High Temperature Fracture Toughness and Fatigue Behavior of Ti-Zr-Mo and W-Re Alloys for X-ray Tube Application

(X線管に用いる Ti-Zr-Mo および W-Re 合金の高温破壊じん性と疲労挙動)

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ABSTRACT

Commercial x-ray targets for computed tomography (CT) applications consist of two major components, a metal disc made of the titanium-zirconium-molybdenum (TZM) alloy, and a surface layer in the bombarding region made of the tungsten-rhenium (W-Re) alloy. The target must endure extremely high temperature, associated with high thermal stress, and mechanical stress due to the centrifugal force induced by high speed rotation of the target. Therefore, studies on high temperature fracture and fatigue behavior of these materials would be the most important for reliability assessment and safety design of the x-ray target. However, they have been rarely reported and high temperature fracture and fatigue behavior of these materials has been not always clarified.

In the present study, high temperature fracture toughness was evaluated for two kind of TZM alloys, one with higher C content and the other with higher O content. Moreover, effect of forging rate on high temperature fracture toughness was discussed. Fatigue properties at room temperature and 1000 °C were evaluated for three kinds of materials, layered W-Re/TZM, bulk W-Re and bulk TZM, and a fatigue failure definition in the high temperature fatigue test was investigated to evaluate high temperature fatigue strength. The fatigue processes of these x-ray target materials at high temperature were also investigated.

High temperature fracture toughness of two TZM alloys with different kinds of grain boundary particles was successfully evaluated using the convenient $J_{IC}$ test method. The result indicated that the $J_{IC}$ values at temperatures ranged from 800 °C to 1000 °C were almost constant regardless of temperature, while the $J_{IC}$ values of the TZM with
higher C content were higher than those of the TZM with higher O content. The TZM with different forging rates showed similar $J_{IC}$ values, which suggested the effect of forging rate would be not significant at high temperatures.

High temperature fatigue characteristics of W-Re and TZM were successfully evaluated under load-controlled four point bending test at 1000 °C by introducing a fatigue failure criterion as two-times increase of initial compliance, which was corresponding to nucleation and propagation of multiple cracks from specimen surface. The layered W-Re/TZM specimen exhibited the similar fatigue strength to the bulk W-Re specimen. The bulk TZM showed much lower fatigue strength compared to the layered W-Re/TZM and the bulk W-Re. The total crack length measured on the specimen surface at 1000 °C would be a dominant indicator for evaluating progress of fatigue damage.
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International Conference:


National Conference:

1.1 Introduction to refractory metals

For some decades, machines and equipment for high temperature operation have been developed with increasing demand for operating at a higher temperature, such as in industries, engineering and constructions, aerospace, power generations, etc. All of these machines in common are using refractory materials, which can keep their strength at high temperature. A material during their service time on high temperature, will suffering a severe condition due to extreme thermal shock, mechanical load, and oxidation attacks [1]. Hence, to deal with this condition, materials must be chemically and physically strong at high temperatures. However, after a long period of usage all of those effects will lead to make some damage of material and fractured.
Refractory metals can be classified as metals that are outstandingly resistant to heat and wear. The most common definition includes metallic elements of niobium (Nb), molybdenum (Mo), tantalum (Ta), and tungsten (W) based on the criteria of body centered cubic (bcc) crystal structure and minimum melting temperature of 2200 K [2]. The latest finding its entry in this special category of metals is rhenium (Re) because of its high melting point close to tungsten. All of these materials have some similarities in properties, such as a melting point higher than 2000 °C, high hardness at ambient temperature, chemically inert and have a relatively high density compared to other metals [3]. Table 1.1 shows a property comparison of Nb, Ta, Mo, W and Re.

Table 1.1 Comparison of some physical properties for pure refractory metals [4].

