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# THE EFFECTS OF WELD GEOMETRY ON WELD QUALITY AND FATIGUE PROPERTIES OF GALVANIZED HSLA LASER SEAM WELDMENTS

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# The Effects of Weld Geometry On Weld Quality and Fatigue Properties of Galvanized HSLA Laser Seam Weldments

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## 1. INTRODUCTION

Laser welding possesses the advantages of high power capability, welding speed, welding precision, flexibility. Laser welding results in higher productivity, efficient use of energy and is adaptable to automated welding of large and complex structures. Very narrow, accurate, low distortion, low contamination welds can be obtained by laser welding; and no electrode or filler materials are generally required[1,2]. In many instances, laser welds exhibit better mechanical properties than do welds made by conventional arc welding[3].

Thinner gauges of galvanized HSLA sheet steel have replaced thicker, heavier sections of mild steel in automotive applications due to the need to reduce automobile weight for increasing fuel efficiency. However, there are some difficulties in laser welding galvanized HSLA steel since the zinc coating vaporizes during welding and results in a poor weld quality and fatigue resistance. In addition, the weld geometry is an important factor which affects the fatigue properties of laser welds[4]. Thus, the current study investigated the effects of weld geometry and welding conditions on the weld quality and the fatigue life of laser welds.

## 2. MATERIALS, WELD GEOMETRIES, WELDING AND TESTING PROCEDURES

A galvanized high strength low alloy sheet steel AISI 050-XF 1.00 mm (0.039 inch) thickness with a zinc coating of 0.0635 mm (0.0025 inch) was used in this study. The steel had a chemical composition which is shown in Table 1.

The specimens were fabricated with 15 kW $CO_2$ industrial laser. Specimen blanks were fixed on a movable, motor-driven table whose velocity was controlled. Since the sheet is very thin, the focal point of the incident laser beam was located on the sheet surface. The focal point diameter of the incident beam was 3 mm (0.12 inch). Helium was used as the shielding gas. The diameter of the shielding gas nozzle was 25.4 mm (1 inch), and the shielding gas flow rate was 40 l/min and was directed onto the weld at a 45 degree angle. Nine weld geometries were considered in this study and are shown in Fig. 1. For each of the different weld geometries, various welding parameters were employed but the welding speed was constant 38 cm/min (15 inches/min.). The welding parameters are listed in Table 2.

Tensile and fatigue tests were conducted on as-welded laser welds. Prior to testing, all specimens were examined by X-ray radiography to eliminate defective welds. Fatigue specimens were machined to remove notches on the sides of the welded sheets. Tensile tests were carried out on a MTS machine under stroke control using a strain rate 1.5 mm/min. (0.06 inch/min.). Fatigue tests were carried out under load control at frequency of 20 Hz using a sinusoidal wave form load cycle. To avoid the introduction of bending stresses during testing, the specimens were gripped with shims. The load ranges of fatigue tests were adjusted to result in failures at lives between $10^4$ and $10^6$ cycles.

## 3. RESULTS AND DISCUSSION

### 3.1 Welding Parameters

The welding parameters, such as welding power, welding speed and shielding gas flow, are important factors which affect weld quality, welding energy efficiency and welding productivity[4,5,6]. For some of the laser welds considered in this study (Geometries 2, 5 and 9), the required welding power was adjusted to maintain a constant width of weld bead on the back surface. The bead width and penetration were dependent on welding power and welding speed.

For the same width of back weld bead, the variation of welding power versus welding speed for both Geometries 2 and 9 is plotted in Fig. 2. There was a minimum value of welding power required to maintain a given back weld width and satisfactory weld quality which occurred at a certain high welding speed. Low welding speed caused a very wide top bead which drops through the sheet in the melted state to form void. Low welding speeds also give the zinc vapor time to interact with weld metal to form porosity. At higher welding speeds, a higher power is needed to keep the back bead constant, but the zinc coating is quickly vaporized before appreciable heat can be conducted into the material [7] and evaporated and dispersed by the shielding gas. The reaction between the residual zinc vapor and weld metal is further reduced by the rapid solidification of the weld metal. It was difficult to guarantee good weld quality below a 25 ipm welding speed.

Thus, good quality laser welds can be obtained with high welding speed. The effects of welding speed on the welding power are reflected by the ratio P/V owing to the variation of power with welding speed. A power relation between the ratio of input power to welding speed (P/V) and the welding speeding (V) for both types of weld is shown in Fig. 3 which describes the effect of the welding speed on the ratio (P/V). As seen in Fig. 3, there is a minimum in the energy versus welding speed relationship and therefore there is a welding speed at which the power requirements to create the constant width, full penetration laser weld are minimum .

