CONF-9010282--2

SAND--90-3114C

DE91 005861

Received by OSTI

JAN 0 8 1991

Calorimetric Measurements Of Energy Transfer Efficiency And Melting Efficiency In CO_2 Laser Beam Welding

P.W. Fuerschbach
Sandia National Laboratories
Albuquerque, New Mexico

Introduction

Our previous calorimetric studies[1] of weld melting efficiency and arc efficiency in the GTAW and PAW processes have naturally led us to speculate as to the magnitude of the efficiencies in the LBW process which to date have also not been adequately investigated. Most welding engineers that have had experience with the LBW process are acutely aware that the metals' absorptivity, the surface finish, and the laser wavelength, all play an important role in affecting the energy transfer efficiency, but the extent of their influence and our understanding of the influence of other process variables is not well understood. In addition, it is widely thought that only the LBW or EBW processes can be selected for applications where thermal damage and distortion from the welding process must be kept to a minimum. For these reasons, we have looked forward to performing these calorimetric experiments since they potentially can answer such important questions as: whether or not the melting efficiency of the LBW process is superior to that obtainable with conventional GTAW and PAW welding processes? This study was prompted by poor production yields on a switching device due to cracking of the ceramic header after final closure welding with the CO_2 LBW process. This calorimetric study was begun in hopes of determining if allowed variations in production process control variables were responsible for increases in heat input and the resulting thermal stresses. By measuring the net heat input to the workpiece with the calorimeter and by measuring the laser output energy and the weld fusion zone size it was possible to determine the magnitudes of both the energy transfer efficiency and the melting efficiency as well as observe their dependence on the process variables.

Experimental

The production weld schedule in question is given in the appended figures, the weld schedule is not unusual since the laser power was quite low and the travel speed was relatively high; we would expect from our past GTAW and PAW studies that these conditions would produce a weld with a high melting efficiency. Of a much greater concern however was the inexact method of determining the focused spot size, and the fact that the spot size had to be increased in order to bridge joint gaps necessitated by part mismatch due to generous fabrication tolerances and deburred edges. Since spot size strongly affects the power density the experimental variables were chosen in order to vary the power density and yet produce welds with penetration depths similar to the production parts. This was accomplished by defocusing and selecting different focal length focusing lenses to vary power density; since the depth of melting was found to increase with power density, a reduction in power and/or an increase in travel speed were required in order to compensate.

Welds were made directly into an open Seebeck envelope calorimeter[2] mounted on a CNC table in the workstation of a slow flow 1200 watt CO_2 laser. The welds were bead-on-plate type located in the center of an 0.050 in wide 304L stainless steel machined sample. The calorimeter

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

output trace was recorded with a digital oscilloscope and subsequently integrated to determine the energy absorbed by the sample. Fusion zone geometrical parameters(volume,penetration,width) were determined from the average of four metallographic cross-sections for each weld.

LBW Melting Efficiency

It was found that the practice of defocusing the laser beam could significantly reduce the melting efficiency. Sharp focus welds with penetration depths equivalent to defocused welds were made with net heat inputs to the part up to 50% less. It was also found that welds with equivalent net heat inputs were produced with differences of over 300% in penetration as a result of changes in the focusing optics. These observations indicated that the melting efficiency was increasing with power density, although the actual dependence could not be determined since it was not feasible to measure the spot size in the experiment. However, the suspected dependence was corroborated by the additional finding that melting efficiency was proportional to depth-to-width ratio, which is consistent since weld depth-to-width ratio is usually a good indicator of laser power density.

For most conditions melting efficiency showed a roughly linear dependence on fusion zone aspect ratio from a low value of about 5% to a high value of about 32%. These top values were surprisingly low when compared to the best values we have measured in the past for arc welding processes. There was however a small group of welds that had unusually high melting efficiencies(a peak of ~45%) when compared with the rest of the data. Upon further examination it was discovered that these welds had melted all the way to the edge of the sample producing a two dimensional heat flow geometry that was more like the heat flow in the arc welds we had studied previously. A literature search on the subject of melting efficiency revealed that the maximum melting efficiency obtainable for any welding process is dependent on the heat flow geometry in the workpiece. Based on analytical solutions using Rosenthals' moving heat source equations it has been reported[3] that joint geometries that establish a two dimensional heat flow condition can produce a higher melting efficiency than three dimensional heat flow geometries. The predicted maximum value for two dimensional heat flow is 48% and the maximum value for three dimensional heat flow is 37%. These values are very close to the maximum values reported above for the two distinctly different groups.

It appears that the three dimensional heat flow geometry that is typical of most of the welds in this study is responsible for the lower peak melting efficiencies when compared to previous values obtained for arc welding where two dimensional heat flow occurred and when compared to the small group of welds in this study that melted to the edge and therefore also had two dimensional heat flow. It is important to note that the maximum melting efficiency obtained in this study for the CO_2 LBW process is not any higher than the maximum obtained in our eartlier studies of the PAW and GTAW processes. It was also observed that when the melting efficiencies we have measured for these welding processes are compared on the basis of weld size, it does appear that the LBW process may have an advantage in achieving a high melting efficiency for very small welds. More arc welding calorimetry needs to be done for very small welds however to verify this observation.

