ISSN : 0974 - 7486 Volume 8 Issue 11

Materials Science

Trade Science Inc.

An Indian Journal

Full Paper

MSAIJ, 8(11), 2012 [434-442]

Thermomechanical fatigue behavior of burnished 7075–T6 aluminum alloy

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Received: 7th April, 2012 ; Accepted: 1st October, 2012

ABSTRACT

This paper presents the results of series of isothermal fatigue (ITF) and thermomechanical fatigue (TMF) tests of both unburnished and burnished 7075-T6 Al specimens. A designed roller burnishing tool was employed to improve the strength of the surface layer of the fatigue specimens. The fatigue stresses were developed in the specimens by combining constant amplitude rotating bending stresses along with constant temperature variation. Both isothermal (ITF) and TMF tests were conducted on a rotary bending fatigue testing machine. The ITF tests were carried out at two different constant temperatures namely 523 and 623 K, while the TMF tests were carried out at the temperature range between 523 and 623 K. All these tests were conducted at a constant operating speed of 1200 rpm. These investigations were performed in order to gain more understanding of the effect of interaction between mechanical and thermal stresses on fatigue resistance and fracture behavior of burnished 7075-T6 Al specimens. The present results revealed that roller burnishing processes have played a significant role in increasing the fatigue lifetimes for both ITF and TMF specimens. The enhanced fatigue strength of the burnished specimens was attributed to the overall increase in the surface layer strength which may delay fatigue crack growth from the surface. Two distinct fatigue fracture regions were observed: region I and region II. In region I, the fracture surface is associated with the formation of fatigue striations. In region II, the fracture surface is covered with surface dimples. This indicates that local strain softening mechanism has dominated the final stage of fatigue failure. Extensive effort has been paid at investigating the fracture surface of ITF and TMF specimens.

KEYWORDS

Thermomechanical fatigue;
7075-T6 Al;
Fatigue lifetime;
Burnishing;
Fracture.

INTRODUCTION

Thermomechanical fatigue (TMF) is one of important phenomena deciding upon the cracking processes in machine components and devices exposed to mechanical and thermal influences in the power, chemical and metallurgical industries, in aviation and transport[1,2]. In many applications, mechanical components are constrained and not free to extend and contract in response to variations in mechanical and thermal stresses. These types of components are more likely to endure variable amplitude or randomly fluctuating cyclic loading and temperature, whilst in service[3,4]. The evolution of microstructure and micromechanisms of degradation differ from that encountered in monotonic deformation or in isothermal fatigue (ITF)[5]. Under operating conditions, component lifetime may not be limited by strength as the primary design parameter, but lifetime may be limited by various damage mechanisms such as fatigue, creep or oxidation, which can act indecently in combination[6]. Fatigue damage, for example, is generated by cyclic loadings and the process is primarily time independent. When these damage mechanisms act in condition, a creep-fatigue-oxidation interaction exists[7]. Consequently, the component undergoing such conditions most possesses highly mechanical and thermal properties particularly at elevated temperatures as well as ambient temperatures.

Burnishing processes of mechanical parts is a surface enhancement means in which plastic deformation of surface irregularities occurs by exerting pressure through a very hard and smooth roller or ball on a surface to generate a uniform and work-hardened surface layer[8]. This technique overcomes the complications associated with the machined surfaces produced by conventional machining processes such as turning and milling that have inherent irregularities and defects like tool marks and scratches which cause energy dissipation and surface damage[9]. Besides producing a good surface finish, burnishing has additional advantages over other surface enhancement techniques, such as securing increase in hardness, corrosion resistance and fatigue lifetime due to the generated compressive residual stress in the surface layer. The developed residual stresses are probably the most important aspect in assessing surface integrity because of their direct impact on the performance of the mechanical parts in service[10,11]. Furthermore, roller burnishing has been found to improve the surface roundness and dimensions stability[12].

