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Tensile Properties of Recrystallized and Unrecrystallized Tungsten at Elevated Temperatures

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Abstract. As a fundamental study to prolong the lifetime of tungsten electrode for fusing joining, i.e., a kind of resistance welding for conducting metals such as copper and aluminum, deformation and fracture behaviors have been studied as a function of temperature, strain rate and microstructure. Specimens of recrystallized and unrecrystallized tungsten sheets were tensile-tested at temperatures ranging from 300 to 600°C and at strain rates from 1.4×10^{-3} to 1.4×10^{-1} s^{-1} in air. In the recrystallized tungsten tested at 400°C, elongation to failure was decreased from 80% to 10% while yield stress was increased by 50%, when strain rate was increased from 1.4×10^{-2} s^{-1} to 1.4×10^{-1} s^{-1}. This was presumed to be based on the fact that ductile/brittle transition in BCC metal is affected by strain rate as well as temperature, which is attributable to the thermally activated manner of the close slip of screw dislocations. In contrast, in the recrystallized tungsten tested at 600°C, elongation to failure was increased by approximately 10%, when the strain rate was increased from 1.4×10^{-3} s^{-1} to 1.4×10^{-1} s^{-1}. This may be caused by alleviation of some environmental embrittlement, probably associated with oxygen in air. Intergranular fracture took place in almost all conditions within the experiments, even in the unrecrystallized tungsten where majority of the grain boundaries are parallel to the tensile direction.

Introduction

Tungsten has higher melting point than any other metals and has an excellent properties at high temperatures. Therefore, tungsten is applied to the filament, the electrode for resistance welding, etc. The tungsten electrodes for resistance welding are mainly used for fusing joining because of their high resistance against being alloyed with work metal pieces, as well as their high heat resistance. However, from the results on the repeated joining tests for the tungsten electrode, Iijima et al. reported that cracking occurs on the electrode surface, which was attributable to the thermal stress during heating and cooling in a joining cycle [1].

From the above conclusion, they emphasized the importance of deformation and fracture behaviors at elevated temperatures, and preliminarily investigated tensile properties of recrystallized and unrecrystallized tungsten at a strain rate of 1.4×10^{-3} s^{-1}. At and below 300°C, the recrystallized tungsten fractured before reaching the maximum stress with very small elongation to failure of about 5%. On the other hand, at and above 400°C, elongation became over ten times larger (increased to above 50%) with appreciable necking. The unrecrystallized tungsten had a higher yield stress than the recrystallized tungsten. The nominal stress-strain curves of the unrecrystallized tungsten showed a maximum at an early stage followed by gradual decrease in the stress.

In this study, the deformation and fracture behaviors at elevated temperatures for tungsten was further investigated as a function of strain rate as well as the difference in the microstructure and temperature, to acquire the basic knowledge on the cracking in the tungsten electrode for fusing joining to extend the lifetime.

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Specimens and Experimental Procedures

Specimens. Tungsten powder was sintered and hot-rolled into a plate of 2mm in thickness. Part of this plate was annealed at 1800°C in a hydrogen atmosphere to obtain a recrystallized microstructure. Tensile test pieces shown in Fig. 1 were cut by wire electric discharge machining from the two kinds of plates: as-rolled and annealed which will be referred to as unrecrystallized and recrystallized, respectively. The two types of microstructures are shown in Fig. 2.

Experimental Procedures. Tensile tests were carried out in an air furnace at strain rates of 1.4×10^{-2} s^{-1} and 1.4×10^{-1} s^{-1}, and temperatures ranging from 300 to 600°C. The test pieces were fixed at their shoulders with a set of jigs, heated in the furnace, kept for 15 min after the temperature of the furnace reached the predetermined temperature, and then subjected to the test. Results obtained were discussed together with those by Iijima et al [2] (strain rate: 1.4×10^{-3} s^{-1}).

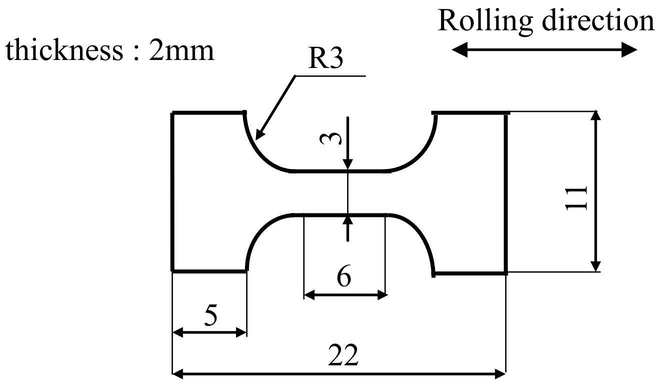

Fig. 1 Dimension in mm and morphology of tensile the test piece.