As shown in Fig. 4, a power relation was also fitted to the ratio P/V and welding power P for the groove-welded lap joint (Geometry 9). For the groove welded butt joint (Geometry 2), even though a power law dependency was not obtained, the ratio P/V still decreases with increasing welding power. The efficiency with which electrical power is converted to optical power and heat melting efficiency has been reported as 15% and 90% for laser welding, respectively [8] and was assumed constant in calculating the heat input H:

$$H = \frac{\eta P}{V} \qquad \text{where: } \eta = \text{thermal efficiency}$$

The heat input is controlled by laser power and welding speed. Since the heat input is proportional to the ratio P/V, the ratio P/V also represents the heat input at certain welding speed. The negative slope of P/V vs V curves in Fig. 3 means that the heat input per unit weld length required for a constant width back weld decreased with increasing welding speed. Thus, welding power is most effectively and economically utilized as one increases the welding speed. Moreover, good weld quality were more easily obtained at higher welding speeds for galvanized HSLA sheet steel studied.

There is a considerable difference between the results of this study and those of Carlson[9] as regards the relation of the ratio P/V (or H) and welding power P. Carlson reported that welding speed varies as a function of welding power for full penetration with laser welding in 12.7 mm (0.5 inch) type 304 stainless sheet steel. As the welding power increased, the welding speed increased. While the initial portion of the curve appeared nearly linear, the curve tended to bend at some power value. Beyond this value the slope decreased. There was a minimum in the curve of P/V vs. P, which means there is an optimum welding power and welding speed which produces a full penetration weldment with the least expenditure of energy.

However, in this study there does not appear to be any minimum in the curve of P/V (or H) vs. V or P/V vs. P under the condition of a constant back-weld width. For both Geometries 2 and 9, the ratio P/V (or H) always decreases with increasing welding power and welding speed for the conditions studied. This result is explained by which the increase of welding speed and welding power improves thermal efficiency [10].

In this investigation, it was found that the weld quality of galvanized sheet laser welds was quite sensitive to the welding direction relative to the flow of the shielding gas. The weld quality is much better when the direction of shielding gas flow is opposite to that of the welding process. When the table moves into the shielding gas flow, high quality welds are produced which are free of voids and porosity. This arrangement favored the removal of the plasma from the surface of sheet. When the direction of the table is the same as the direction of shielding gas flow, the shielding gas flow does not remove the plasma entirely; and, the plasma interacts with the welding pool to form voids and porosity. The angle between nozzle and laser beam, the shielding gas flow rate and pressure have a large influence on weld quality [11]. This effect is attributed to effect a keyhole forming, surface convection and radiation. The optimization of these parameters decreased the detrimental influence of the plasma. The optimum angle of nozzle proved to be 45 degrees.

## 3.2 The Effects of Weld Geometry On The Ease of Welding Galvanized Steel

Nine types of seam weld geometries were employed to compare their ease of welding and the mechanical properties of resulting from these weld geometries. Generally, it is difficult to ensure good weld quality for galvanized sheet steel due to the vaporization of the zinc layer at the sheet surface during formation of the weld pool which causes voids and porosity in the weld. To avoid the problems with the vaporization of zinc and to permit zinc vapor to escape into the air quickly, the weld geometries were designed with three criteria in mind:

(1) minimize the irradiated zinc surface area to produce the least zinc vapors;
(2) provide a means of escape for any zinc vapors generated;
(3) trap the laser beam within the weld joint wall to reduce the loss of energy caused by beam by back reflection.

The first specimen design concept was to weld against the sheared sheet edges which were not coated by zinc to decrease its vaporization. It is found that all the Geometries (Geometries 2, 4, 5, 7 and 8) which had bare edges before welding showed the best weld quality.

The second specimen design concept was to create large open zinc area to air, which promoted rapid vaporization of zinc before forming the weld pool. These measures promoted good weld quality in the instance of Geometries 1, 3 and 6. In addition, three sheets of paper were placed into between the two sheets in order to release zinc vapor quickly for Geometries 5, 6 and 9. Before the melting of the steel, the paper chars to form a gap between both sheets, and which permits that the zinc vapor to escape. Thus, the detrimental effect of zinc vapor is greatly reduced. Excellent quality welds were achieved by this method.

The third specimen design concept was based on the consideration of fully utilizing the incident laser energy. The designs of Geometries 1, 3, 4, 5, 6 and 8 trapped the beam in the gap between sheets greatly decreasing reradiated and increasing the thermal efficiency of laser welding.

## 3.3 Mechanical Properties of Different Weld Geometries

Tensile tests were conducted on Geometries 2 - 9. It was not possible to run a tensile test on weld Type 1. The results presented in Table 3 show that weld Geometry 2 fractured in base metal and possessed higher fracture strength in the weld zone and HAZ. Geometries 3, 4 and 6 broke in the HAZ, and Geometries 5, 7 and 8 fractured in the weld zone, and their tensile fracture strengths are comparatively low.