LBW Energy Transfer Efficiency

Just as melting efficiency was found to correlate well with the fusion zone aspect ratio the energy transfer efficiency also correlated well with the aspect ratio. Unlike the arc welding processes the LBW energy transfer efficiency is not a constant and was found to vary from about 20% to 73%. It is thought that the increasing fusion zone depth to width ratio helps to trap the laser light in the workpiece due to the Mendenhall wedge effect(multiple internal reflections). The inability to accurately estimate the energy transferred to the workpiece is a serious shortcoming with the LBW process at least for the partial penetration conditions represented here. Noting that the energy transfer efficiency was found to approach its maximum value for the high aspect ratio welds, it is reasonable to expect that when the process is used in the deep penetration keyhole mode the energy transfer efficiency will be more stable at a high percentage for most conditions and likely easier to estimate. For welds like the partial penetration welds represented here it may prove beneficial to measure the depth to width ratio of a weld in order to estimate the energy transfer efficiency since there is a good correlation between the two dependent variables.

As a consequence of the wide variation in energy transfer efficiency that occurred in this study the traditional welding heat input parameter in j/in, which is found by dividing the heat source output power by the travel speed, has been shown to be a poor indicator of the actual heat input to the part and therefore has diminished value in LBW weld schedule development.

1. Knorovsky, G.A., Fuerschbach, P.W., "A Calorimetric-Based Comparison of Gas Tungsten and Plasma Arc Welding Processes", *Proc. JOWOG 22D Joining Subgroup Meeting*, (Aldermasten,UK, Oct 4-6,1988).

2. W.H. Giedt, P.W. Fuerschbach, L.N. Tallerico, "GTA Welding Efficiency-Calorimetric and Temperature Field Measurements," *Welding Journal*, 68(1), pp. 285s-325s (1989).

3. Okada, A. 1977. "Application of Melting Efficiency and its Problems", *Journal of the Japan Welding Society*, 46 (2) :56-61.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DEFINITIONS

ENERGY TRANSFER EFFICIENCY =

NET INPUT ENERGY / LASER OUTPUT ENERGY

MELTING EFFICIENCY =

ENTHALPY OF WELD VOLUME / NET INPUT ENERGY

$$\text{ENTHALPY} = [\,\Delta H_f + \int_{RT}^{MP} c_p\,(T)\,dT] \cdot \text{Volume}$$

REASONS FOR THIS STUDY

- Poor production yields due to cracking of the ceramic header after closure welding. (~20% need reworked)
- Determine if allowed variations in production process control variables affects net heat input and resulting thermal stresses.
- Measure the melting efficiency of the Laser Beam Welding(LBW) process in order to quantitatively compare it with traditional welding processes such as GTAW.
- Determine what process variables affect the energy transfer efficiency and its magnitude.

Production Weld Schedule

Materials:	Kovar to 304L SS
Required Penetration:	0.005 in
Laser Output Power:	260 watts cont. wave
Travel Speed:	40 in/min
Focussing Lens:	2.5 in focal length meniscus*

* operator visually determines sharp focus position then defocuses 0.025 in.