<table>
<thead>
<tr>
<th>Property</th>
<th>Niobium</th>
<th>Tantalum</th>
<th>Molybdenum</th>
<th>Tungsten</th>
<th>Rhenium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal structure</td>
<td>bcc</td>
<td>bcc</td>
<td>bcc</td>
<td>bcc</td>
<td>hcp</td>
</tr>
<tr>
<td>Density, g/cc</td>
<td>8.6</td>
<td>16.6</td>
<td>10.2</td>
<td>19.3</td>
<td>21.0</td>
</tr>
<tr>
<td>Melting point, °C</td>
<td>2470</td>
<td>3000</td>
<td>2620</td>
<td>3410</td>
<td>3170</td>
</tr>
<tr>
<td>Thermal expansion, (ppm/K)</td>
<td>7.3</td>
<td>6.3</td>
<td>4.8</td>
<td>4.5</td>
<td>6.2</td>
</tr>
<tr>
<td>Thermal conductivity (W/m. °K)</td>
<td>52</td>
<td>54</td>
<td>146</td>
<td>166</td>
<td>71</td>
</tr>
<tr>
<td>Modulus of elasticity at 20 °C (kN/mm²)</td>
<td>100</td>
<td>190</td>
<td>320</td>
<td>400</td>
<td>460</td>
</tr>
<tr>
<td>Tensile strength (recrystallized) at 20 °C (N/mm²)</td>
<td>200</td>
<td>300</td>
<td>500</td>
<td>700</td>
<td>800</td>
</tr>
</tbody>
</table>
1.1.1 Molybdenum

Molybdenum is one of the refractory metals which has been utilized as elevated temperature structural material as a result of its high melting temperature (2620 °C), high strength and creep resistance at high temperature. These excellent properties were provided by its body-centered cubic (bcc) structure which is stable at high temperature and high pressure [5]. Even though it has less oxidation resistant compared to tungsten, yet molybdenum posses limited coefficient of thermal expansion, excellent heat resistance, as well as thermal conductivity. The moderate density also has make molybdenum appropriate employed as base for heat-resistant materials [6].

1.1.1.1 TZM alloy

When higher temperature strength is needed, titanium-zirconium-molybdenum (TZM) alloy has shown potential as the candidate material. TZM is widely used as material for high temperature application with heavy mechanical load, dies and cores for the die casting, extrusion as well as forging dies, and other high temperature applications when high temperature strength is required such as a base material of x-ray tube’s anode target [1,6,7]. TZM alloy consists of (0.40–0.55) wt.% Ti, (0.06–0.12) wt.% Zr, (0.01–0.04) wt.% very fine carbides C and Mo in balance. Alloying molybdenum with Ti and Zr has shown significant increasing of high temperature strength (720 MPa), higher recrystallization temperature (1100 °C) and better creep resistance compare with pure molybdenum. The small amount addition of Ti and Zr has strengthened Mo solid solution due to the dispersion of composite carbides in the molybdenum matrix by the formation
of precipitates of TiC and ZrC [1,6]. Table 1.2 shows the basic mechanical properties of molybdenum in comparison with TZM alloy.

Table 1.2 Property comparison of Molybdenum and TZM alloy [5].

<table>
<thead>
<tr>
<th>Nominal alloy addition, wt.%</th>
<th>Common designation</th>
<th>Usual condition</th>
<th>Low temp. ductility</th>
<th>Typical high-temperature strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Unalloyed Mo&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>S-R-A</td>
<td>B-C</td>
<td>Temp., ºC</td>
</tr>
<tr>
<td>0.5Ti, 0.08 Zr, 0.03 C</td>
<td>TZM&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>S-R-A</td>
<td>B-C</td>
<td>1000</td>
</tr>
</tbody>
</table>

*S-R-A: stress relieved annealed, B: excellent RT ductility, C: may have marginally ductility at RT, <sup>(c)</sup>: available in both powder metallurgy and arc cast forms.

1.1.2 Tungsten

Tungsten (W) is the material with the highest melting temperature of all metals \( T_{\text{melting}} = 3410 \, {\degree}\text{C} \) [8] and for that reason has been used as many decades in elevated temperature utilizations [9]. Tungsten alloys have become the best candidate for very high temperature functions due to their thermal capabilities as well as excellent elevated temperature mechanical properties. These properties also consist of low vapour pressure, high emissivity, and exceptional high-temperature rigidity and strength. In contrary, the exceptional elevated temperature properties of tungsten are compensate by obstacles in preparation as well as manufacturing due to its high melting temperature and low ductility at room temperatures [10].
1.1.2.1 Tungsten-rhenium alloy

Research works have been conducted to produce tungsten alloys with enhanced low temperature manufacturing ability and elevated temperature mechanical properties as nuclear and aerospace utilizations, in an effort to overcome some of the problems. It has been established that a limited addition of rhenium able to enhance the tungsten’s ductility at low temperature and strength at elevated temperature [10]. The rhenium addition to tungsten revealed a significant reduction in the ductile to brittle transition temperature (DBTT), and finer grained materials furthermore cause to the needed reduce in the DBTT as presented in Fig. 1.1(a) [11].