Fatigue lives were determined for Geometries 2 to 9 under a zero-to-maximum load cycle of 4003 and 5338 N (900 and 1200 lbf). It is seen in Fig. 5 that the fatigue properties of Geometries 2, 9 and 4 are excellent . Geometries 3, 6 and 5 also shows a high fatigue resistance. The fatigue performance of Geometries 7 and 8 is poor. S-N curves for Geometries 5, 6 and 9 are given in Fig. 6. Weld type 9 performs better than the other type of weld. In Fig. 6 it is seen that S-N curves for Geometries 5 and 6 cross. at low load levels; Geometry 6 has longer fatigue lives and at high load levels. Geometries 2 and 4 possessed higher ultimate strengths had better fatigue resistance. The welds of Geometries 7 and 8 exhibit poor ultimate strengths and fatigue resistance, and failure occurs in the weld metal.

It is well known that mechanical properties of welds are related to the severity of the geometrical discontinuities (notch) inherent in the specimen and residual stresses. It is evident that there are acute notches which are perpendicular to stress direction and produce high stress concentration in Geometries 7 and 8. Geometries 9 and 5 have severe notches but the direction of those notches is parallel to the direction of stress, and thus have only a small influence on the ultimate strength and fatigue strength. Geometries 7 and 8 have very rigidly constrained joints which leads to high welding residual stresses and poor mechanical properties of the weldments. Geometries 2 and 4 give a high ultimate strength and fatigue strength due to absence of severe notches and the existence of smaller residual stresses.

## 4. CONCLUSIONS

1) For the condition of constant bead width on the back of sheet, the required welding power increased with the increasing of the welding speed in the laser welding of galvanized HSLA sheet steel. There was a power relation between the ratio (P/V) and the welding speed (V). As the welding speed increases, the heat input per unit length of weld decreased and the efficiency of energy utilization increased. Weld quality improved with increasing welding speed.

2) Good weld quality has been obtained by improving the design of weld geometry for laser seam welding galvanized HSLA sheet steel by welding against the bare edges of galvanized sheets. Groove welded butt joint and flare bevel groove welded butt weld (Geometries 2 and 4) showed a great welding flexibility and excellent fatigue resistance for galvanized HSLA sheet steel.

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Table 1
Base Metal Nominal Chemical Composition of Galvanized AISI 050XF Sheet Steel

| C | Mn | P | S | Si | Nb | Al |
|---|---|---|---|---|---|---|
| 0.08 | 0.46 | 0.009 | 0.009 | 0.01 | 0.021 | 0.021 |

* weight percentage (wt %)

Table 2

Welding Parameters for Different Welds Type

| Welding Type | Welding Power (kW) | Welding Speed (cm/min) | Laser Beam Angle (deg.) | Shielding Gas Flow (l/min) | Note |
|---|---|---|---|---|---|
| 1 | 1.75 | 38 | 80 | 75 | |
| 2 | 2.12 | 38 | 10 | 75 | |
| 3 | 1.75 | 38 | 10 | 75 | |
| 4 | 2.25 | 38 | 10 | 75 | |
| 5 | 2.12 | 38 | 75 | 75 | * |
| 6 | 1.75 | 38 | 80 | 75 | * |
| 7 | 2.25 | 38 | 10 | 75 | |
| 8 | 2.00 | 38 | 10 | 75 | |
| 9 | 2.25 | 38 | 10 | 75 | * |

The laser beam angle is the angle between the incident direction and the normal of steel sheets.

The shielding gas pressure was 100 psi..

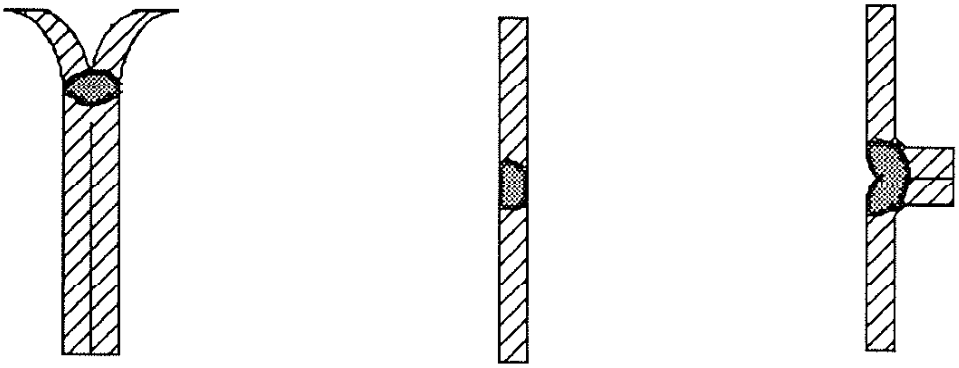
*Paper was placed between the two steel sheets.