RANGE OF EXPERIMENTAL VARIABLES

Output Power: 180-350 watts

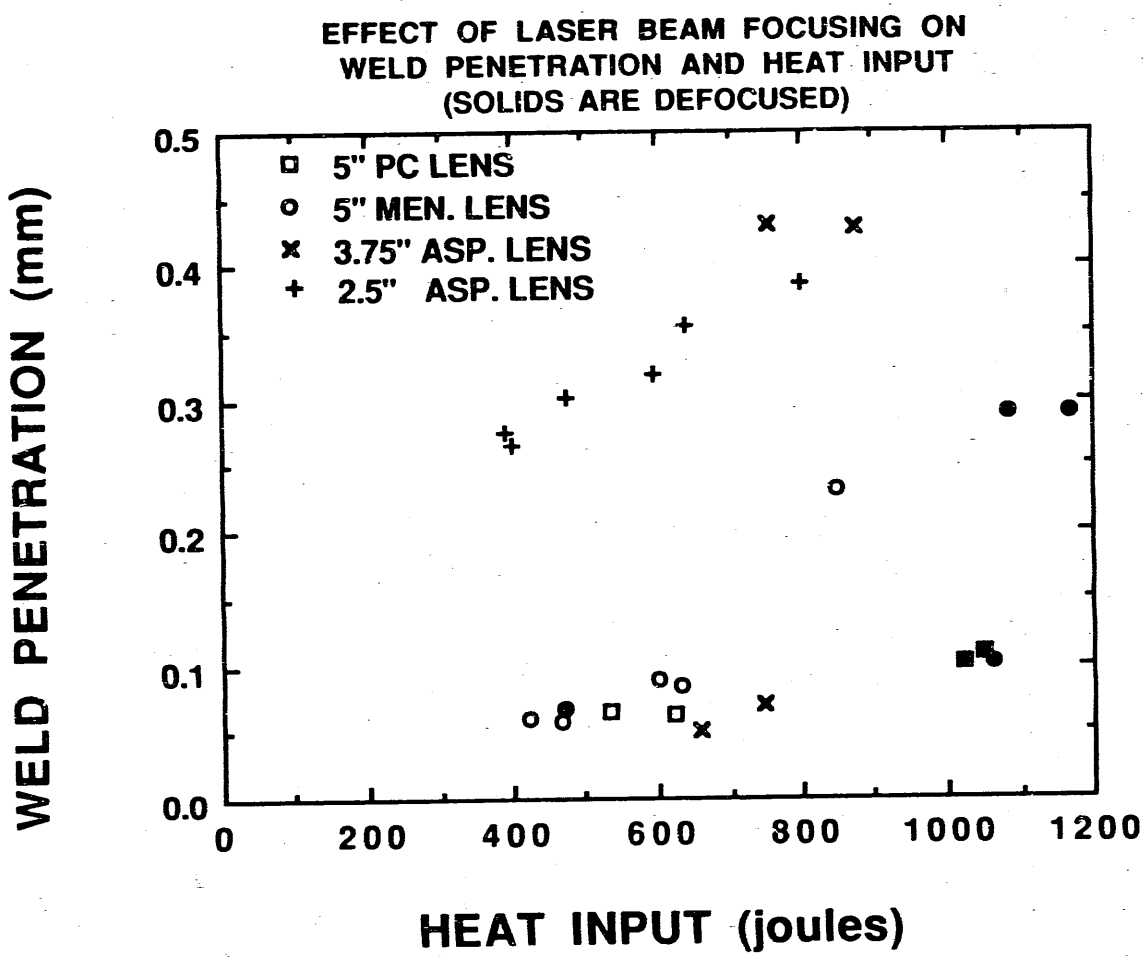
Travel Speed: 40-144 in/min

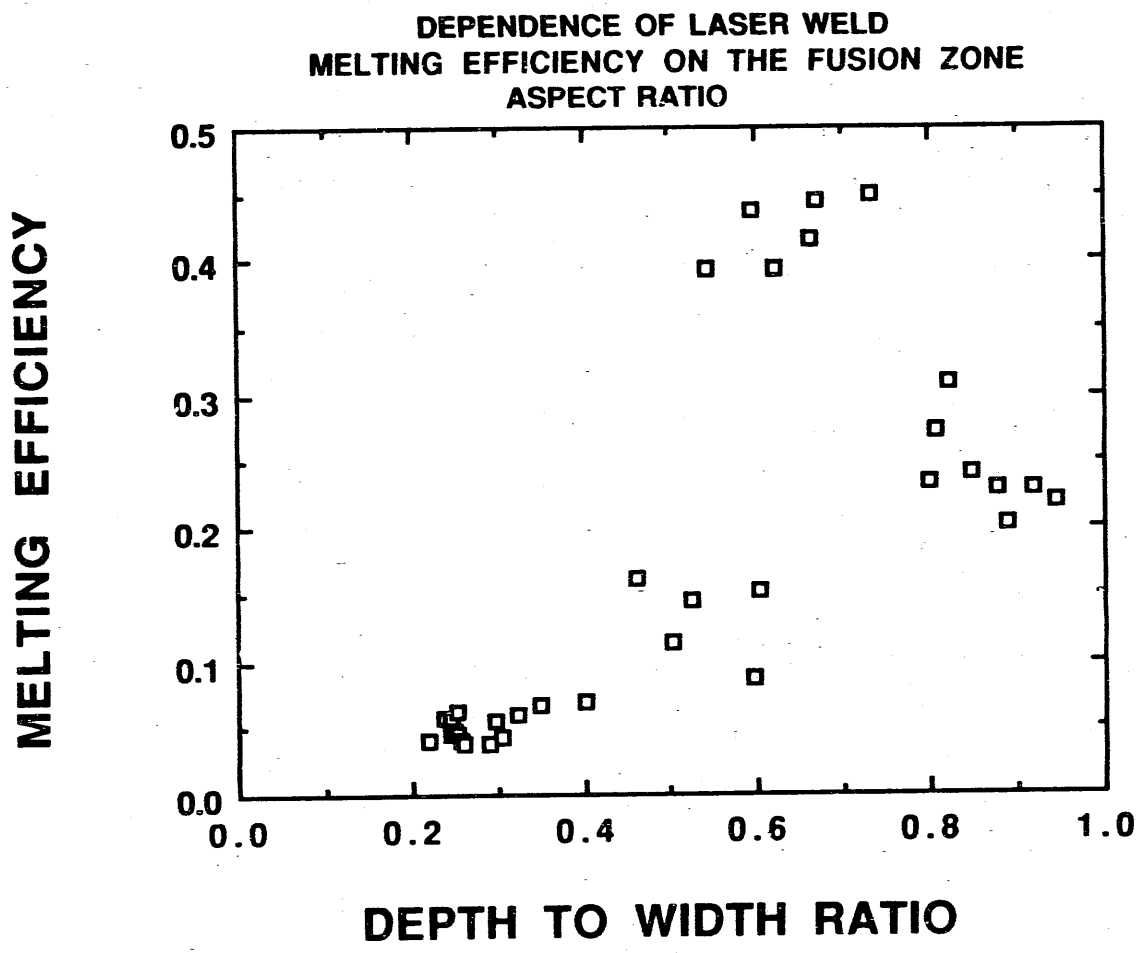
Focusing Lenses: 5"FL PC, 5"FL Men., 3.75"FL Asp., 2.5"FL Asp.

