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Determination of Blowout Pressures during Electron Beam Welding

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Introduction

During electron beam (EB) welding of developmental units, weld blowouts occurred. It is well documented that the presence of moisture causes the weld blowout. The detrimental effects of water vapor on the weld are experimentally proven [1]. The availability of water vapor in the melt increases the onset and severity of blowout and porosity. Because water vapor is insoluble in the molten metal, it will consequently form either bubbles or boil. On the other hand, hydrogen will react with other impurities present in the melt to form insoluble gas bubbles, which most likely will be entrapped in the fusion zone as porosity.

The motivation of this work is to answer the question of what is the critical pressure that could blowout the molten weld pool. In order to cause the weld blowout, a certain amount of molten metal has to be displaced. The pressure to do this must be greater than the sum of the opposing pressures of viscosity, hydrostatic pressure, and surface tension. The viscosity was considered because it determines the rate at which the gas bubbles can rise to the surface. A highly viscous molten metal entails slower bubble rise than a less viscous molten metal. Similarly, a larger gas bubble will rise faster than a smaller bubble. Hydrostatic pressure is another opposing pressure exerting on the bubble. In order to push the molten metal out of the weld, it has to overcome the hydrostatic pressure. Lastly, after the bubble rises to the surface, it has to overcome the surface tension to break to the surface of the molten metal [2]. In all these calculations, the size of the bubble greatly depends on the material properties, which, in turn, influence the thermal profiles of the weld and heat affected zones. To simplify the calculations, these blowouts are assumed as the spherical bubbles. The material property values used are from ref. [3]. Of these opposing pressures, the preliminary calculations [4] indicate that compared to viscosity and hydrostatic pressure, the surface tension is the dominating factor (Figure 3).

This study attempts to answer the question of what is the critical weld blowout pressure, and to compare the experimental results to the estimated pressure values, so that validated calculations could be extended to other weld configurations.

Experimental procedure

Figure 1 schematically illustrates the special vacuum-fixture used for the tests. A pressure transducer was attached to the side to accurately determine the in-situ blowout pressure. The fixture was helium leak checked and pressurized to absolute pressures of 25, 30, 35, 40, 50 torr, using argon. A 1.0mm-thick strip of stainless steel Type 304 laid on top of it. The calculations suggest that the blowout pressures were in a range of 25-55 torr, depending on the size of the blown hole. Hence the apparatus was pressurized starting from 25 to 50 torr using argon. Electron beam welding parameters of 120kV, 9mA, and 42.3mm/s were used. A series of bead-on-strip welds was produced along the length of the strip and a run-on plate was used to achieve a full beam power at the start of the bead.

Results and Discussion

The initial pressures less than 30 torr had no adverse effect on weldability. Blowouts started to occur at initial pressure of 35 torr. Increasing pressures over 35 torr caused the blowouts to occur sooner and more aggressively. A typical weld blowout that transpired with 35 torr fill is shown in Figure 2. The shape of these blown holes tends to be oblong, due to its travel speed and it is enhanced by the keyhole mode used during electron beam welding. The process employs the keyhole mode to produce a high aspect ratio weld. When a high energy density beam hits the workpiece surface, it induces local vaporization and subsequently produces a cavity. As the beam travels, the molten metal flows around the cavity to the rear of the pool and solidifies in a characteristic chevron pattern [5]. If the solidification is perturbed by the presence of water vapor and the blowout occurs at the rear of the pool, then this interrupts continuous solidification and a certain amount of molten metal has to flow to the rear to reestablish the molten pool. This results in an oblong hole formation.

The importance of a particular pot setting on blowout was not apparent until three series of welds produced using the same welding parameters and the constant 35 torr pressure exhibited three different results: no blowout, a blowout; and continuous blowouts. A review of optical photographs of the fusion zones revealed that a 2% difference in the fusion zone width caused the blowout. The sharpness of the beam focus is controlled by the pot setting, which in turn is set by the operator. A series of bead-on-plate welds was produced with varying pot settings. It appears that because the fusion zone width is correlated to the minimum surface tension pressure, a weld produced with a sharper beam is less susceptible to blowout.