Table 3

Tensile Test Results of Different Geometrical Weldments

| Weld Type | Fracture* Position | $S_b$ (ksi) |
|---|---|---|
| 2 | B | 71.3 |
| | B | 58.6 |
| | B | 66.5 |
| 3 | HAZ | 57.7 |
| | HAZ | 59.8 |
| | HAZ | 48.5 |
| | W | 68.0 |
| 4 | B | 66.9 |
| | HAZ | 61.7 |
| 5 | W | 40.3 |
| | W | 51.2 |
| | B | 67.0 |
| | W | 34.5 |
| 6 | HAZ | 59.5 |
| 7 | W | 37.2 |
| | W | 42.0 |
| 8 | W | 43.7 |
| | B | 53.0 |

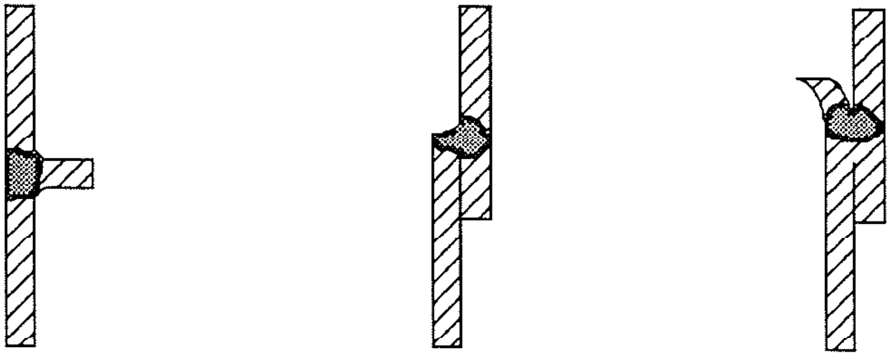
*B = Base Metal HAZ = Heat Affected Zone W = Weld Zone