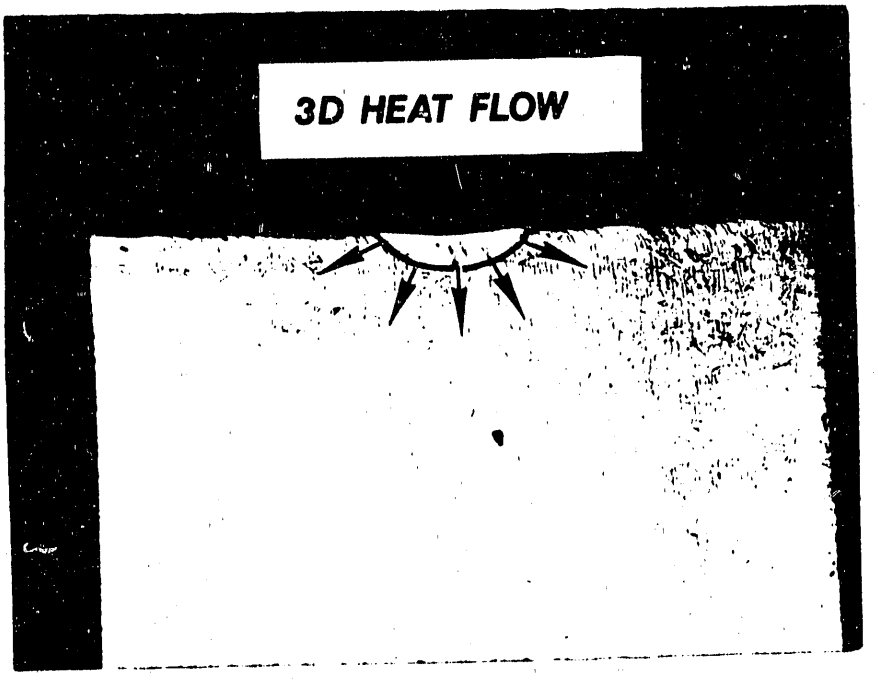
Lenses were used to increase power density, which in turn, increased melting, and required decreases in power, and increases in travel speed to compensate.

EXPERIMENTAL

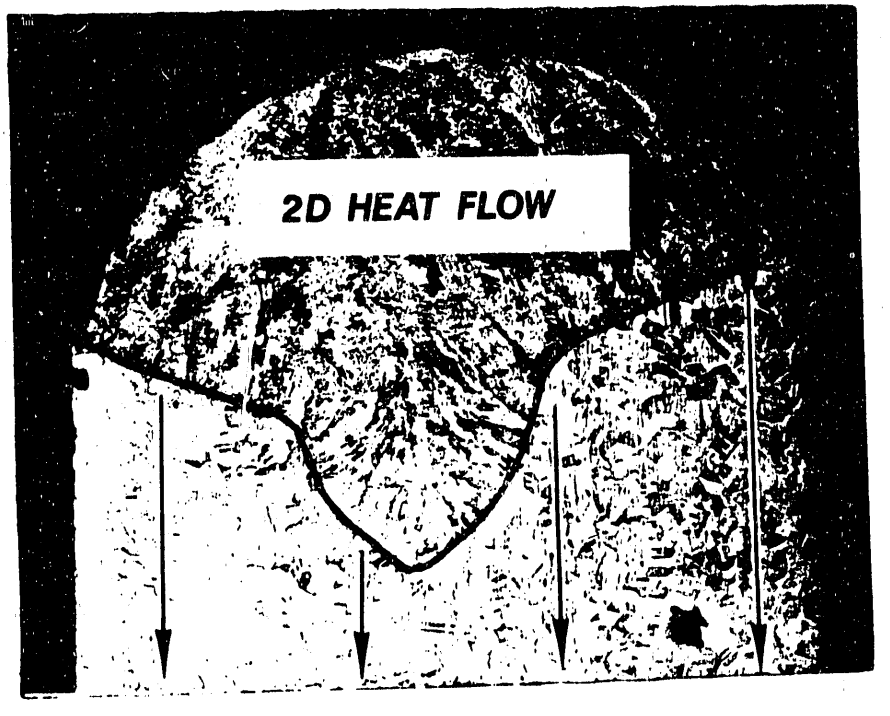
- Photon Sources Versa-Lase 1200 CO_2 Laser
- Welds made directly into open Thermonetics Seebeck envelope calorimeter mounted on CNC table in workstation.
- 100 mm long welds made in center of 1.3 mm wide edge of 304L SS machined sample.
- Calorimeter output trace recorded with digital oscilloscope and subsequently integrated to determine the energy absorbed by the sample.
- Average of four metallographic cross-sections for each weld was used to find the fusion zone geometrical parameters (i.e. weld volume, penetration, depth to width ratio)


EFFECT OF LASER BEAM FOCUSING ON
WELD PENETRATION AND HEAT INPUT
(SOLIDS ARE DEFOCUSED)
5" PC LENS
5" MEN. LENS
3.75" ASP. LENS
2.5" ASP. LENS
WELD PENETRATION (mm)
0.0
0.1
0.2
0.3
0.4
0.5
0
200
400
600
800
1000
1200
HEAT INPUT (joules)


DEPENDENCE OF LASER WELD
MELTING EFFICIENCY ON THE FUSION ZONE
ASPECT RATIO
MELTING EFFICIENCY
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.2
0.4
0.6
0.8
1.0
DEPTH TO WIDTH RATIO



(a)



(b)

Fig. 3— Laser welds on 304SS illustrating different heat flow patterns: (a) melt eff. = 0.04, (b) melt eff. = 0.39

