LETTERS TO THE EDITOR

On the Mechanisms of Annealing Aluminium Cold Pressure Welds

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The well established technique of cold pressure welding implies welding of metallic pieces under load provided a threshold amount of plastic deformation is supplied to the weld region\(^1\). Post heat treatment may be carried out after welding and adjusted to provide a further improvement of the weld interface and therefore enhancing the weld strength. Obviously solid state transport mechanisms are responsible for such enhancement. The present work attempts to throw light on strengthening and softening mechanisms operating during annealing of aluminium cold pressure welds.

Commercial purity 99.5\% Al was used. Specimens 10 mm in diameter and 49 mm long were machine cut from the as-received cold worked rods and annealed for 3 hr at 400°C before welding. The welding faces were then scratch brushed and the specimen couple placed properly in a special die and the desired compressive welding load applied. After welding the specimen was removed from the die and the diameter of the weld bead measured. The amount of deformation was calculated as the percentage increase of the weld area. Subsequently, the specimens were machined down to 8 mm in the weld area (in order to localize tensile fracture in such area) and annealed in a salt bath at different temperatures. After annealing, the specimens were tested in tension. Each strength value is an average over three successful measurements and is reliable within \( \pm 2\% \).

**Group (A):**

- **Deformation Percentage** = 117\(\pm 4\)
- **Welding Load** = 2.5 t

The variation of strength with annealing temperature and time under such welding conditions is given in Fig. 1. For each annealing temperature \( T \) the strength increases with time \( t_A \) above the unannealed value 5.15 kg/mm\(^2\), reaches a maximum and then decreases upon prolonged annealing. The time at a strength peak decreases as \( T \) increases. The rising part of each curve indicates that weld strengthening was dominating. On the other hand, the second part refers to softening which would be expected when annealing a cold worked metal. A characteristic time, taken as that required to increase the weld strength from 5.15 to 7.0 kg/mm\(^2\), was determined from each curve as a function of temperature and an Arrhenius plot made (Fig. 2). The activation energy as determined from the slope is 8300 cal/mol. This apparent energy of the weld strengthening process is in excellent agreement with previous work\(^2\).

The 117\% deformation is slightly higher than the minimum required for welding (98\% in this work). Obviously, a perfect weld was not obtained and the existence of micropores in the weld area is expected. This encourages surface diffusion during subsequent annealing and thus enhances the weld strength. This view should gain the support of the experimental activation energy.

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The vacancy formation energy of Al was reported as 0.76 eV\(^{(3)(4)}\) and its migration energy 0.55 eV\(^{(4)(5)}\). Accordingly, the activation energy for self-diffusion may be taken as 
\(0.76 + 0.55 = 1.31\) eV i.e. 30 kcal/mol. Another estimated value is 37.5 kcal/mol\(^{6}\). The present experimental activation energy is thus about one quarter that of volume diffusion. Considering the ratios of surface diffusion energy to volume diffusion energy for different metals\(^{7}\) and the discussion given by Tylecote\(^{1}\) we can draw the conclusion that the experimental energy is that of surface diffusion of Al and weld strengthening takes place via surface diffusion accordingly.

**Group (B): Deformation Range 193–310\%, Welding Load Range 4–8 t**

A typical example for the results obtained under such conditions is given in Fig. 3. In contrast to the first group all findings here show that the strength decreases during annealing from the very beginning. The higher is the annealing temperature the faster is the strength decrease. Within the limits of experimental error one may generalize that during the first 15 min of annealing the strength has fallen practically to its lowest value corresponding to the annealing temperature in question.

In this high deformation range (and the consequent weld perfection) recovery mechanisms are expected to be dominating during annealing. Arrhenius plots were thus prepared for the softening rate over such a deformation range. This rate was determined as the initial slope of the strength vs \(t_A\) curve. Such plots are presented in Fig. 4. They all are parallel within the limits of experimental error, indicating a single activation energy of 11600 cal/mol for the softening process. Moreover, deformation appears to mainly affect the frequency factor in the Arrhenius-type equation.

Well defined cells were observed to rapidly sharpen and grow during annealing after deformation in Al\(^{8}\). This behavior is due to the rather easy climb of dislocations in Al. The easy climb is attributed to the high stacking fault energy of Al which adversely affects the
chance for dissociation of dislocations. As climb is a recovery mechanism which necessitates migration of point defects to dislocations and vacancies are expected to be present in the weld region with sufficient concentrations, we may conclude that the migration of vacancies is the rate limiting step during recovery. This conclusion gains the support of the fact that the experimental energy of 11.6 kcal/mol is in excellent agreement with the migration energy of vacancies in Al (12.6 kcal/mol).

The finding that the activation energy does not change with deformation and the lines of Fig. 4 only shift to higher rate values with increasing deformation underlines the view that the thermally activated process remains essentially unchanged. The rate increases with deformation due to the increase of vacancy concentration.

REFERENCES

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By A. A. Hussein and A. E. El-Mehairy

Department of Metallurgy, Faculty of Engineering, Cairo University, Egypt.