Fatigue lifetime and fracture of the mechanical components depends primarily on loads, material, geometry and environmental effects. Its evolution is generally based on tests of three forms of fatigue loadings: isothermal strain-controlled low cycle fatigue (LCF) tests, TMF tests on specimens and components, and thermal shock tests[13]. Extensive research efforts have been devoted on identification of fatigue of 7075 Al alloy under isothermal conditions which have contributed significantly to knowledge of the general features of fatigue failure under high temperatures[8-10,14]. This alloy has been the focus of a number of experimental studies due to its technological importance[9,10]. These studies are of great importance from technical point of view, since this material is widely used in applications at intermediate temperature. On the basis of this, not only measuring the elevated temperature ITF behavior is essential, but also a study of TMF behavior is necessary. Although a large number of studies have dealt with TMF behavior under tension-tension and tension-compression for other materials from mechanical and microstructural point of view[8-12], there is a lack of systematic studies on the fatigue behavior of 7075-T6 Al alloy, especially under thermomechanical rotating bending fatigue conditions.

This investigation aims to study thermomechanical fatigue-(TMF) behavior of both burnished and unburnished 7075-T6 Al specimens. For comparison, basic data of (ITF) of the alloy used will be measured at 523 K and 623 K. Attempts were made to study the fracture behavior of TMF specimens using SEM with reference to ITF behavior.

EXPERIMENTAL PROCEDURES

Materials and test specimens

The material used in the present investigation was extruded cylindrical bars 7075-T6 aluminum alloy (7075-T6 Al) with a diameter of 12 mm. The chemical composition of this alloy is given in TABLE 1. The main mechanical properties of the alloy are σ_{ult} = 540 MPa and σ_y = 480 MPa. Cylindrical test specimens were machined from the as received bars with identical dimensions, shown in Figures 1(a and b). Burnished and unburnished specimens were fatigue tested under ITF and TMF conditions.

Burnishing Process

A roller burnishing tool was designed and fabri-

TABLE 1 : Chemical composition of 7075-T6 Al alloy used

Element	Zn	Mg	Cu	Fe	Cr	Mn	Al
Weight (%)	5.5	2.5	1.5	0.25	0.20	0.2	Balance

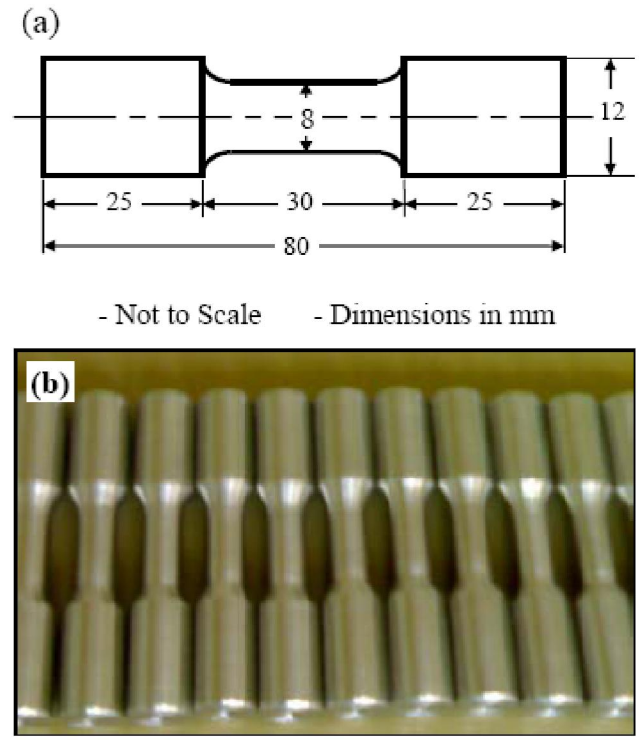

Figure 1 : (a) Schematic drawing of fatigue test specimen and (b) some of burnished specimens

cated from a high strength Nickel-Chromium super alloy. The roller, as shown in Figure 2.a, consists of two different sections, with a total length of 7 mm; the first has a conical outside surface with a cone angle of about 7Ë% and the other has a normal cylindrical surface. The tool is designed in such a way to burnish the surface in two stages. The former is to deform a very thin surface layer and the later is to iron the deformed layer. The roller is supported by a sufficient pressure to keep its depth constant and is free to roll on the surface of the specimen[10]. Figure 2.b shows a photo of the burnishing tool which is firmly clamped on a general lathe machine. The roller is always in mechanical contact with the surface to be burnished. So that, with the roller lateral motion, the surface is covered with a series of overlap passes to achieve maximum compression with minimum cold working. The burnishing parameters are listed in TABLE 2[15]. A single burnishing pass process was applied to the fatigue specimens. More details regarding the burnishing process are found elsewhere[10,14]. Suitable mineral oil was used for cooling and improving the tribological behavior during the process. Surface roughness of burnished samples was measured by using a Surftest-402 system. The average surface roughness of the specimens, before and after burnishing, was found to be ~2.25 μm and ~1.14 μm, Ra, respectively.

