005
        NIN = NIND
        NOUT = NOUTD
        GO TO 9005
    5 NIND = NIN
      GO TO 9005
    10 NOUTD = NOUT
9005 RETURN
    END
C
    SUBROUTINE USPKD (PACKED,NCHARS,UNPAKD,NCHMTB)
C
C          SPECIFICATIONS FOR ARGUMENTS
C          INTEGER          NC,NCHARS,NCHMTB

```

```

C      CHARACTER          UNPAKD(1),IBLANK
      CHARACTER*(1)      PACKED(1)
      DATA              IBLANK '/' '/'
C                               INITIALIZE NCHMTB
      NCHMTB = 0
C                               RETURN IF NCHARS IS LE ZERO
      IF(NCHARS.LE.0) RETURN
C                               SET NC=NUMBER OF CHARS TO BE DECODED
      NC = MIN0 (129,NCHARS)
      DO 5 I=1,NC
        UNPAKD(I) = PACKED(I)
5 CONTINUE
150 FORMAT (129A1)
C                               CHECK UNPAKD ARRAY AND SET NCHMTB
C                               BASED ON TRAILING BLANKS FOUND
      DO 200 N = 1,NC
        NN = NC - N + 1
        IF(UNPAKD(NN) .NE. IBLANK) GO TO 210
200 CONTINUE
210 NCHMTB = NN
      RETURN
      end
C
C *****
C CALL SUBROUTINE ENDPROGRAM
C *****
C
      subroutine endprogram()
      include 'fgraph.fd'
      integer*2 dummy
      read(*,*)          ! Wait for ENTER to be pressed
      dummy = setvideomode($defaultmode)
      end

```

VITA

Santosh Gopinathan was born in Trichur, India on April 14, 1965. He finished his high schooling at Loyola High School, Poona, India and his Bachelor of Engineering in Metallurgical Engineering from the College of Engineering, Poona, India. He obtained his Master of Science degree in Metallurgical Engineering from the South Dakota School of Mines and Technology, Rapid City, South Dakota. He joined the University of Tennessee Space Institute in September 1988 and received his Doctor of Philosophy degree in Engineering Science and Mechanics in August 1992.