Sequential stages of internal pressure weld blowout are exhibited in a series of micrographs, Figure 3. For stainless steel, the blowouts occurred at pressure about 55 torr, but at 35 torr, the pressure has already started to push the molten metal upward. When the internal pressure was increased to 45 torr, the molten metal had displaced 0.3 mm upward, and that equivalent amount of metal formed a prominent bead. Moreover, the off-centered solidification, coupled with weld shrinkage, enhanced the distortion, as indicated by the uplifting of the weldment. When the internal pressure reached its instability pressure, most of the unsolidified metal blew out. Figure 3c shows a partially solidified fusion zone and a perfectly spherical displaced metal. The figures also reveal the unique thermal characteristics of stainless steel, which has a relatively low thermal diffusivity and a slow solidification time. These attributes allow the pressure to push uniformly across the fusion zone.

The experimental results are compared to the calculated values plotted as a function of bubble size in Figure 4. In the calculations, the blown holes were assumed to be spherical, as observed in the radiographs. It is apparent that the surface tension is the predominant pressure controlling the occurrence of a blowout. Because of the inverse relationship between pore size and blowout pressure, the pressure required to blowout the molten metal decreases as the pore size increases. Since pore size is proportional to the fusion zone width, this illustrates the importance of the pot setting. The figure also shows that viscosity plays almost no role in blowout since the joint is about 2 mm deep and solidifies within 50 ms. Similarly, the contribution of hydrostatic pressure is small but constant, independent of the pore size. Both viscosity and hydrostatic pressure might be more significant factors in a deeper weld. For the stainless steel the calculations coincided very closely with the experimental results, where the blowout pressure of 55 torr and the size of the hole matched the total pressure curve.

Conclusion

The experiments and calculations for this weld configuration agreed fairly close. The surface tension is the primary factor in controlling the blowout phenomenon observed during welding. The other opposing pressures of viscosity and hydrostatic pressure had a minor effect. The blowout pressure was determined to be about 55 torr.

Acknowledgment
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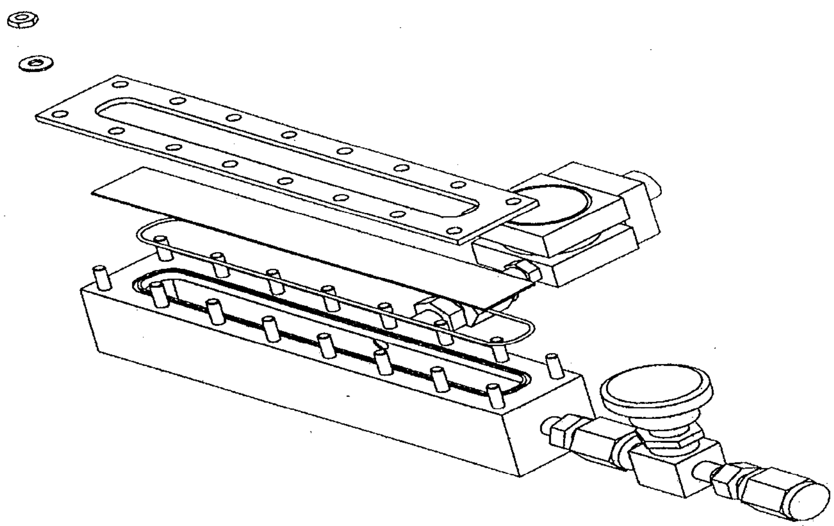


Figure 1. Weld fixture with a pressure transducer attached at the side.

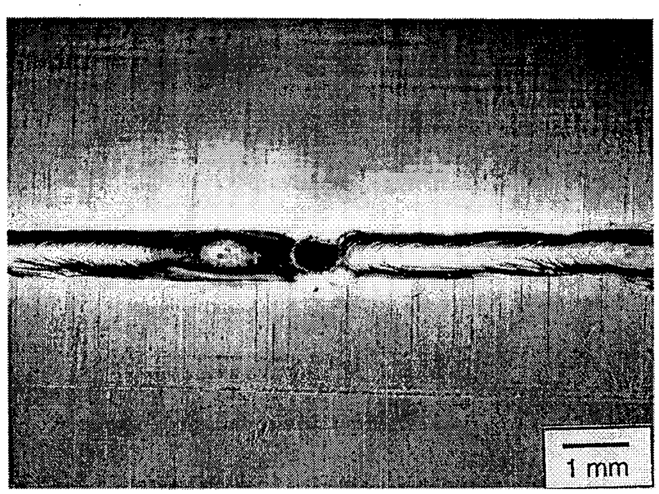


Figure 2. Stainless steel weld blowout that occurred at initial absolute pressure of 35 torr.