(1)
Flare Groove Welded Edge Joint

(2)
Groove Welded Butt Joint

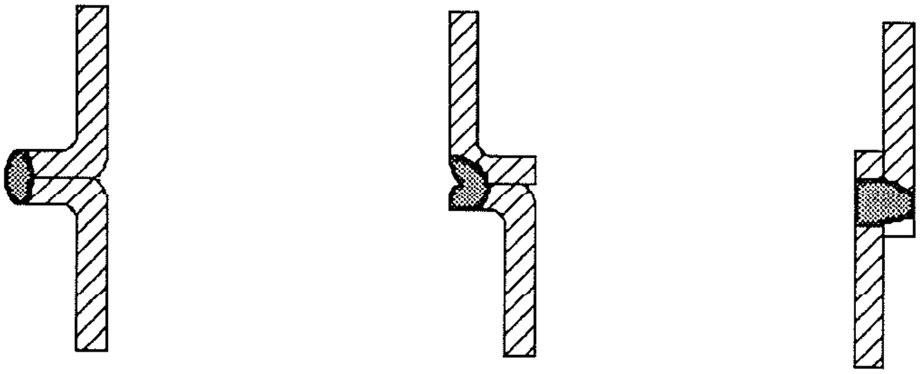
(3)
Flare Groove Welded Butt Joint



(4)
Flare Bevel Groove Welded Butt Joint

(5)
Single Piled Welded Lap Joint

(6)