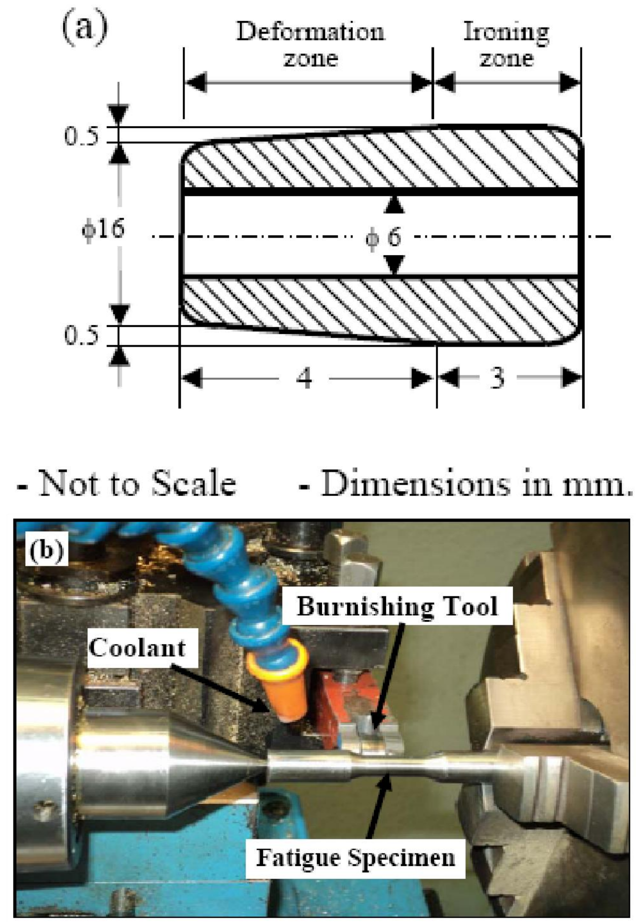

Figure 2 : (a) Schematic drawing of the roller of the burnishing and (b) a photo of the burnishing set-up on a general lathe machine before starting the burnishing process

TABLE 2 : Burnishing parameters used in the burnishing process

Burnishing Force, N	Burnishing Speed, rpm	Burnishing Feed, mm/rev	Max. Roller Contact width(mm)
235	523	0.1	~7

Fatigue testing and fracture surface investigation

ITF and TMF tests were conducted in an open furnace using a Rotating Bending Fatigue Testing Machine (Model H7), Shimadzu Co., Kyoto, Japan, shown in Figure 3.a. A separate unit was connected with the furnace controller to adapt the temperature variation for developing TMF tests. Three sets of fatigue tests were designed for fatigue testing under constant amplitude fatigue stresses ranged from ~ 120 to ~ 350 MPa. Two of them are ITF tests at temperatures of 523 K and 623 K (±2K) and the third one is TMF tests at cyclic temperature between 523 and 623 K with a trapezoidal waveform, Figure 3.b. A thermal loading, with trapezoidal waveform, with heating and cooling rates of ±1.11 K.s^{-1} and high-and low-temperature holding times of 60 sec., was applied. The whole thermal cycle takes ~5 minutes. All fatigue tests were conducted at a constant speed, 1200 rpm. Some points on S-N curves represent the average value of at least three data points.