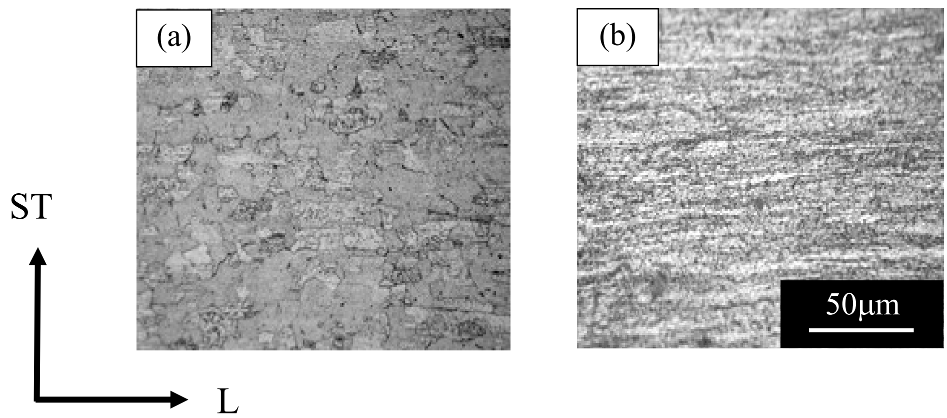

Fig. 2 Optical microstructures of the two specimens. (a) recrystallized and (b) unrecrystallized.

Results and Discussion

Effect of temperature. Engineering stress–strain curves at each temperature of recrystallized and unrecrystallized tungsten at a strain rate of 1.4×10^{-1} s^{-1} are shown in Fig. 3. The curves have been modified so that the fracture strain in the curves coincides to the fracture elongation measured from the change in gage length before and after the tensile test. The general behavior is similar to that reported by Iijima et al [2] in the following aspects. (i) The unrecrystallized tungsten has higher yield (or 0.2% proof) and flow stresses than the recrystallized tungsten. (ii) The stress of the unrecrystallized tungsten reaches its maximum at an early stage of deformation and then gradually decreases up to the fracture, irrespective of temperature. (iii) In the recrystallized tungsten, fracture takes place prior to the stress maximum at lower temperatures with smaller elongation than the unrecrystallized tungsten, while elongation larger than the unrecrystallized tungsten is obtained at higher temperatures, i.e., explicit ductile/brittle transition can be observed at a certain temperature region. This ductile/brittle transition is also consistent to the sharp change in reduction of area reported by Bechtold and Shewmon [3]. In this study, however, the transition temperature lies between 400 and 500°C, being higher than the transition temperatures reported by Iijima et al. [2] and Bechtold and Shewmon [3] both lying between 300 and 400°C. The reason for this difference will be discussed in the next section in terms of the effect of strain rate.

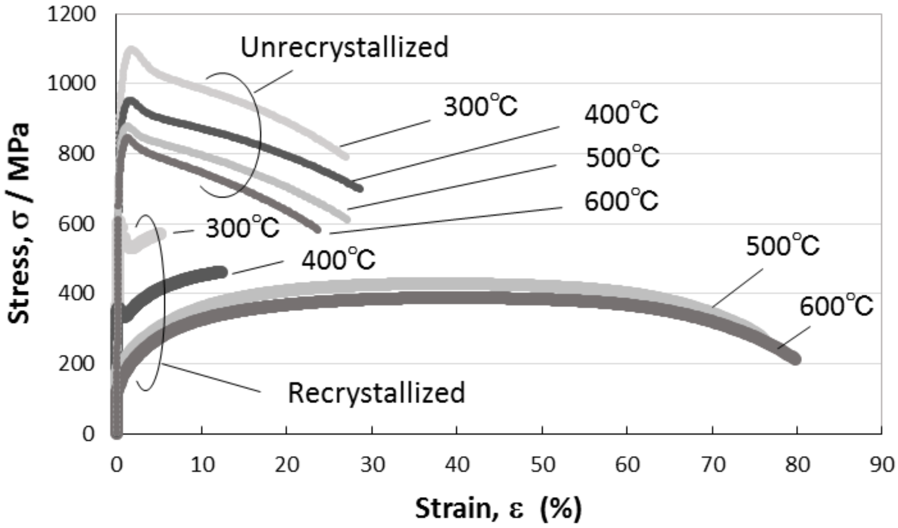

Fig. 3 Stress-strain curves of the specimens with two microstructures at various temperatures at a strain rate of 1.4×10^{-1} s^{-1}.