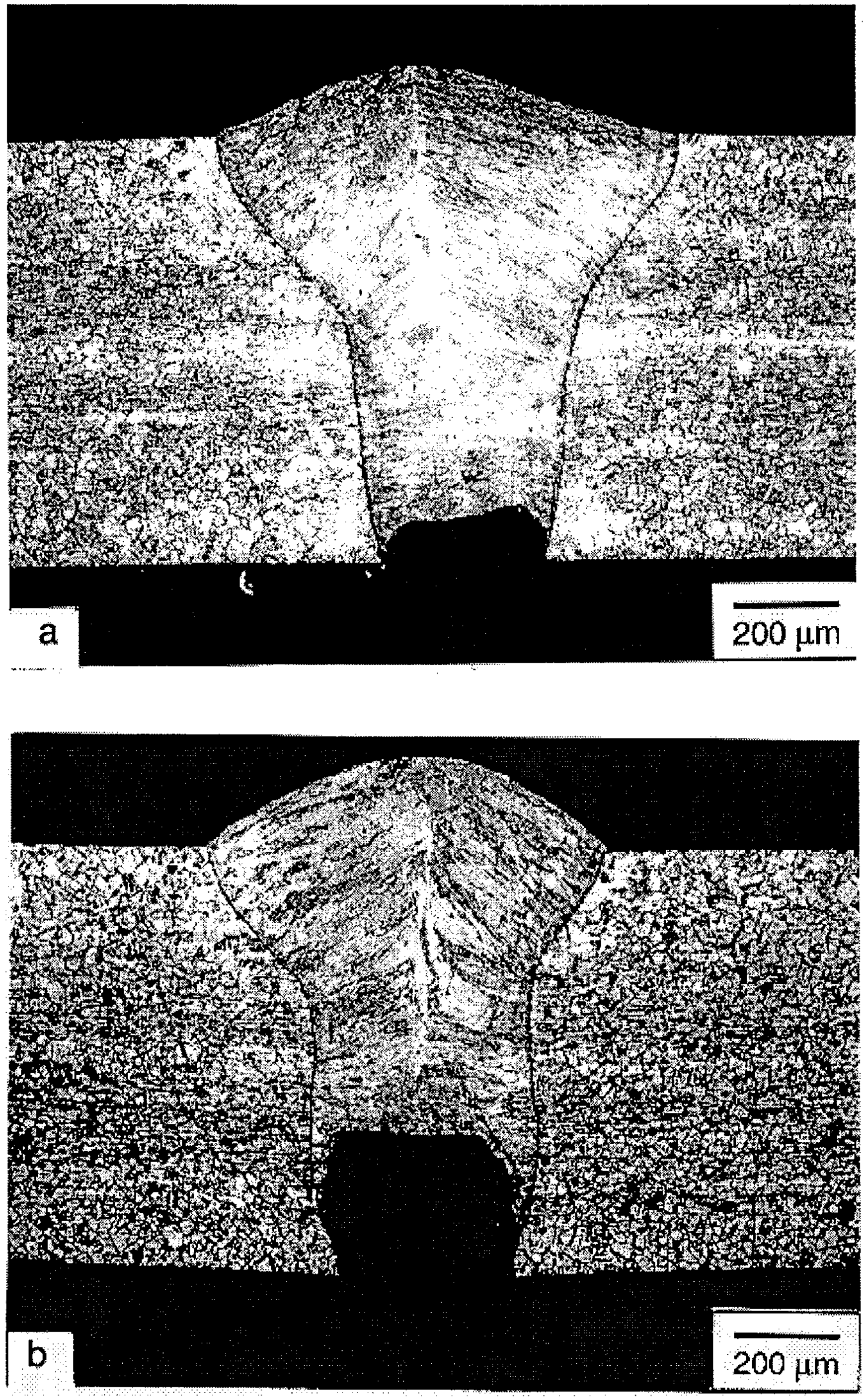
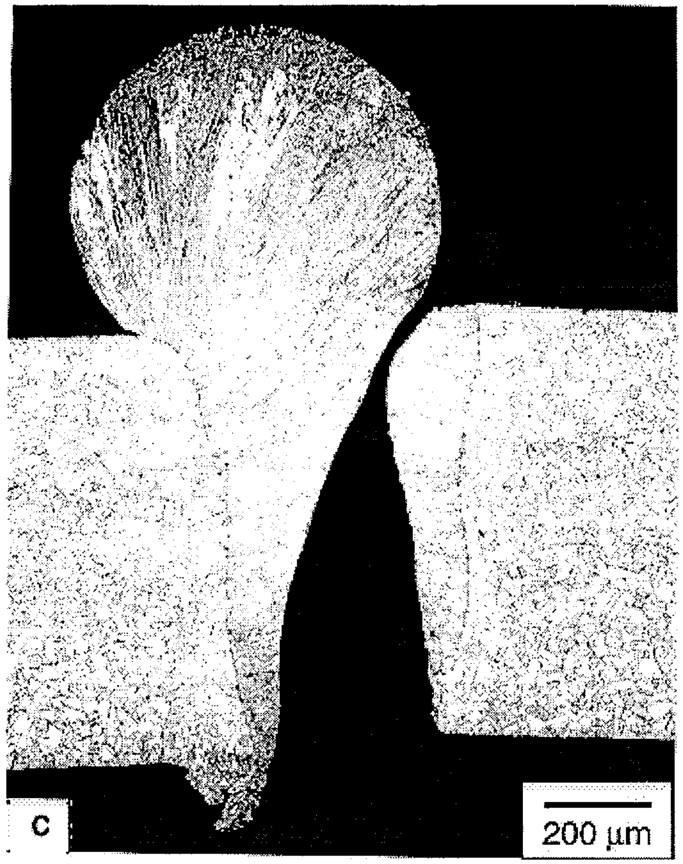