Flare Bevel Welded Lap Joint



(7)
Flare Welded Edge Joint

(8)
Groove Welded Edge-butt Joint

(9)
Groove Welded Lap Joint

Fig. 1 Geometries of Laser Seam Welds

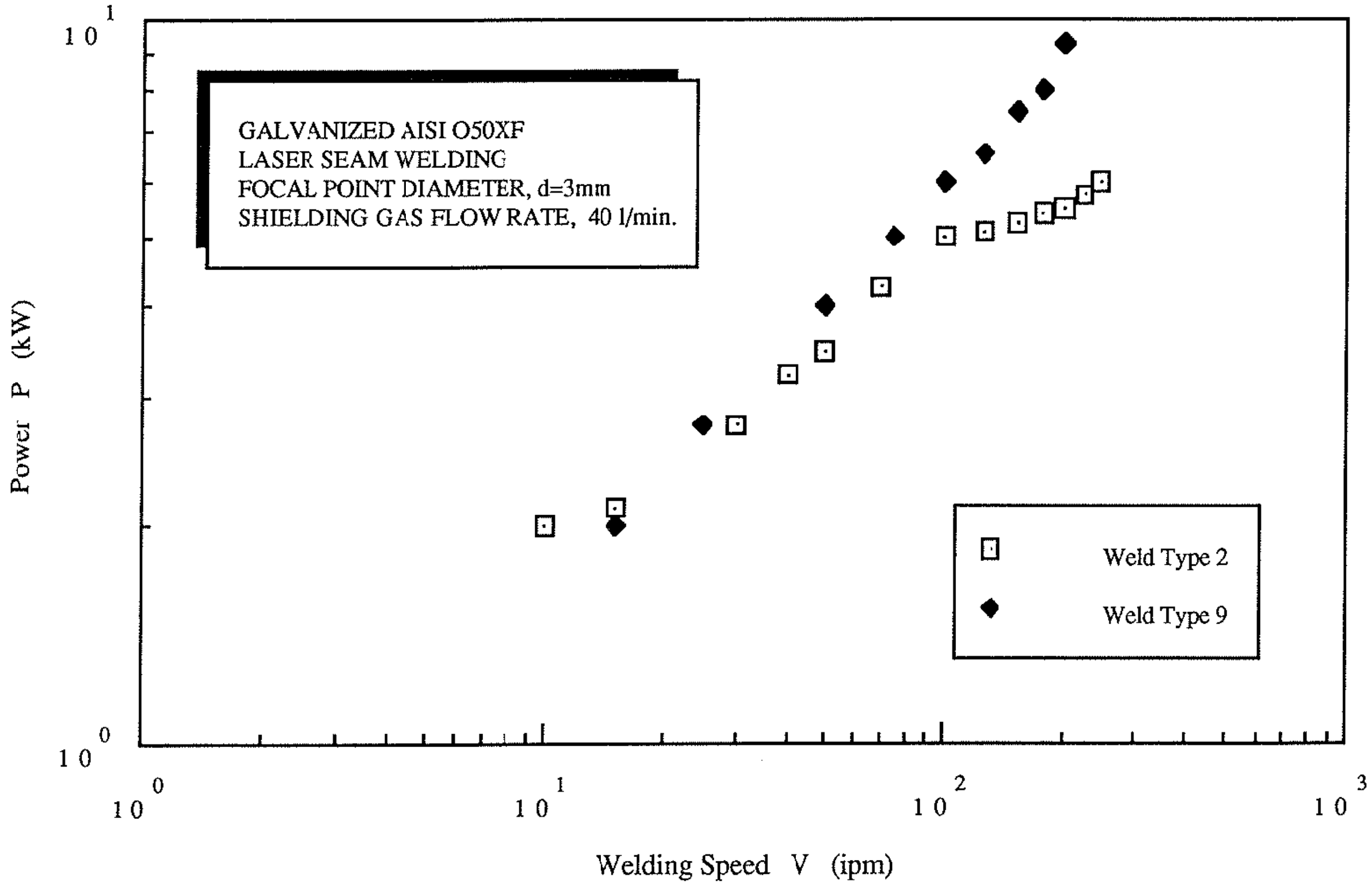