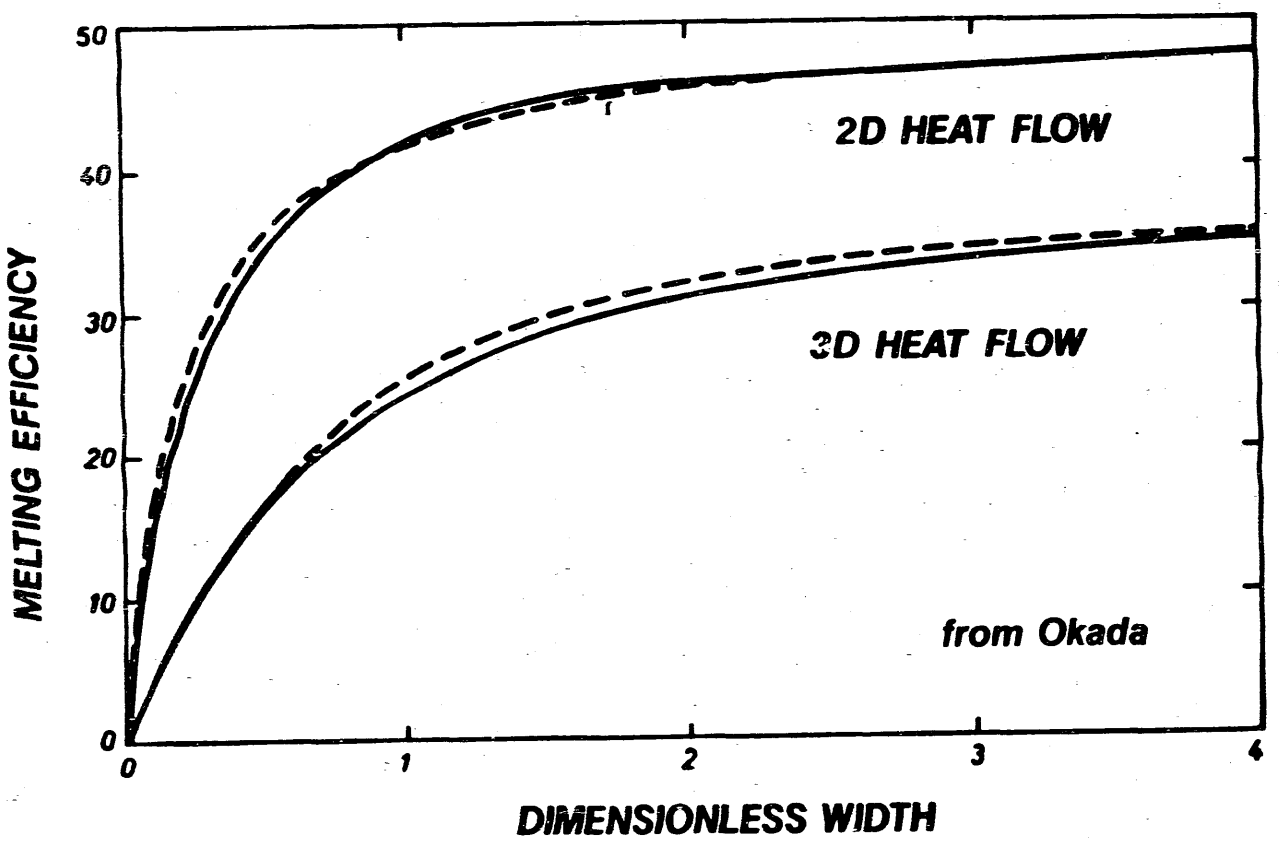
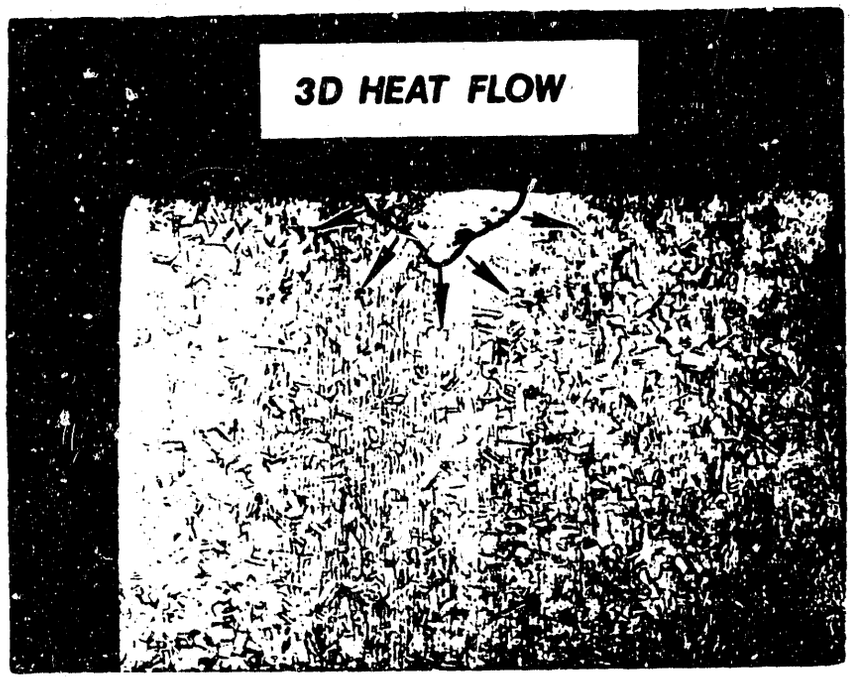
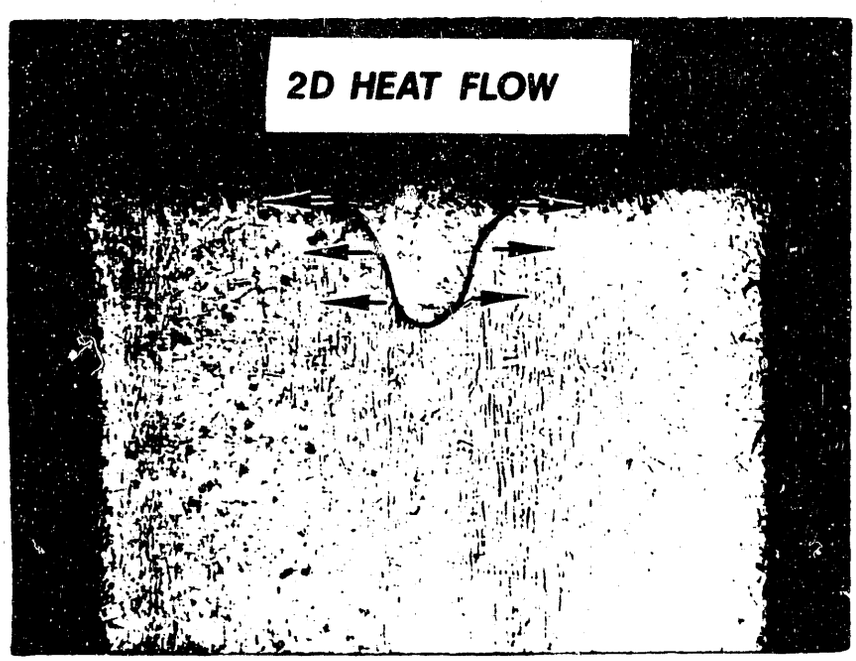