The fatigue curves were determined by measuring the number of cycles to failure, N, at each constant bending fatigue stress, S. The bending fatigue stress was calculated according to the applied bending moment, M, and diameter of the gauge length of the specimen, d, assuming that the specimen stays in elastic condition through its fatigue lifetime. It is expressed as:

$$S = (M.r) / I \qquad (1)$$

where; r = (d/2), and I = ($\pi.r^4/4$)

Fractures surfaces of some broken specimens were examined using scanning electron microscopy (SEM),

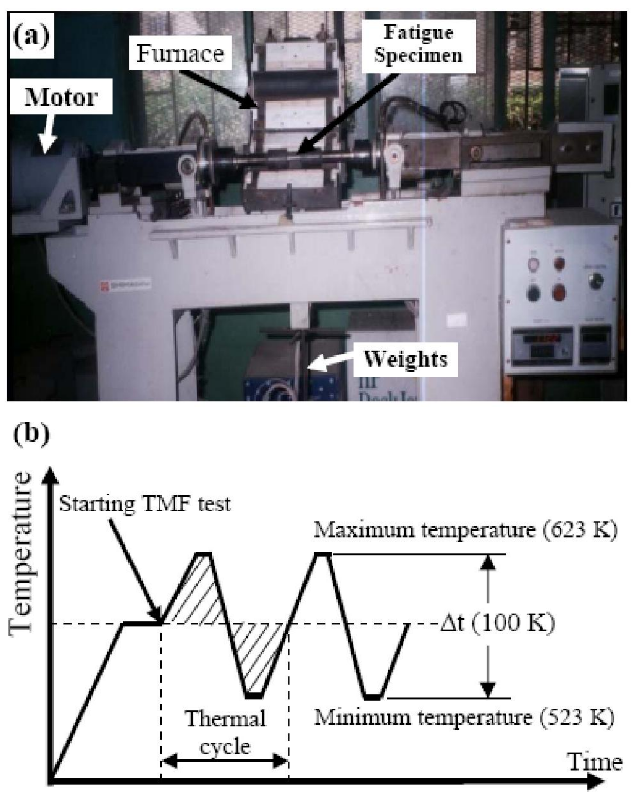

Figure 3 : (a) The fatigue testing machine used and (b) schematic drawing of TMF load history

Hitachi SU-70 UHR FE-SEM. These investigations were made in order to gain more understanding of the fracture mechanism that governs TMF behavior of the present alloy.

RESULTS AND DISCUSSION

ITF and TMF behaviors

Figure 4 shows the S-N curves of unburnished 7075-T6 Al specimens, on semi-logarithm scale, for three sets of fatigue data where the fatigue stress is plotted against number of cycles to failure. The figure presents the results of two sets of ITF data obtained at 523 K and 623 K and that of one set of TMF data tested at temperature alternated between 523 and 623 K. Form ITF results, it is obvious that there are small differences between the fatigue lifetimes of the specimens tested at 523 K and those tested at 623K, and at all fatigue stresses applied, the fatigue lifetime for specimens tested at 623 K are lower. It appeared from these results that this alloy keeps its good strength at these high temperatures. However, for TMF in Figure 4, it clearly indicated that the fatigue lifetime deceased significantly compared with that of ITF conditions. For example, at fatigue stress equal to 200 MPa, the fatigue lifetime for ITF specimens tested at 623 K decreased from ~2.2x10^5 cycles to be ~1x10^5 cycles for TMF specimens. This decrease in fatigue lifetime may be attributed to the increase in material's brittleness that may be developed due to the interaction between thermal and mechanical loadings which eventually makes the material loses some of its toughness[1,14]. In this situation, temperature variations will produce damaging thermal stresses and strains across the specimen in a complex way which limit the lifetime of the specimens.

Figure 5 shows the S-N curves for burnished specimens under same testing conditions of unburnished ones. By comparison between Figure 4 and Figure 5, it is obvious that the burnished specimens have a similar trend of unburnished ones with a reasonable increase in the fatigue strength. These results reveal that roller burnishing process has generally improved the fatigue strength for all studied cases. For example, for fatigue lifetime of 1x10^5cycles, the fatigue strength increased from ~195 MPa for unburnished TMF specimens to be ~220 MPa for burnished TMF specimens. Also, for TMF specimens tested at 225 MPa, the fatigue lifetime increases from ~7.5x10^{4} cycles for unburnished specimens to be ~9.5x10^{4} cycles for the burnished specimens. This increase in fatigue lifetime is attributed to the increase in fatigue strength of the surface layer as a result of the application of burnishing process[9,10]. It is believed that application of roller burnishing processes on 7075-T6 Al specimens have introduced a significant amount of compressive residual stress into a surface layer of about 0.4 mm. The presence of residual stress in the surface layers may be a good reason for this improvement. The development of compressive residual stresses will partially or completely compensate the induced tensile stresses that simultaneously exist in rotating bending fatigue specimens[10,16].