Fig 2 Relationship Between Welding Speed and Welding Power

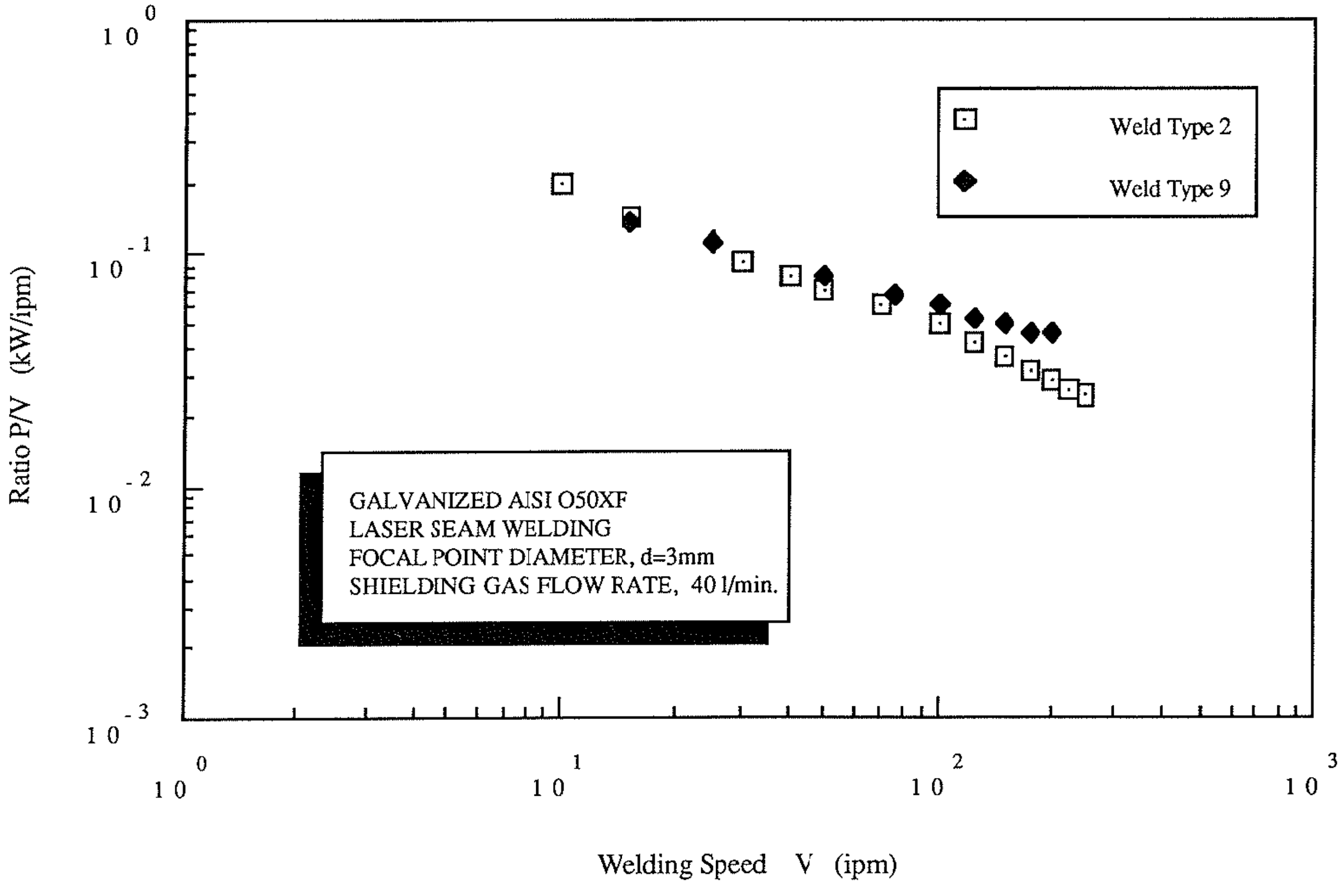


Fig 3 Relationship Between Welding Speed and Ratio P/V

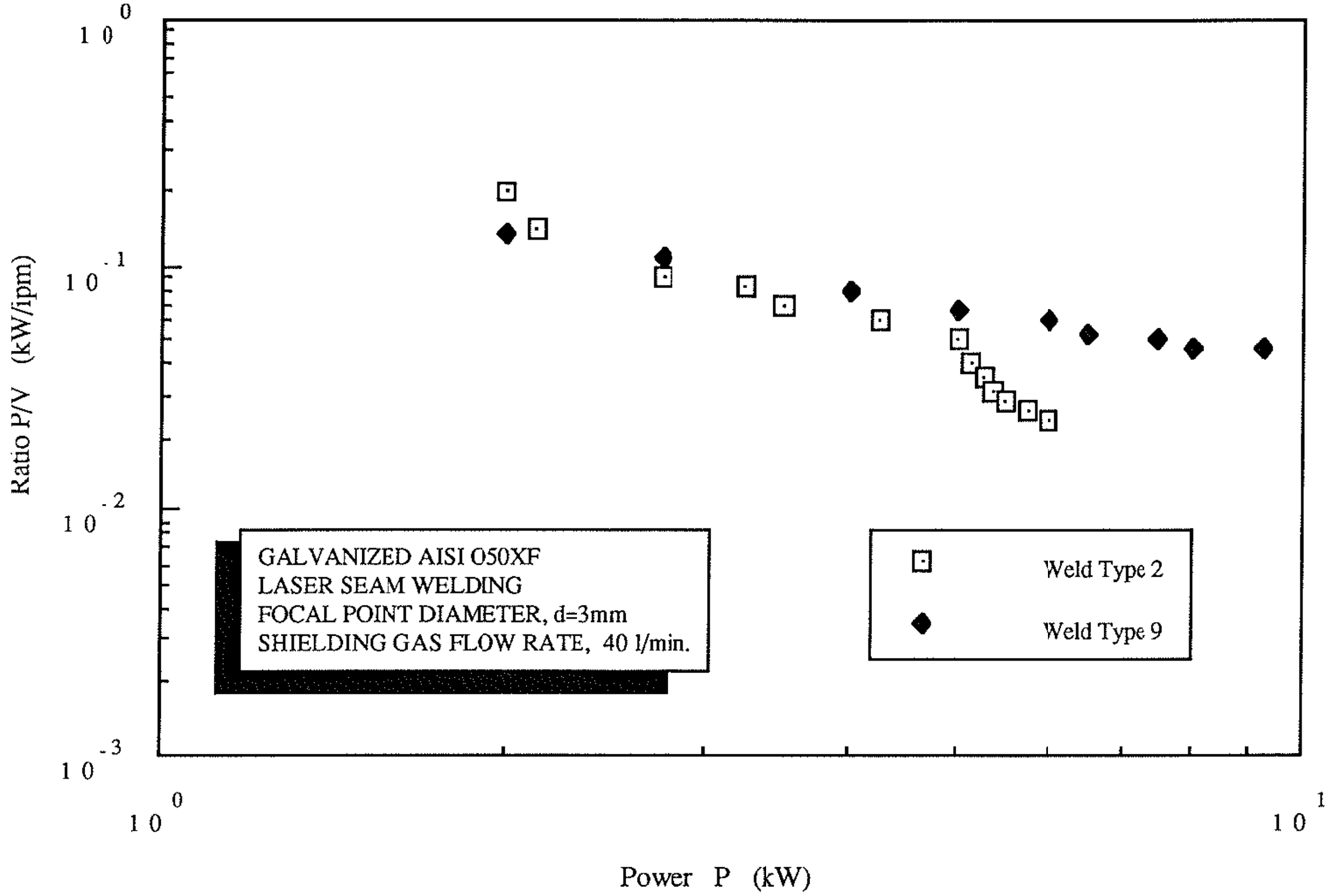


Fig 4 Relationship Between Welding Power and Ratio P/V

