Effect of Heat Input on Properties of Inconel Filler Metal 82 Weld Deposits

Study strongly suggests that the yield strength of a single phase weld metal is a function of dendrite arm spacing rather than grain diameter

BY J. C. THORNLEY

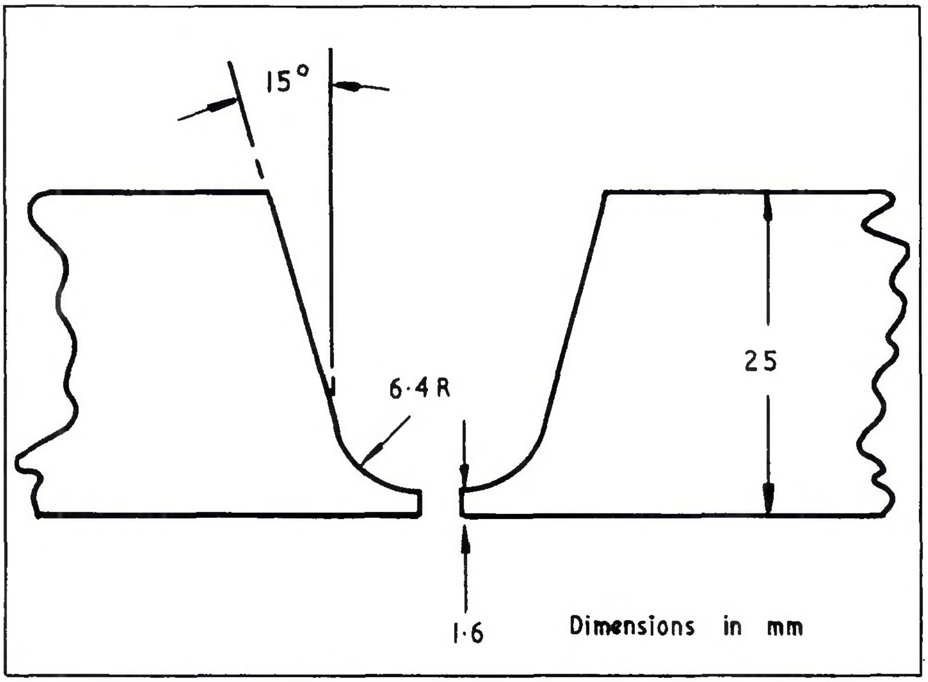

Fig. 1 — Edge preparation for the Inconel plates. Root opening varied from 0 to 3 mm depending on heat input. No root opening was used for submerged arc welds

Table 1 — Details of Welding, Weld Ductilities and Weld Grain Sizes

Voltage, V	Current, A	Speed, mm/sec	Heat input, kJ/mm	Grain diam, μm	Elongation, % on 51mm	Reduction in area, %	Charpy energy, J	Method
17	130	11.2	0.20	140	21	22	160	GMAW[a]
23	134	8.3	0.37	185	37	53	160	GMAW[a]
27	235	6.7	0.95	140	41	47	140	GMAW[b]
28	210	4.9	1.23	200	39	53	130	GMAW[b]
26	135	1.8	1.95	185	41	43	230	GMAW[c]
38	320	4.4	3.00	220	38	29	—	SAW
35	350	3.0	4.10	230	40	43	100	SAW

(a) Short circuiting mode
(b) Spray transfer mode
(c) Pulsed arc mode

Introduction

The effect of heat input variations upon the mechanical properties of weld metals has been investigated previously (Refs. 1, 2, 3). Although large variations in mechanical properties and microstructure (particularly grain size) have been observed, almost all of the reported work concerned with room temperature mechanical properties has been on mild steel. The austenite-ferrite allotropic transformation and the cooling rate through the transformation range have complicated the interpretation of these experiments, so that it is not possible to separate solidification rate (heat input) effects from cooling rate effects. Similarly, work upon the relationship between the rate of solidification of ingots and their mechanical properties has been on two phase alloys (Refs. 4, 5, 6) where the solidification rate alters the relative volume fractions of the phases.

In contrast, many important welding alloys are single phase and do not go through an allotropic transformation, and results on steels and two phase alloys do not help to predict the probable effects on their mechanical properties of varying the heat input. Therefore, it was decided to determine the relationship between the mechanical properties of a single phase filler metal and the welding heat input used to deposit it. The filler chosen was Inconel* filler metal 82 (Ref. 7); it satisfies the requirements of being single phase and not having an allotropic modification; it is also technologically important and can be readily deposited in a

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J. C. THORNLEY is associated with the Research Laboratory, International Nickel Limited, Birmingham, England.

crack-free condition using a wide range of welding heat inputs.