Fig. 4—The relationship between melting efficiency and dimensionless weld width for two different heat flow conditions.



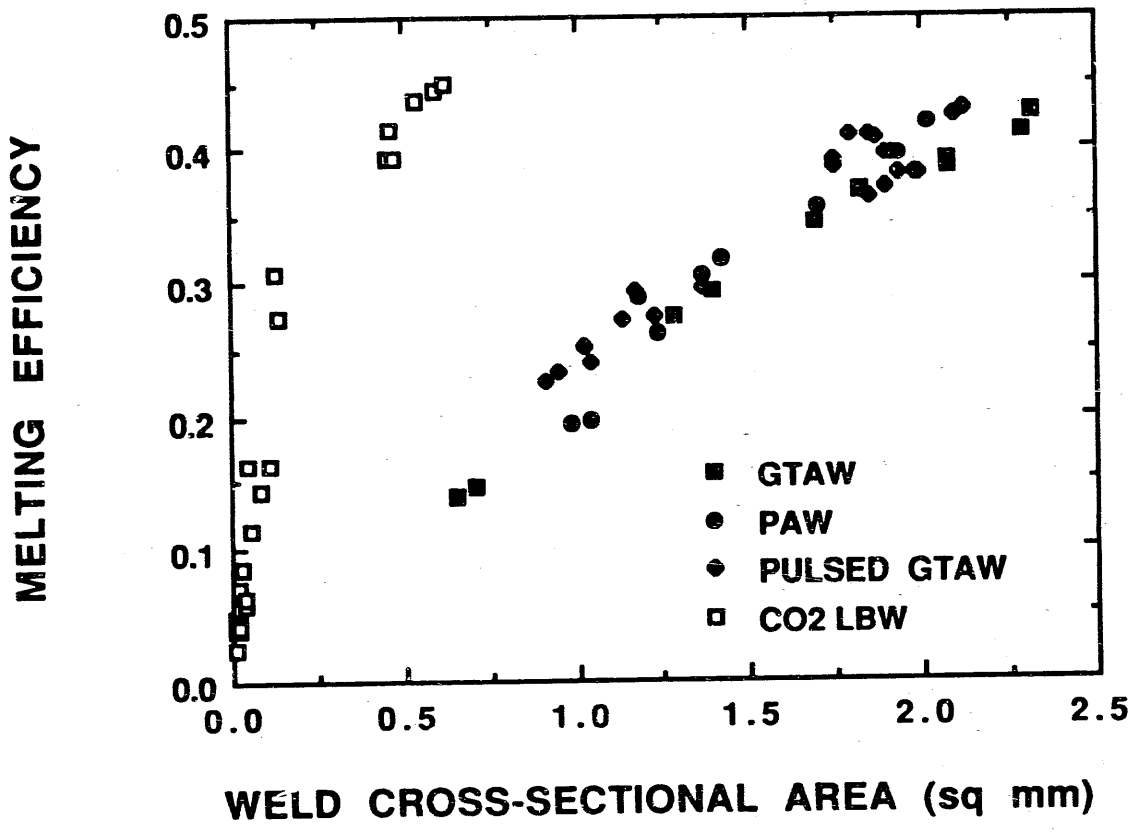
(a)