In addition, purity, surface condition, strain rate and also testing environment (for example, high temperature) likely to affect DBTT. Hardness results of pure tungsten and W-Re alloys with different compositions are presented in Fig. 1.1 (b). It can be observed that there exists a particular reaction, where at lesser Re concentrations (5 to 15 at.%), solid softening effect occurs before it starts strengthening the matrix metal at higher concentrations. The better ductility is accomplished by so called ‘rhenium ductilizing effect’ where Re generates substantial twinning and a raise in the number of slip planes [11]. In the succeeding decades, the research works on fatigue and fracture behavior of tungsten-rhenium alloys is quite rare, which possibly associated to the reality that rhenium is a very hard to find and thereby high-priced metal. It is not targeted to be utilized at high concentrations at a broad or in industry scale. Nonetheless, because of its high density and high atomic number (Z), it is widely used in medical x-ray devices as an anode target [12,13].
Fig. 1.1. (a) Relationship of DBTT and average recrystallized grain diameter for pure tungsten and W-24Re/W-26Re and (b) relationship of Vickers hardness (VHN) and rhenium content [11].

1.1.3 Fabricating process of refractory metals

Given all the interesting features of refractory metals, it is important to establish appropriate fabrication procedures for tungsten and molybdenum alloys. Given the high melting points of the constituents, it was unrealistic to consider the conventional solidification process of casting as the fabrication route. Work in the 1960s and 1970s
used materials that produce by vacuum arc remelting (VAR) as well as electron beam melting (EBM) techniques which purity were suspected [11].

Tungsten and molybdenum alloys are commonly fabricated by powder metallurgy methods as casting ingots is a difficult and expensive process due to it high melting temperature [14,15]. The isothermal powder metallurgy process begins with consolidation of the powder by pressing at room temperature become rods and plates with different geometries and sizes. Conventionally, sintering is conducted by giving outside pressure such as Hot-Isostatic-Pressing (HIP). The process of sintering is conducted in furnaces at elevated temperatures (normally in the temperature range of 1800 to 2200 °C) and in hydrogen environment in some duration of time (2 to 3 hours) to earn densities around 90% of theoretical density [16]. Hot rolling, extrusion or forging at temperatures between 1200 to 1500 °C are afterward used for higher densities. Spark plasma sintering (SPS) is a recent technology for compression of metal powders. It has a brief time for sintering process, where metal powders are compacted by pressing and heating at the same time from a pulsed electric field. Compared to conventional sintering methods, densification by SPS is very quick. Hence, the sintering temperatures can be reduced which it can inhibits the grain growth [16].

Recently, metal injection molding (MIM) also has been used to produce tungsten and molybdenum alloys [17]. Additive manufacturing type of powder metallurgy also can be applied, such as selective laser sintering (SLS) [18], selective laser melting (SLM) [19] as well as electron beam melting (EBM) [20]. Figure 1.2 shows the typical fabrication processes of Mo and W products.
1.2 Application of refractory metals

Refractory metals and their alloys are able of satisfying an aggressive environment with respect to radiation, temperature, corrosion and stress for extended periods. These materials are thus being studied as high temperature structural materials, for current generation reactors like accelerator driven system (ADS), compact high temperature reactor (CHTR), advanced heavy water reactor (AHWR), fusion equipments [21,22] and space aircrafts [23]. There is an expanding interest for materials that able to sustain reliability under developing temperature environments. Above 1200K, the refractory metal alloys are particularly possible choice elements as structural use. Fig. 1.3 demonstrates the possible choice materials with increasing operational temperatures, in the application of nuclear power systems [3].
Fig. 1.3 Recommended operating temperature range for structural materials in space nuclear power systems [3].

Tungsten has been used in various applications, such as filament for light bulbs and x-ray tubes (for both the filament and target). Due to its high melting temperature as well as low vapor pressure, tungsten is practical for electrodes in tungsten inert gas (TIG) welding. Excellent heat resistance produces it highly handy for heating elements, radiation shielding for vacuum and controlled atmosphere furnaces [24,25].

Molybdenum most significant utilization is as an alloying inclusion in steel. It contributes tool steels and stainless steels with superior wear resistance, strength and toughness. It also improves high temperature strength and corrosion resistance. It also has been used in nickel- and cobalt-based alloys in turbine engine parts. It enhances hot
strength and corrosion resistance. For high temperature application, it's also used as die casting dies and cores, such as for extrusion dies and forging dies [25].

