ADHESIONAL REACTIONS OF TITANIUM
WITH REFRACTORY METALS

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The increasingly complex conditions of operation encountered in many fields of modern technology necessitate more and more often the use in one and the same construction of parts made of different materials. In such circumstances high temperatures and loads inevitably induce adhesional reactions under static or dynamic contact conditions, which frequently shorten the useful lives of machines and mechanisms. On the other hand, adhesional reaction processes constitute the basis of one of the most promising new methods of forming permanent joints, namely vacuum diffusion welding. The processes under consideration play an important part also in powder metallurgy, in particular in the production of composite materials by hot pressing.

Adhesional reactions of refractory materials have already been the subject of a number of investigations [1-5], but in most of them attention has been concentrated on reactions between similar metals. In view of this, the work described below was undertaken with the aim of studying the adhesional reactions of titanium with several transition metals of Groups IV-VI. Experiments were carried out in which a pressure of 1 kgf/mm² was applied "instantaneously" or for periods of up to 16 min in a vacuum corresponding to 1 \times 10^{-5} \text{ mm Hg} at temperatures in the range 700-950°C. The experimental procedure and apparatus were similar to those described in [3]. Some characteristics of the metals investigated are given in Table 1.

Briefly, adhesional tests were performed as follows. Cylindrical, mushroom-shaped specimens with carefully polished end faces (Class 9-10 finish) were placed, out of contact with each other, in the chamber of the apparatus evacuated to a residual pressure of 1 \times 10^{-6} \text{ mm Hg} and preheated to the required temperature. After any adsorbed films were removed from them by calcining for 5 min, they were brought into contact, held for the required time at the required temperature and load, and finally separated at the same temperature, the separating force being measured. The adhesional reactivity of the specimens was assessed by their coefficient of adhesion, expressed as the ratio between the joint breaking force and the compressive load applied to the specimens.

In Fig. 1 are shown curves of the coefficients of adhesion of the metal pairs investigated plotted against time of load application at various constant temperatures. The values of the coefficients of adhesion on the axes of ordinates correspond to "instantaneous" loading, i.e., loading for a fraction of a second. It will be seen from these data that the character of these curves is different for different metals, and changes also with rise in test temperature. For Ti-Mo and Ti-Nb pairs at comparatively low temperatures and up to the α-β transition point of titanium the coefficients of adhesion vary almost linearly with time. In all the remaining cases (Ti-Zr and Ti-Cr at all temperatures and Ti-Nb and Ti-Mo in the temperature range of existence of β-titanium) the relationship is represented by ascending curves with gently sloping initial portions, followed by sharp rises in adhesional bond strength, indicative of the occurrence of volume reactions.

The external appearance of specimens subjected to these tests provides evidence for creep with such metals as titanium and zirconium. Within the time range investigated, 2-16 min, the character of coefficient of adhesion vs temperature curves shows but little change (Fig. 2). The greatest increase in value of coefficient of adhesion is observed with a titanium-zirconium pair and the least with a titanium-niobium pair. Generally, however, the susceptibility of the metals investigated to seizure with titanium increases in the order Nb < Mo < Cr < Zr.

The adhesional properties of metals are usually linked by investigators with such characteristics as melting point, crystal lattice energy, relative size of atomic radius, position in the periodic table of the elements,

TABLE 1. Some Characteristics of Metals Investigated

<table>
<thead>
<tr>
<th>Metal</th>
<th>Crystal lattice</th>
<th>Atomic radius, Å</th>
<th>Melting point, °C</th>
<th>Method of preparation</th>
<th>Microhardness, kgf/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium</td>
<td>Hexagonal, bcc</td>
<td>1.47</td>
<td>1668±5</td>
<td>Iodide, forged</td>
<td>145±5</td>
</tr>
<tr>
<td>Chromium</td>
<td>bcc</td>
<td>1.36</td>
<td>1845</td>
<td>Electrolytic</td>
<td>250±5</td>
</tr>
<tr>
<td>Zirconium</td>
<td>Hexagonal, bcc</td>
<td>1.60</td>
<td>1852±10</td>
<td>Iodide, forged</td>
<td>130±4</td>
</tr>
<tr>
<td>Niobium</td>
<td>bcc</td>
<td>1.47</td>
<td>2468±10</td>
<td>Sintered</td>
<td>195±2</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>bcc</td>
<td>1.40</td>
<td>2620±10</td>
<td></td>
<td>175±15</td>
</tr>
</tbody>
</table>

Fig. 1. Variation of coefficients of adhesion of titanium to refractory metals with time of holding under load at various temperatures: a) Mo; b) Nb; c) Zr; d) Cr. Pressure 1 kgf/mm², vacuum corresponding to 1.5 x 10⁻⁵ mm Hg.

Fig. 2. Temperature dependence of coefficients of adhesion of titanium to refractory metals at load application times of: a) 2; b) 4; c) 8; d) 16 min. Pressure and vacuum as for Fig. 1.

and the like [1]. Arranged in increasing order of values of these characteristics, the metals under consideration form the following series:

- crystal lattice energy [6] (E x 10⁻⁶, J/kg-mole)
  
  Cr (337.5) — Zr (584) — Mo (652) — Nb (773);

- melting point (°C)
  
  Cr (1845) — Zr (1852) — Nb (2468) — Mo (2620);

- microhardness (kgf/mm²)
  
  Zr (130) — Mo (175) — Nb (195) — Cr (250);

- atomic radius difference (aMe — aTi, Å)
  
  Nb (0) — Mo (— 0.07) — Zr (+ 0.13) — Cr (— 0.19).