Effect of strain rate. Strain rate dependence of the 0.2% proof stress and the tensile strength in the two kinds of tungsten tested at 400 and 600°C is shown in Fig. 4. At 400°C, 0.2% proof stress in the recrystallized tungsten sharply increases when the strain rate increases from 1.4×10^{-2} to 1.4×10^{-1} s^{-1}. Tensile strength at both temperatures as well as the 0.2% proof stress at 600°C does not change with strain rate. In the unrecrystallized tungsten, 0.2% proof stress slightly increases while tensile strength is almost constant, as the strain rate increases both at 400 and 600°C.

Figure 5 shows the total elongation of the specimens with the two microstructures tested at 400 and 600°C as a function of strain rate. In the recrystallized tungsten, at 400°C, the total elongation decreases sharply when the strain rate increases from 1.4×10^{-2} to 1.4×10^{-1} s^{-1}. This decrease as well as the increase in the proof stress mentioned above is probably due to the fact that the close slip of screw dislocation in BCC metals is a thermally activated process that becomes more difficult with increasing strain rate as well as decreasing temperature [4], [5]. Considering this thermally activated manner of the close slip, the difference in ductile/brittle transition in the present study from those in the previous reports [2], [3] mentioned in the previous section can be understood: the larger strain rate in this study will cause the same effect as lower temperature, resulting in the occurrence of the transition at higher temperature. Another aspect shown in Fig. 5 is the tendency of the increase in elongation with increasing strain rate, in contrast to the decrease in elongation discussed above. This will be discussed in the next section together with fractography.

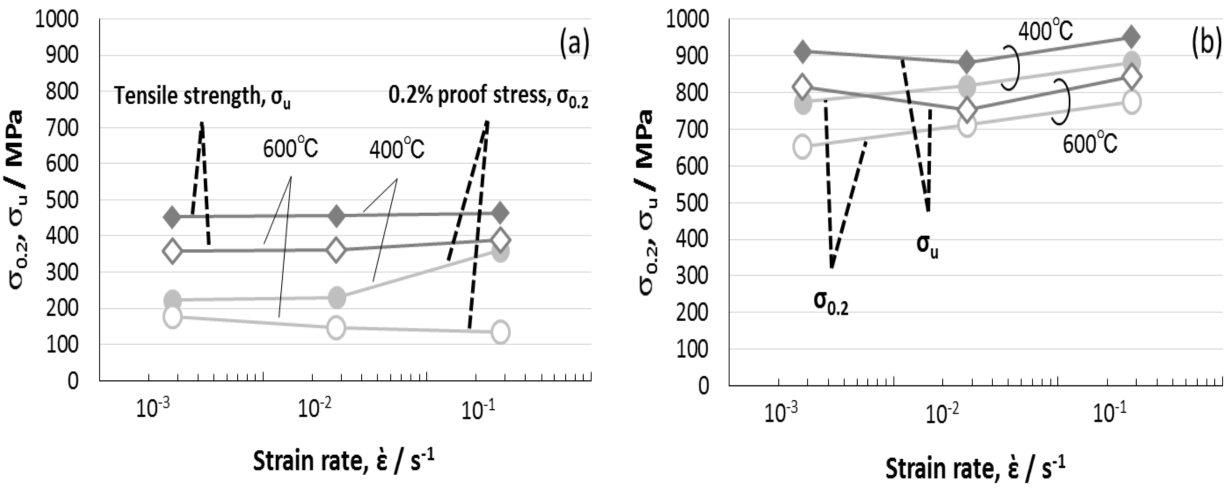

Fig. 4 Strain rate dependence of the strengths of the specimens with two kinds of microstructures. (a): recrystallized, (b): unrecrystallized.