Experimental Procedure

Welding heat input was varied by changing the welding process. Short circuiting gas metal-arc welding was used for the lowest heat input and submerged arc welding with Incoflux* 4 was used for the highest. All welds were made in the flat position in 25 mm thick Inconel alloy 600 plate. The welding details are given in Table 1 and the preparation is shown in Fig. 1. All-weld-metal tensile specimens and 10 × 10 mm Charpy impact specimens, which were transverse to the weld and had notches parallel with the weld axis, were made from the center of each weld. The tensile specimens had 33 mm gage lengths and were 6.4 mm diam. The welds were also examined metallographically and whenever possible statistical techniques were used to examine relationships between various parameters.

Results

Both tensile strength and the 0.2% yield stress of each weld were determined. The results are presented in Fig. 2. Each of these parameters increased with decreasing heat input, but the yield stress was more sensitive to heat input variations than the tensile strength. As the heat input was reduced from 4.1 to 0.2 kJ/mm the tensile strength increased only by 10%, whereas the yield stress increased by 35%. Ductility (measured as elongation or reduction in area) was not sensitive to heat input while impact toughness, always good, varied in a somewhat erratic manner. Defects, e.g. lack of fusion in some samples of GMA welds seemed to be more important than welding conditions in determining toughness (Table 1).

Weld grain sizes were determined transverse to the joint and are therefore columnar grain diameters. The finest grained weld was made with the lowest heat input and the coarsest grained weld was made with the highest heat input, but apart from this observation the correlation between grain diameter and heat input was poor (Table 1). However, there was a good correlation between the dendrite arm spacing and the heat input (Figs. 3 and 4). The relationship was a linear one; previously dendrite arm spacings have been seen either to be a function of the square root of heat input (Ref. 8) or, as here, to be a linear function of heat input (Ref. 9), depending on welding conditions.