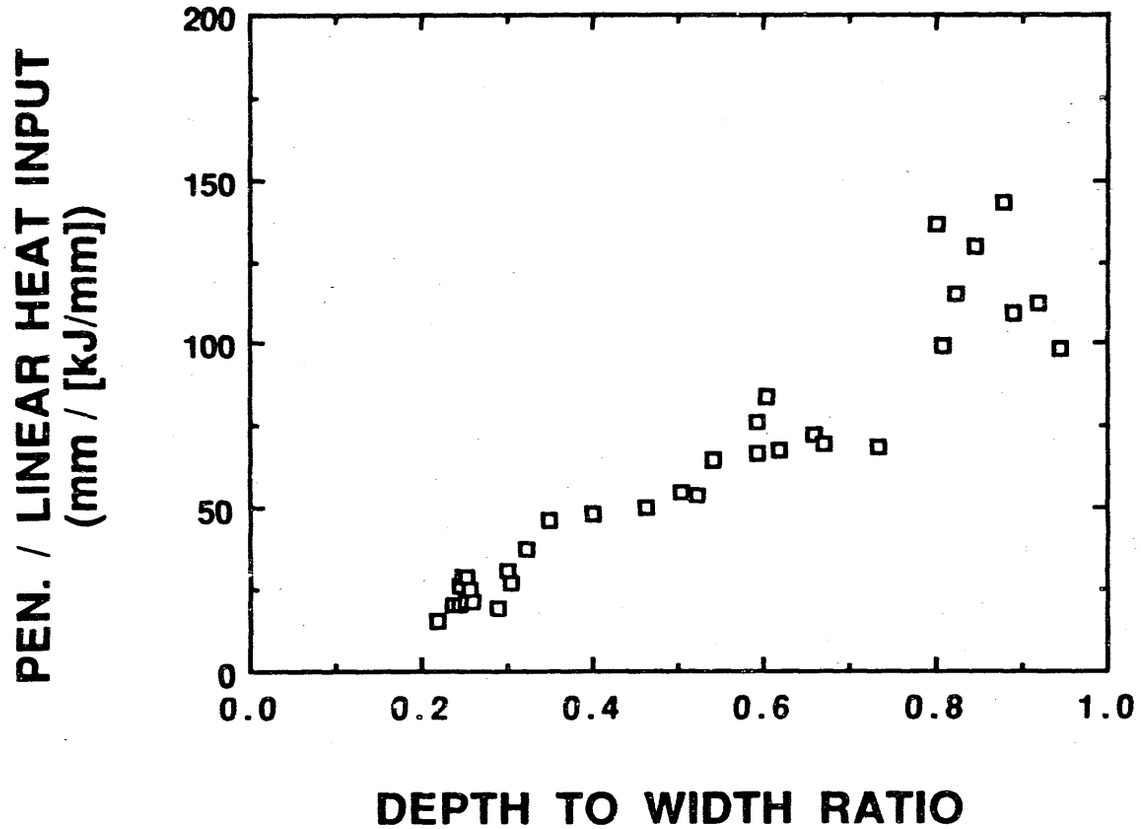
(b)

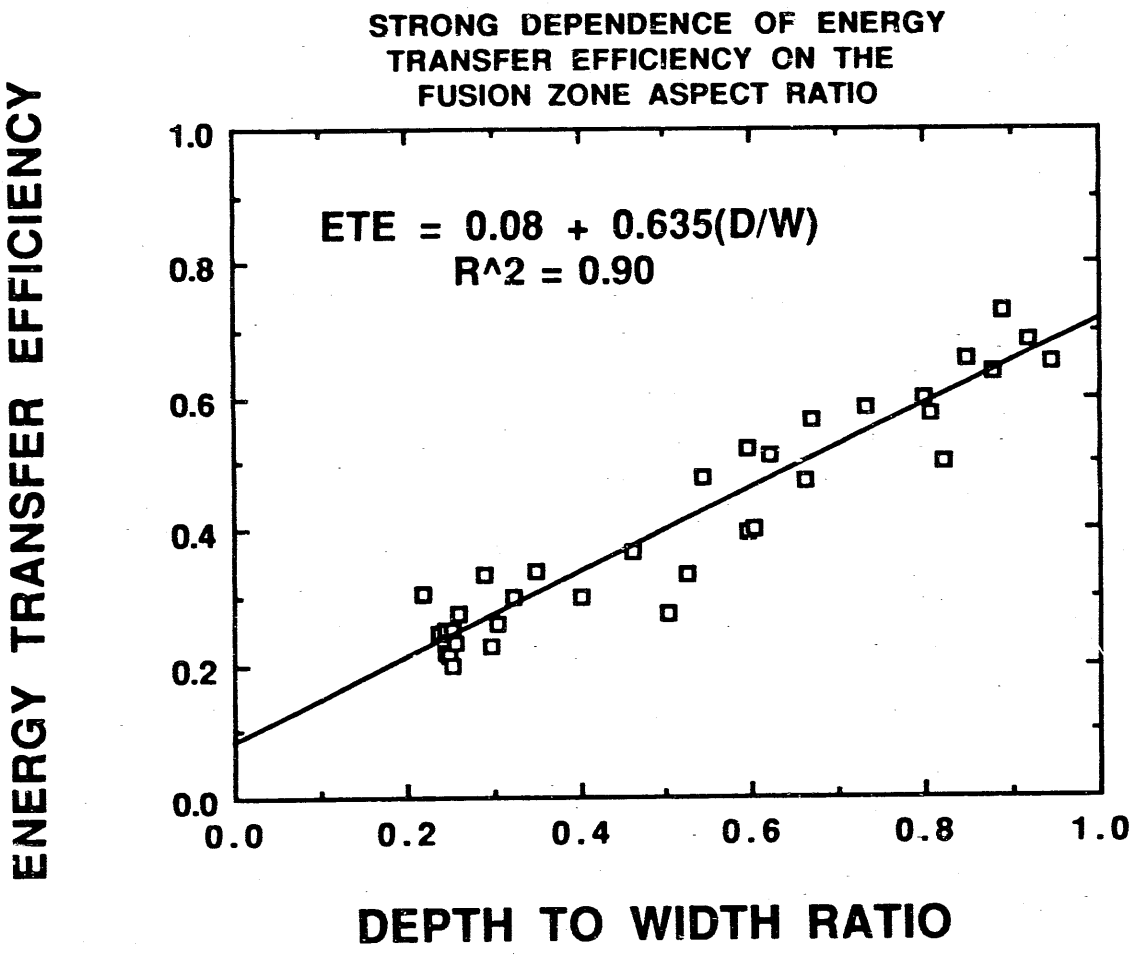
Fig. 5—Laser beam welds on 304SS illustrating postulated heat flow patterns: (a) D/W = 0.40, (b) D/W = 0.80