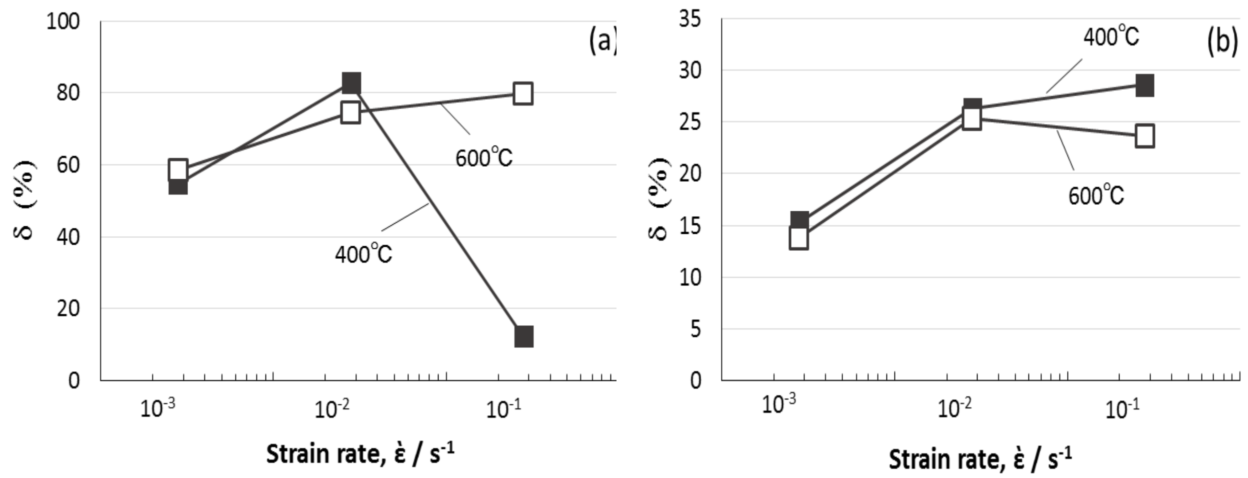

Fig. 5 Strain rate dependence of the total elongation (δ) of the specimens. (a): recrystallized, (b): unrecrvstallized.

Observation of fracture surface. Figure 6 shows SEM images of the fracture surface of the recrystallized tungsten after testing, as a function of temperature and strain rate. At 400°C, the fracture surface of the test piece stretched at the strain rate of 1.4×10^{-1} s^{-1} is macroscopically flat and perpendicular to the tensile direction with no necking, corresponding to the low ductility demonstrated in Figs. 3 and 5. This feature is considered to be arisen from intergranular fracture. In contrast, corresponding to the large elongation, the test pieces tested at 600°C at both strain rates and tested at 400°C at 1.4×10^{-3} s^{-1} have intricate fracture surfaces with necking. In addition, the recrystallized tungsten tested at strain rate of 1.4×10^{-3} s^{-1} had greater number of subcracks on the surface near the fracture point than tested at higher strain rate, as shown in Fig. 7. Although explicit evidence is lacking, these subcracks as well as the main crack seemed to be along grain boundaries and environmental embrittlement probably by oxygen from the air is deduced to be the cause of the lower elongation at the slower strain rate.

Figure 8 shows SEM images of the fracture surface of the unrecrystallized tungsten. The fracture feature of unrecrystallized tungsten is fibrous irrespective of strain rate and temperature. This implies the fracture occurs at grain boundaries even in the unrecrystallized (fibrous) microstructure. The lack of sensitivity on strain rate and temperature is in accord with the stress-strain curves.

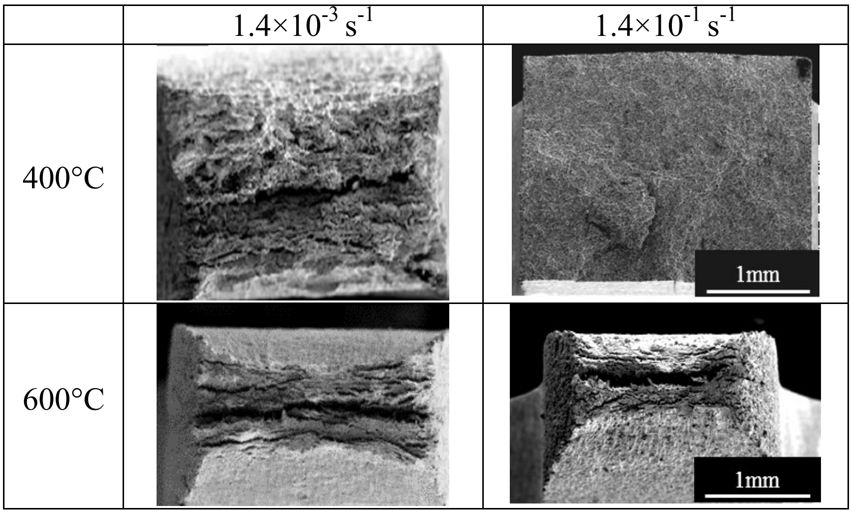

Fig. 6 Fracture surface of the recrystallized tungsten tested at 400 and 600°C at two different strain rates.