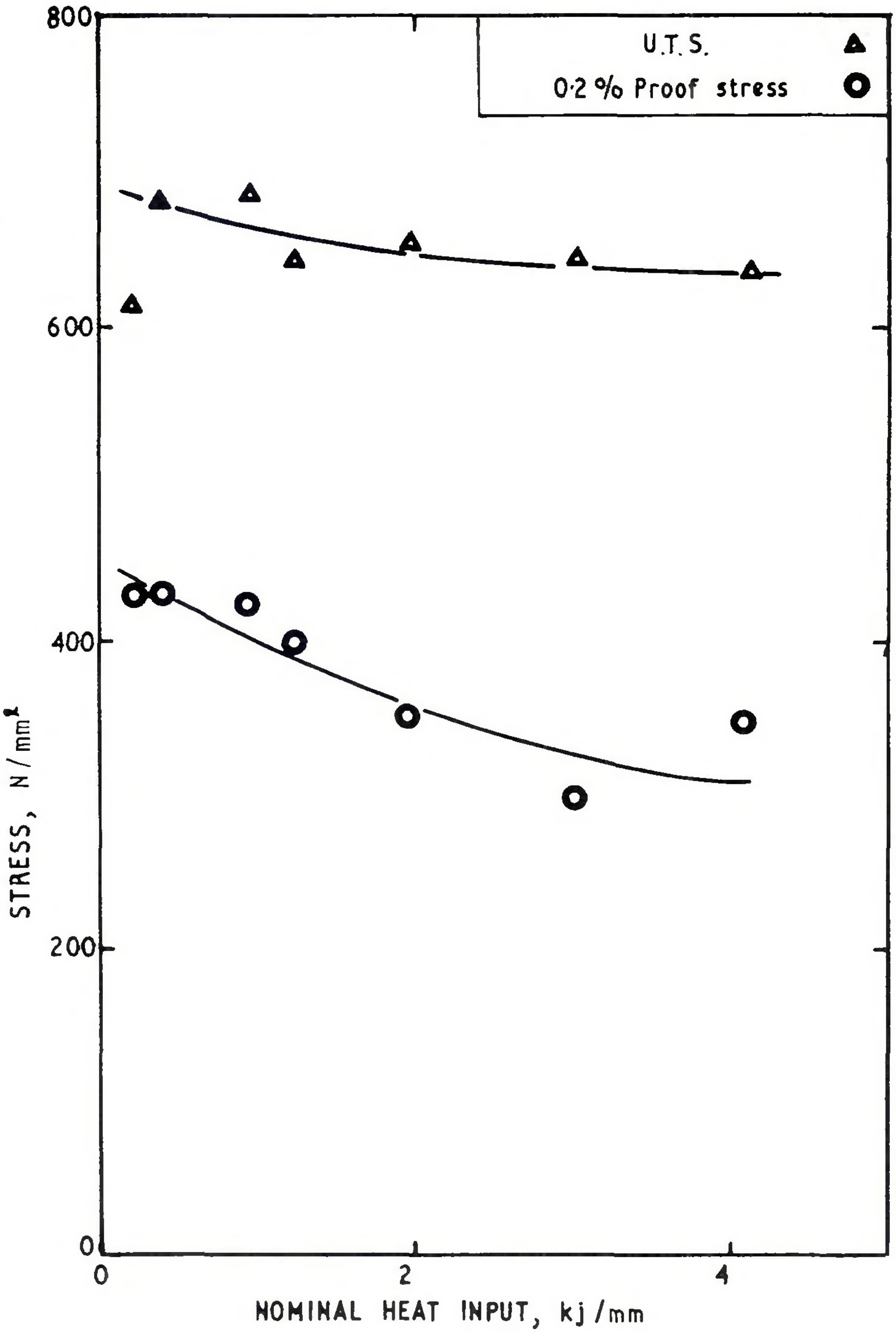

Fig. 2 — Dependence of tensile strength and 0.2% yield stress on nominal heat input for welds made with Inconel filler metal 82

Discussion

In previous investigations of the relationship among heat input, weld grain size and mechanical properties (Refs. 2, 3), weld yield strength and grain diameter have been shown to be related to each other by the Hall-Petch (Refs. 10, 11) equation.

$$\sigma y = \sigma i + K_y l^{-1/2}$$

where σy is the yield stress, l is the grain diameter and σi and K_y are constants; σi generally being referred to as a friction stress. In the present case σy (0.2% yield stress) could only be correlated with $l^{-1/2}$ (where l is the columnar grain diameter) at a confidence level of 90-95% (Fig. 5). Since correlation at a confidence level of >95% is generally only accepted as satsifactory evidence that a correlation exists between two variables, this means that the Petch equation cannot be considered to hold between 0.2% yield stress and columnar grain diameter.

There was a good correlation, however, between welding heat input, strength and dendrite arm spacing. The confidence level for the linear

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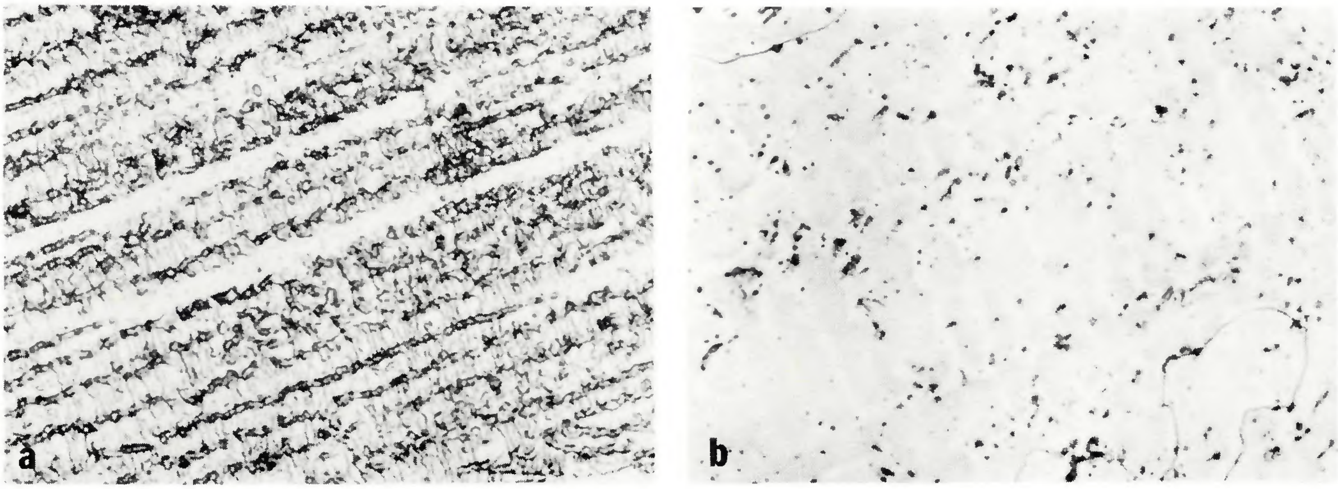