Figure 3. Cross-sections of stainless steel welds showing the effects of pressure on the molten metal movement, leading to a blowout at 55 torr: a) $P_s = 35$ to $P_f = 40$ torr; b) $P_s = 45$ to $P_f = 52$ torr; c) $P_s = 50$ to $P_b = 55$ torr.



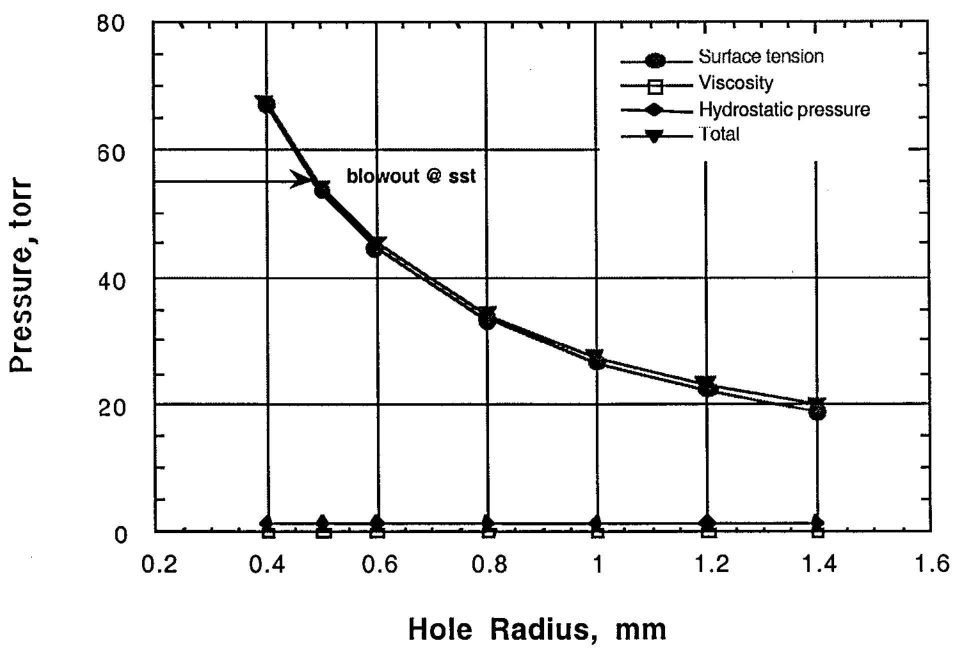


Figure 4. Comparison of calculated values and measured data for stainless steel.