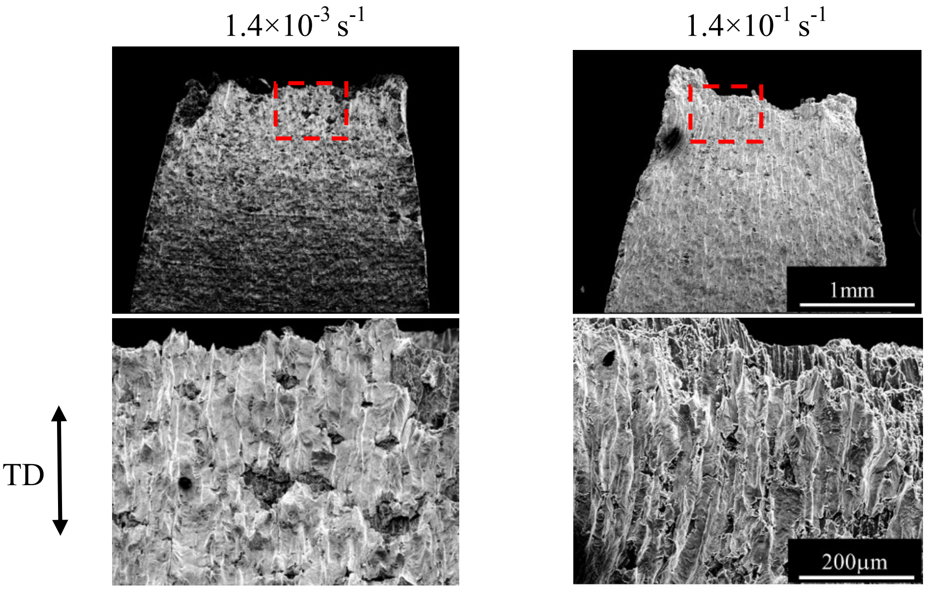

Fig. 7 Surface appearance of the recrystallized tungsten tested at 600°C at two different strain rates.

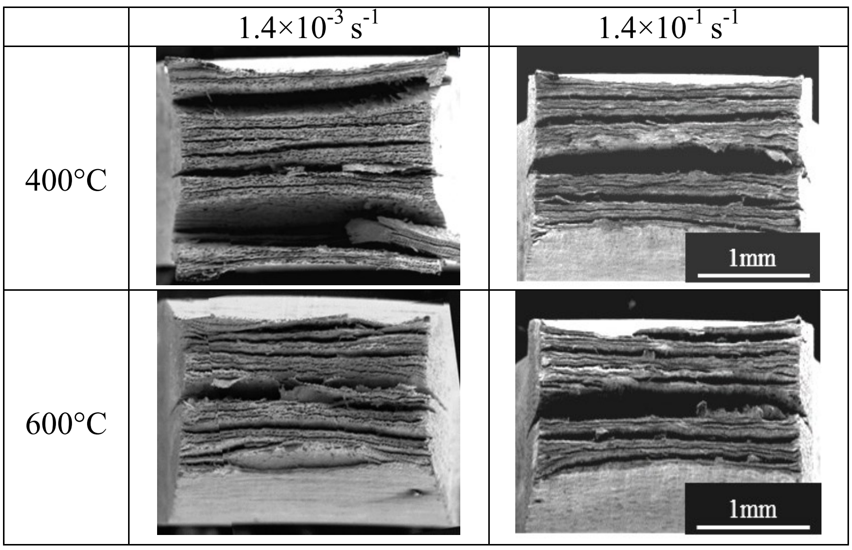

Fig. 8 Fracture surface of the unrecrystallized tungsten.

Conclusions

Tungsten with recrystallized and unrecrystallized microstructures was tensile-tested at strain rates of 1.4×10^{-2} s^{-1} and 1.4×10^{-1} s^{-1}, and testing temperature between 300°C and 600°C. Deformation and fracture behaviors were discussed as a function of temperature, strain rate and microstructure, with the data reported by Iijima et al. [2] where the strain rate was 1.4×10^{-1} s^{-1} as well as those obtained in this study. The conclusion is summarized as follows:

1) In the recrystallized tungsten tested at 400°C, elongation to failure was decreased from 80% to 10% while yield stress was increased by 50%, when strain rate was increased from 1.4×10^{-2} s^{-1} to1.4×10^{-1} s^{-1}. This was presumed to be based on the fact that ductile/brittle transition in BCC metal is affected by strain rate as well as temperature, which is attributable to the thermally activated manner of the close slip of screw dislocations.
2) In the recrystallized tungsten tested at 600°C, elongation to failure was increased by approximately 10%, when the strain rate was increased from 1.4×10^{-3} s^{-1} to 1.4×10^{-1} s^{-1}. This may be caused by alleviation of some environmental embrittlement, probably associated with oxygen in air.
3) Intergranular fracture took place in almost all conditions within the experiments, even in the condition with relatively large elongation or even in the unrecrystallized tungsten where majority of the grain boundaries are parallel to the tensile direction.

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