Fig. 3 — Relation of dendrite arm spacing to heat input. (a) Dendrites with a mean arm spacing of 4.5 μm in a GMA (short circuiting) weld made with Inconel 82 filler metal at a nominal heat input of 0.2 KJ/mm. (b) Dendrites with a mean arm spacing of 13.3 μm in a submerged arc weld made with Inconel 82 at a nominal heat input of 4.10 KJ/mm. Both X500, reduced 15%

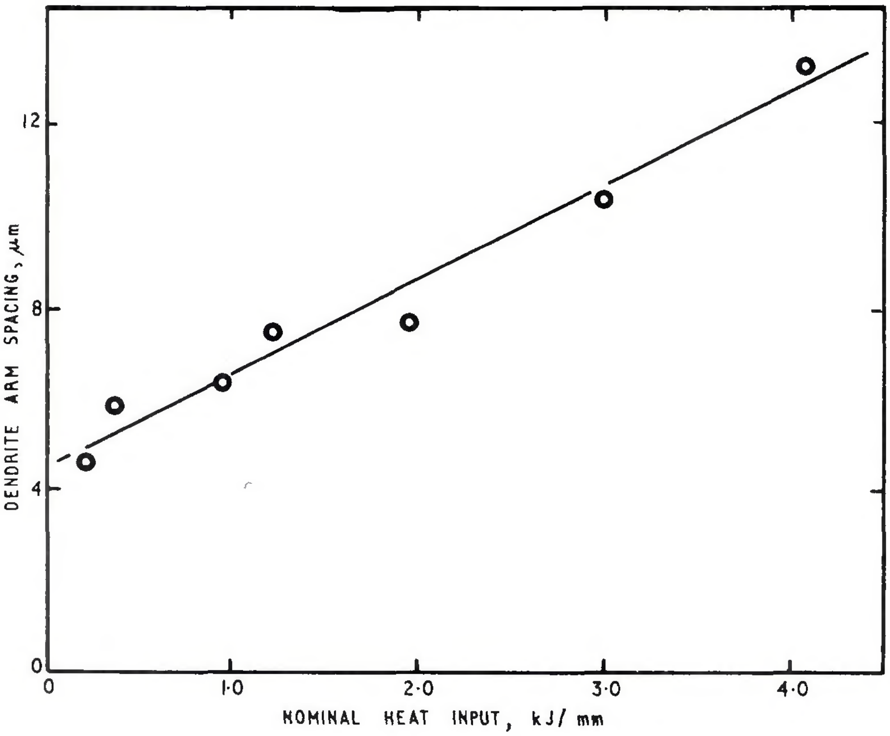

Fig. 4 — Dependence of dendrite arm spacing on nominal heat input for Inconel 82 welds. Probability of the linear relationship shown being correct is more than 99.9%

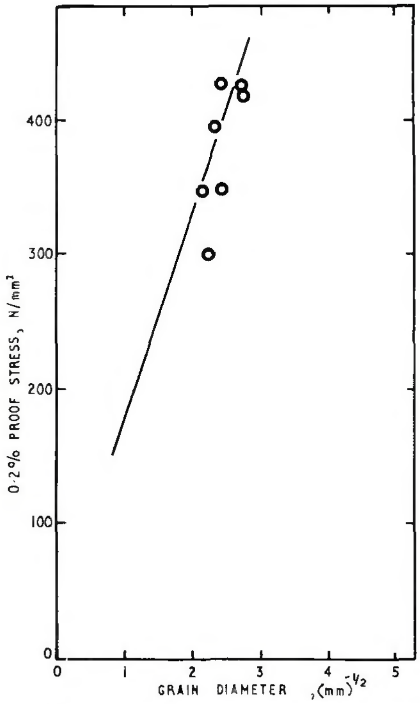

Fig. 5 — A Petch plot of 0.2% yield stress against $l^{-1/2}$ where l is the weld columnar grain diameter. The probability of the linear relationship shown being correct is only 90-95%

relationship between heat input and dendrite arm spacing was 99.9%

Inclusions tend to be concentrated in the walls between the dendrite cells (Fig. 3), and Tiller (Ref. 12) has shown that dislocation densities in cell walls are 10^7 to 10^8 greater than cell dislocation densities. Both of these factors will make the cell walls barriers to dislocation motion — as high angle grain boundaries are. This means that the effective weld grain size may be that of the arm spacing rather than the columnar grain diameter. Accordingly, to test this hypothesis, the 0.2% yield strength was plotted against (arm spacing)$^{-1/2}$ (Fig. 6). A correlation between these variables was shown to exist at a confidence level >97.5% which strongly suggests that the yield strength of a single phase weld metal is a function of dendrite arm spacing rather than grain diameter.