In the application of x-ray tubes, molybdenum and tungsten alloys have been widely used as the anode target material. For example, rotating anode kind of targets are mainly made from tungsten-rhenium (W-Re) and molybdenum TZM composite material. Normally materials are a W-Re target made on a TZM as a core material, which backed with a graphite [26].

1.2.1 X-ray tube application

An x-ray tube can be defined as a vacuum tube that transforms electrical input power become x-rays. X-ray tubes have been used in computed tomography (CT) scanner, airport baggage scanners, material and structure examination, and for inspection in industry [27]. An x-ray CT scanner is one of the commonly used application in medical imaging, as shown in Fig. 1.4. It is found from the figure that the utilization rate of the CT scanner has been increased between 1995 to 2005. The medical images are used for diagnosis and therapy purposes in numerous clinical disciplines. CT scanners have been available since 1970s. The most important part of a CT scanner is the x-ray tube. In this component, an electron beam is irradiated onto a positively charged metal in a vacuum, referred to as an anode target, and thereby generate the x-ray. The focal track, which is bombarded by the electron beam, is formed on the surface of the target [28–32].
In such application, there are several types of x-ray tubes, that is categorized based on the anode type:

(a) Stationary anode tubes

This kind of tube uses a stationary anode target that stays still, as shown in Fig. 1.5. This kind of tube is used for the application that perform mainly short and lower dose exposures, as in pain management needle placement or hand and foot specialties. This type of tubes are commonly build in more compact, space-saving and less expensive equipments [34].
(b) Rotating anode tube

This tube used a rotating anode target, where it spins around a fixed point, as shown in Fig. 1.6. In terms of heat dispersal, all the energy approaching to the target from the cathode generates a large amount of heat. If that heat maintains hitting the same location over and over again, as in a stationary anode tube, sooner or later the surface of the anode can deform and the angle of the x-ray radiation will shift, lowering dose performance and the general image quality produced. Regarding of a rotating anode tube, the heat of the arriving cathode beam is scattered uniformly over the whole surface of the target as it spins. This enables this tube to carry out longer scans and at higher dose, such as run-offs or cross laterals, or scans for larger patients [34]. The Fig. 1.6 below shows the schematic principle of x-ray tube with red rectangular marked as the high duty area. In this study, rotating anode tube type of x-ray tube will be investigated.
Tungsten and tungsten-base alloys are commonly used in the x-ray target. Tungsten is the metal with the highest melting point among the metals and excellent mechanical properties at high temperature. Manufacturing of the x-ray target only from tungsten is undesirable because of the high density and heavy weight of tungsten. In addition, since tungsten is notch sensitive and extremely brittle [37], there is a danger of catastrophic failure with resultant damage of the whole equipment. One of the solutions is that tungsten is used only for the bombarding surface region and the different material with lower density and lower brittleness is used for the remaining part of the x-ray target. As the different material, molybdenum-base alloys are compatible with tungsten, which have good thermal conductivity, match with the coefficient of thermal expansion of tungsten, as well as less susceptible to cracking, lower density and lower cost compared to tungsten [38,39].
As explained above, commercial x-ray targets consist of two major component materials, the tungsten-rhenium alloy for surface layer in the bombarding region and the molybdenum alloy for the remaining part of disc. Figure 1.7 shows the main construction of rotating anode disk that is composed by refractory materials layers, and some, graphite is attached in bottom layer to minimize the rotating mass and to release the extensive heat generated during operation [40]. The titanium-zirconium-molybdenum alloy (TZM) has been developed with addition of 0.5%Ti and 0.07%Zr to improve the high temperature strength and recrystallization temperature [41]. For the tungsten-rhenium alloy (W-Re), the Re element has been added to tungsten to improve ductility and ductile-to-brittle transition temperature [42].

![Fig. 1.7 Rotating anode disk](image.png)

Working temperature of the target is depends on the type of clinical procedure, the size of the target, the power rate of energy input and the pause time between each exposure [44]. Fig. 1.8 (a) shows the simulated temperature distributions at the end of exposure for targets with different sizes and power rates, as well as the temperature evolution at the focal track is shown in Fig. 1.8 (b). Fig. 1.9 shows a common relationship
between temperature and time, for an x-ray target with the size of 200 mm, in different type of treatment exposures. From the figures, the temperature is the highest at the focal spot, where the electron bombardment was occurred and gradually reduced at the focal track, the anode, and the rotor, when away from the focal spot. The temperature of the target was around 450 °C [26] at the start of exposure. As seen in Fig. 1.9, the most concerned temperature in the target component is the temperature of the focal track and the anode, that is around 1000 to 1500 °C.