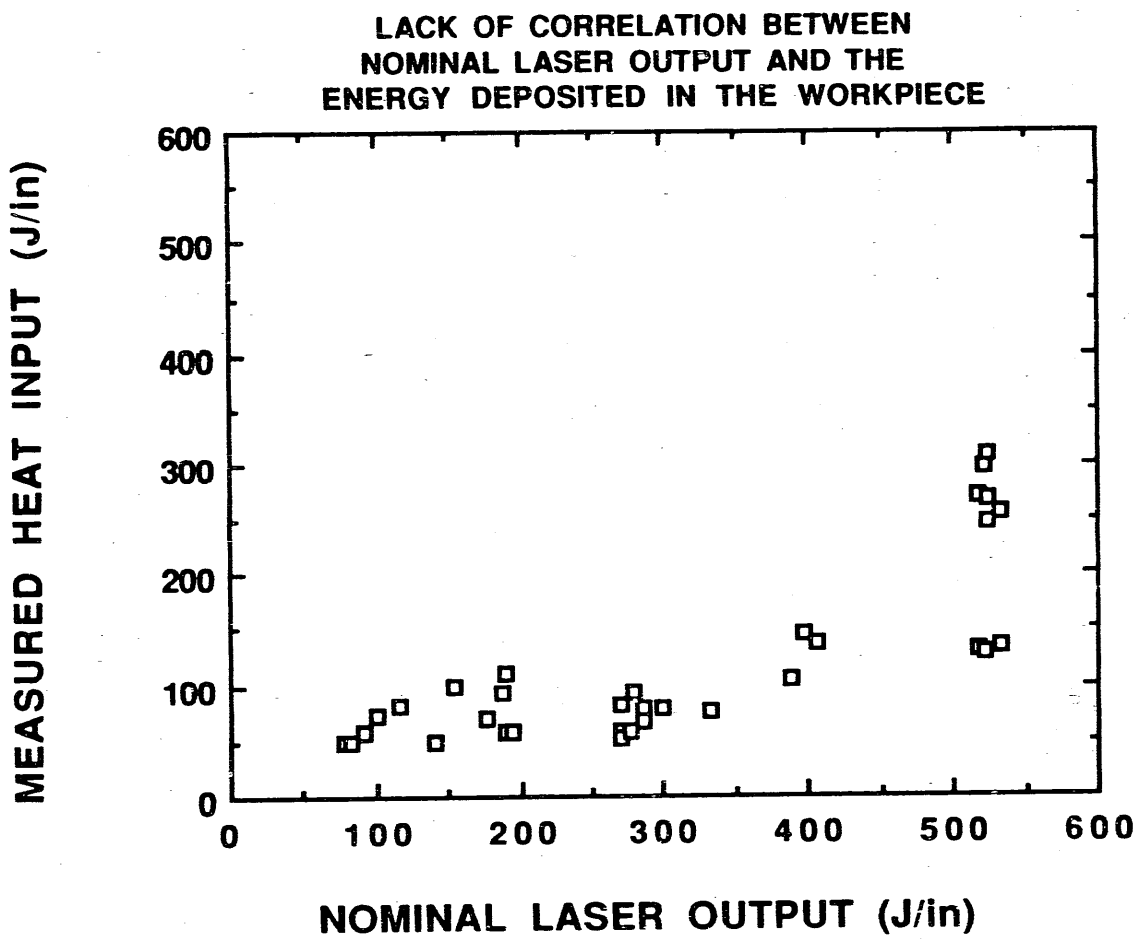
COMPARISON OF MEASURED MELTING EFFICIENCIES FOR THE LBW, PAW AND GTAW PROCESSES ON 304 SS



STRONG DEPENDENCE OF NORMALIZED WELD PENETRATION ON FUSION ZONE ASPECT RATIO




STRONG DEPENDENCE OF ENERGY
TRANSFER EFFICIENCY ON THE
FUSION ZONE ASPECT RATIO
ETE = 0.08 + 0.635(D/W)
R^2 = 0.90
ENERGY TRANSFER EFFICIENCY
DEPTH TO WIDTH RATIO
0.0
0.2
0.4
0.6
0.8
1.0


LACK OF CORRELATION BETWEEN
NOMINAL LASER OUTPUT AND THE
ENERGY DEPOSITED IN THE WORKPIECE
MEASURED HEAT INPUT (J/in)
600
500
400
300
200
100
0
0
100
200
300
400
500
600
NOMINAL LASER OUTPUT (J/in)

CONCLUSIONS

- The production welds should not be made with the lens defocused since defocusing results in significantly higher heat input.
- The measured melting efficiencies for the LBW process are not any higher than values we have measured for the GTAW and PAW processes.
- The weld heat flow geometry was found to influence LBW melting efficiency as predicted in the literature.
- The energy transfer efficiency for partial penetration CO_2 LBW was seen to vary from ~20% to ~73% and to depend strongly on the fusion zone aspect ratio.

END

DATE FILMED

01 / 29 / 91