The dendrite arm spacing of a small volume of an alloy depends upon the time it takes for the small volume in question to solidify. The time taken to freeze, or the rate of freezing, depends upon heat input: increasing the rate of heat input increases the arm spacing which in turn reduces the yield strength. It may be possible on occasion to overcome this disadvantage of using the more efficient, higher heat input processes, by increasing the rate of heat extraction, say by spraying water on the back of a joint while it is being filled. However, this is only likely to be of limited value and the adoption of high efficiency, high heat input processes,

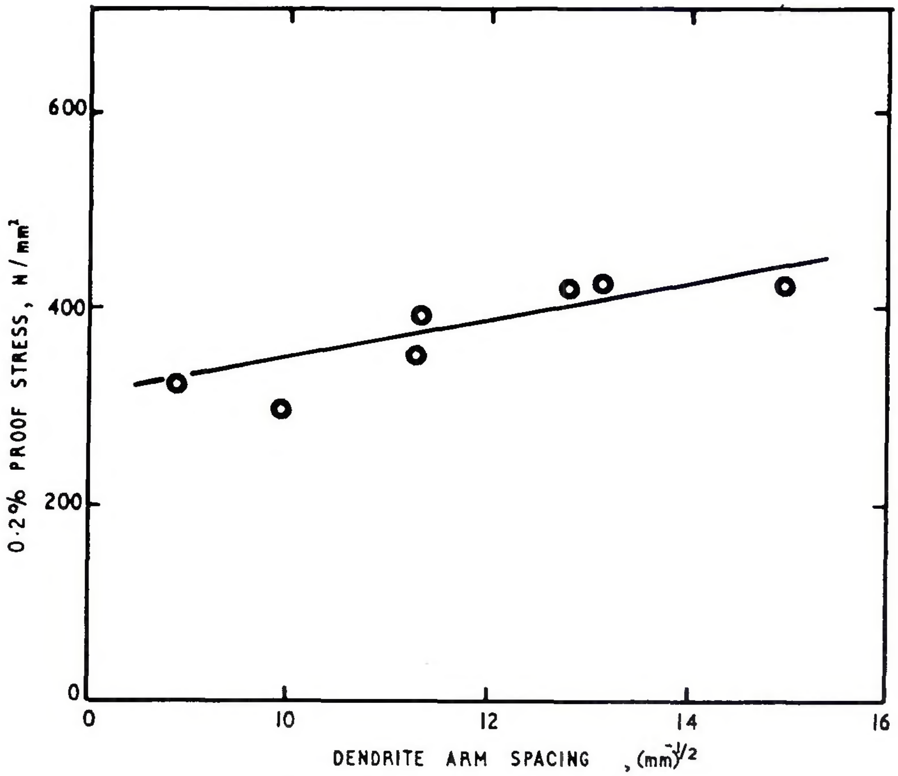

Fig. 6 — A Petch plot of 0.2% yield stress against $l_1^{-1/2}$ where l is the dendrite arm spacing and not the grain diameter. The probability for the relationship shown being correct is over 97.5%

is likely to carry a penalty in a reduction of weld deposit yield strength.

Acknowledgements

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References

1. C. M. Wayman and R. D. Stout, *Welding Journal,* 37 (5), 1958, Research Suppl., pp. 193-s to 200-s.
2. K. J. Irvine and F. B. Pickering, Brit. Weld. J., *7* 353 (1960).
3. H . F. Tremlet, R. G. Baker and J. M. Wheatley, Brit. Weld. J., 8 437 (1961).
4. P. J. Piearcey, B. H. Kear and R. W. Smashey, Trans. A.S.M., *60* 634 (1967).
5. S. F. Frederick and B. A. Bailey, Trans. A.I.M.E., *242* 2063 (1968).
6. J. R. Cahoon and H. W. Paxton, Trans. A.I.M.E., *245* 1401 (1969).
7. U.S. Patent, 3113021.
8. P. E. Brown and C. M. Adams, *Welding Journal,* 39 (12), 1960, Research Suppl., pp. 520-s to 524-s.
9. R. A. Jarman and M. F. Jordon, J. Inst. Met., *98* 55 (1970).
10. E. O. Hall, Proc. Phys. Soc., *B64* 747 (1951).
11. N. J. Petch, J. Iron Steel Inst., *174* 25 (1953).
12. W. A. Tiller, J. App. Phys., *29* 611 (1958).