Fig. 1.8 (a) Temperature distributions at the end of the exposure, and (b) the evolution of temperature at the focal track for different sizes of target and power rates, simulated by FEA [26].
Fig. 1.9 Common relationship of temperature and time, for 200 mm anode, with various clinical operations [44].

1.2.2 Critical issues in x-ray tube design

As explained above, x-ray target is the most critical component in the x-ray tube application. During exposure, focal track is formed on the surface of the target. Under such severe condition, the target must endure extremely high temperature, associated with high thermal stress, and mechanical stress due to the centrifugal force induced by high speed rotation of the target [39,45–48]. These temperature, thermal stress and centrifugal stress are variable during working conditions, such as start-up/shut-down and rotation of the target. Therefore, fatigue would be one of the most concerned failure modes in the x-ray target.

On the other hand, due to the reality of the target’s material, which is made from molybdenum and tungsten alloys, is well known for its brittleness. It is difficult to avoid occurrence of cracks in the such brittle material, whether it occurs during the manufacturing process or during working cycles. TZM alloy is frequently used as the
base materials, designed to have an adequate combination of hot strength, toughness and ductility, as well as thermal conductivity and expansion.

Since the quality of a medical imaging and the cost effectiveness of the production depend on the reliability of the target, the service life of an anode is essential. An important feature is the temperature stability of the target. It is vital that a target maintains its properties even after it has been subjected to a large number of mechanical and thermal load cycles, otherwise premature failure may occur.

1.2.3 Speculated fracture process of x-ray tube

It was speculated that the x-ray target of x-ray tube will be fractured with the process below, as demonstrated in Fig. 1.10.

Firstly, fatigue crack nucleation by fatigue loading during working operation, due to combination of thermal stress from electron bombardment at the focal track and rotation of the target during operation. As shown in Fig. 1.11, during clinical exposure, thermal stress is occurring at the focal track induced by temperature cyclic due to heating (exposure time) and cooling (pause time) processes of the anode target. After several times these processes repeatedly occurred, fatigue cracks can be nucleated near the free surface of the W-Re layer, and further can propagate until the TZM substrate as the base material. Therefore, it is important to investigate the crack nucleation process and the fatigue characteristic of the target materials during high temperature operation.

Secondly, crack due to fatigue loading can be propagated from the W-Re layer until the TZM base material. For material that include a crack, when the static stress near the crack tip is higher than the critical value of crack resistance that called fracture
toughness, catastrophic failure can occur, as shown in Fig. 1.10 (b). Furthermore, the use of TZM alloy as a target posed a problem that impurities in the alloy, such as oxygen, carbon and hydrogen, are gasified and lower the degree of vacuum in the x-ray tube resulting in deteriorated properties of the x-ray tube. Therefore, it is important to study the fracture toughness behavior of the target materials, especially the TZM alloy as the base material.

Fig. 1.10 Speculated fracture process of anode target of x-ray tube.
Fig. 1.11 Typical relationship between temperature and time in the focal track of a rotating anode x-ray target during a clinical exposure.

1.3 Current status of research on high temperature fracture toughness and fatigue behavior of tungsten and molybdenum alloys

There have been various reports on W-Re and TZM about effects of composition, test temperature, fabrication variables, etc. on brittle to ductile transition, tensile properties, microstructure, hardness, and so on [10,14,49–56]. In this section, the status of research on high temperature fracture toughness and fatigue behavior of tungsten and molybdenum alloys will be discussed.

1.3.1 Fracture toughness at high temperature

The earlier fracture toughness investigation of molybdenum and molybdenum-based alloys which is considered a more accurate and conservative was reported since compression precracking method has been developed [57,58]. Toughening mechanism and DBTT molybdenum and molybdenum alloys also were confirmed [54,59–61].
Fracture toughness tests of tungsten and tungsten-rhenium (W-Re) alloys were carried out at elevated temperatures (in the range of room temperature to 1600 °C) by Mutoh et al. [42] to investigate temperature dependence of fracture toughness and effect of Re content on fracture toughness. The fracture toughness of specimens with Re contents of 0, 5 and 10 wt% were nearly the same at room temperature, however fracture toughness at elevated temperatures were increased with increasing Re content, as shown in Fig. 1.12. The brittle to ductile transition and the transition of the fracture mode from ductile dimple to intergranular were obtained.