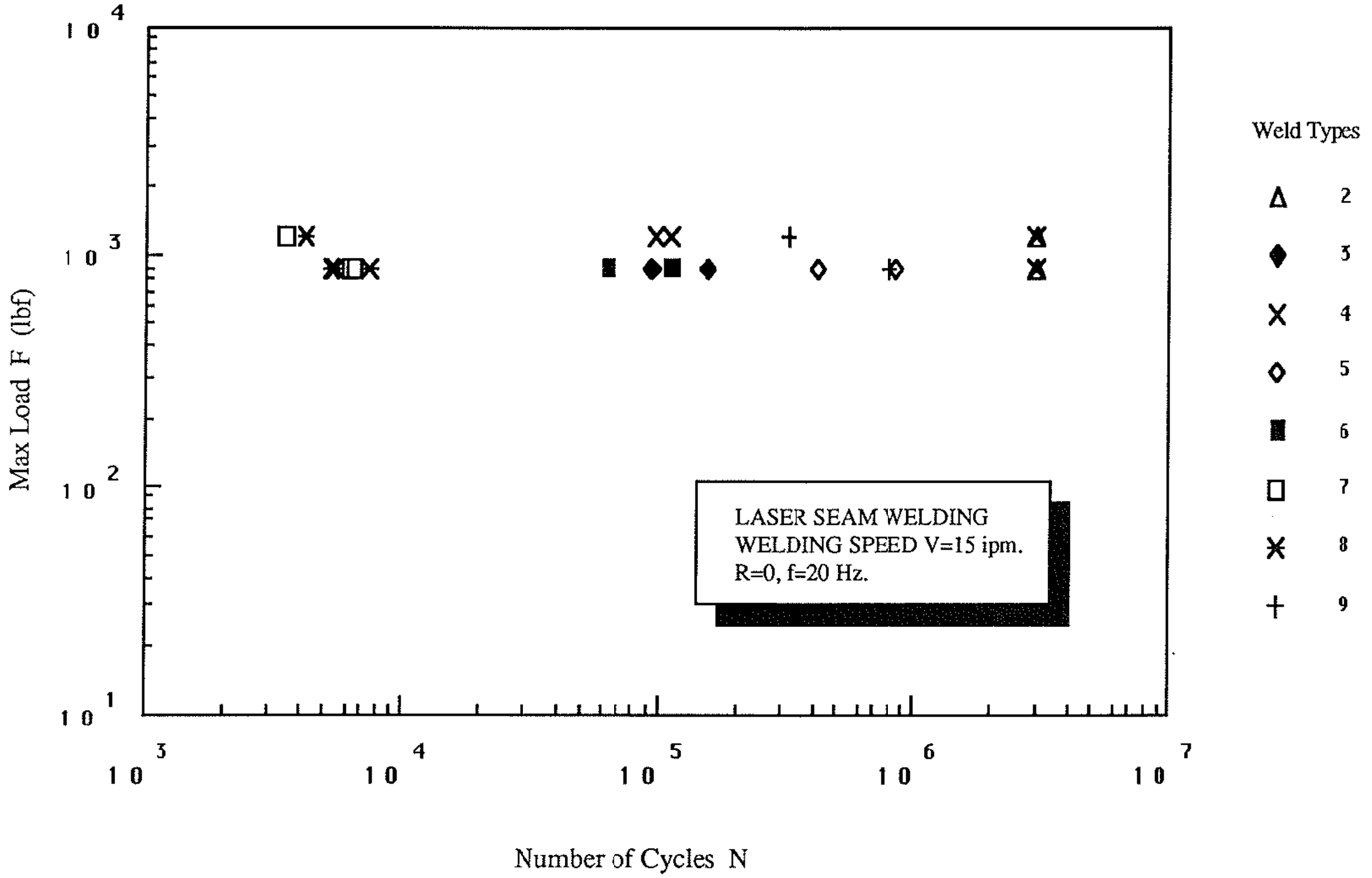


Fig. 5 Fatigue Lives of Different Geometrical Weldments Under A Certain Load Range

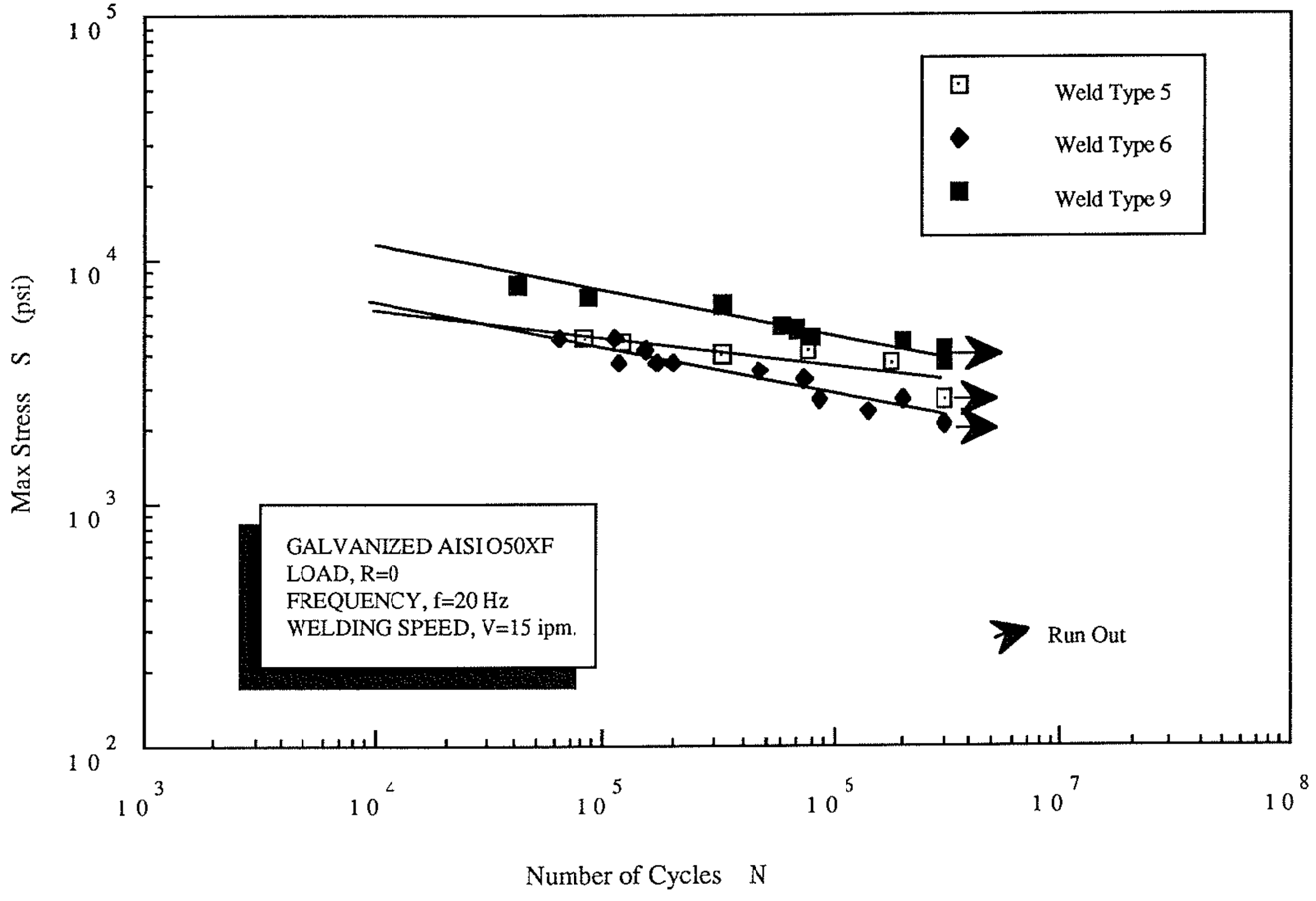


Fig 6 S-N Curve of Weld Types 5, 6 and 9.