Fig. 1.12 Fracture toughness of pure tungsten W (Δ), W-5%Re (●), and W-10%Re (O) alloys [42].
Cockeram [59] has carried out fracture toughness testing at temperatures between -150 and 450 °C to characterize oxide dispersion strengthened (ODS) and TZM molybdenum alloys. A transition from low fracture toughness values to values higher than 30 MPa$^{1/2}$m is observed for TZM in the longitudinal orientation at 100 °C and in the transverse orientation at 150 °C, as shown in Fig. 1.13. He continued the work [54] and has tried to evaluate high temperature fracture toughness $J_{IC}$ of low carbon arc cast (LCAC), TZM and ODS molybdenum alloys at 1000 °C by the compliance method according to ASTM E1820. However, it was not successful due to large deformation during stable crack growth.

Fig. 1.13 Relationship of fracture toughness and testing temperatures, at a temperature range of -150 °C and 450 °C [59].
Wurster et al. [13] carried out high temperature fracture toughness tests on tungsten-rhenium alloy (W-26%Re) at temperatures between room temperature to 900 °C to investigate the influence of rhenium on the fracture process of tungsten-rhenium alloys. The result of the fracture toughness tests can be summarized in Table 1.3. However the specimens that they used were too small to accommodate the plain strain conditions and linear elastic fracture mecchanic (LEFM).

Table 1.3 Fracture toughness results for W-26%Re alloy, tested at different temperatures for recrystallized and as-forged condition [13].

<table>
<thead>
<tr>
<th>Testing temperature (°C)</th>
<th>$K_Q$ recrystallized (MPa m$^{1/2}$)</th>
<th>$K_Q$ forged (MPa m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-196</td>
<td>-</td>
<td>38</td>
</tr>
<tr>
<td>20</td>
<td>22.8</td>
<td>54.2</td>
</tr>
<tr>
<td>300</td>
<td>25.9</td>
<td>-</td>
</tr>
<tr>
<td>400</td>
<td>-</td>
<td>65.4</td>
</tr>
<tr>
<td>600</td>
<td>57.7</td>
<td>52.5</td>
</tr>
<tr>
<td>870</td>
<td>40.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Although some fracture toughness data have been reported for molybdenum and tungsten, most of the data have been measured only at room temperature, except some reports on high temperature fracture toughness of W-Re alloys [42]. The main reason for lack of reports on high temperature fracture toughness will be the difficulty of fracture toughness test at high temperature. Therefore, in this present study, to conform the application of TZM alloy as the high temperature structural material, the fracture mechanism and fracture toughness at higher temperature is analyzed. The variation of
forging rates during powder metallurgy processing was selected as an effort to increase the high temperature strength, but reduce material amount as well as the production cost.

1.3.2 Fatigue properties at high temperature

For fatigue behavior of Mo and its alloys, Alur and Kumar [62] reported fatigue behavior of molybdenum alloys, Mo$_2$SiB and TZM tested under stress ratio of 0.1 at room temperature and 1200 °C. Their results indicated that the fatigue strength at room temperature for Mo$_2$SiB was significantly high compared to TZM and the fatigue strength at 1200 °C for Mo$_2$SiB was significantly high compared to that at room temperature, as shown in Fig. 1.14. They have also provided detailed literature review of fatigue behavior of Mo and TZM in the same paper, which including fatigue behavior of Mo at room temperature [63–66], and fatigue behavior of TZM up to 950 °C [67–71]. It has been also reported that low cycle fatigue strength of TZM up to high temperatures is superior to that of the Ni-base superalloy 713LC [71,72], as shown in Fig. 1.15.

For fatigue behavior of tungsten and its alloys, Schmunk and Korth have conducted tensile and low cycle fatigue tests of tungsten at 815 °C [73]. They reported that low cycle fatigue strength for as-received tungsten was high compared to recrystallized tungsten not only at room temperature but also at 815 °C, as can be seen in Fig. 1.16, where the recrystallized temperature was 1482 °C. Habainy et al. have conducted stress- and strain-controlled fatigue tests of rolled and forged bulk tungsten at temperatures up to 480 °C [37], where the fatigue endurance limits obtained at 2x10$^6$ cycles at 480 °C were 150-175 MPa, as shown in Fig. 1.17.
Fig. 1.14 The S-N curves of Mo$_2$SiB alloy at 20 °C and 1200 °C. As a comparison, S-N curve of TZM at room temperature is shown [62].

Fig. 1.15 The comparison of the fatigue behavior of 713LC alloy and TZM alloy at 850 °C [71].
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