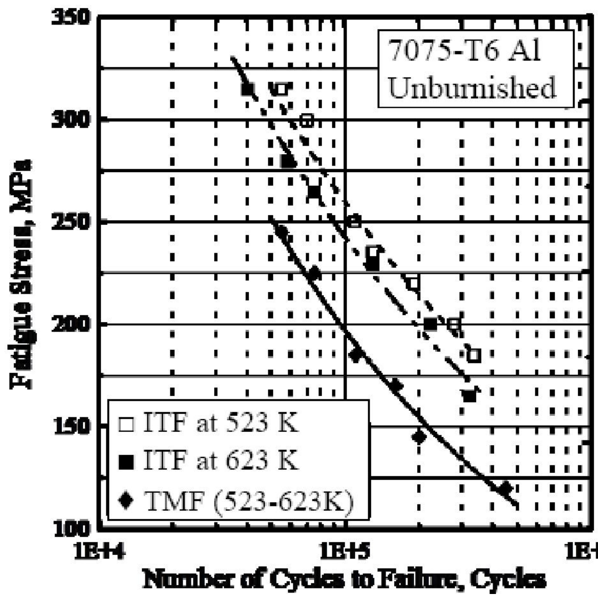

Figure 4 : ITF and TMF lifetimes *vs* bending fatigue stresses for unburnished specimens

The relationship between fatigue stress, S, and fatigue lifetime, N, for all cases, was obtained by applying the power fitting method on the fatigue data, as follows:

$$S = A.N^{B} \quad (2)$$

Where A and B are constants depending on the material and testing conditions.The values of A and B were estimated from power fitting of the S-N data curves and they are listed in TABLE 3.

Fractographic observations

The fracture surfaces of 7075-T6 Al specimens have been examined using SEM. Figures 6 and 7 show

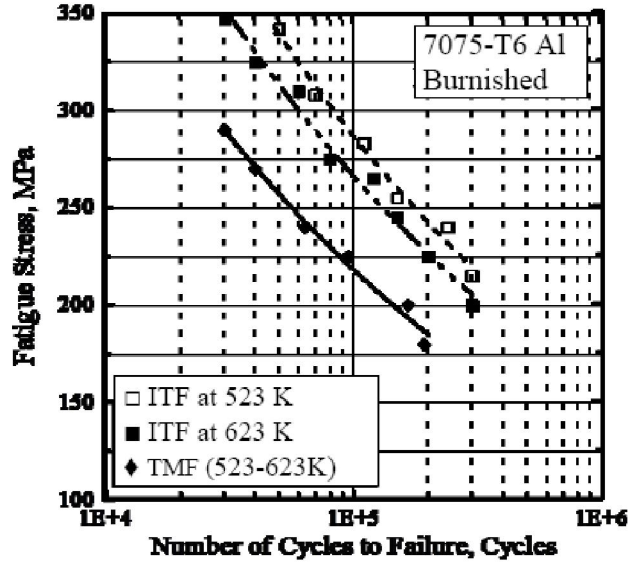

Figure 5 : Fatigue lifetimes *vs* bending fatigue stresses for burnished specimens

TABLE 3 : Constants A and B of Eq. 2 that obtained from power fitting of fatigue data

	Unburnished Fatigue Specimens			Burnished Fatigue Specimens		
	ITF (523 K)	ITF (623 K)	TMF (523-623 K)	ITF (523 K)	ITF (623 K)	TMF (523-623 K)
A	8.742	8.868	9.336	8.449	8.285	8.115
B	-0.276	-0.293	-0.352	-0.242	-0.234	-0.237

SEM fractographs for burnished ITF and TMF specimens, respectively. Both of these two specimens were tested under ~225 MPa. As shown in Figure 6.a, the fatigue fracture exhibited two distinct regions: region I and region II. Region I represents the crack initiation and propagation stage. In this region as shown in Figures. 6.b and 6.c, the fracture surface is associated with the formation of fatigue striations. These striations were formed as the crack propagates through the specimen cross section during opening and closing the crack whilst the specimen rotates. Fatigue striations are the most common feature of fatigue fracture of 7075-T6 Al and they can only be seen on a microscopic scale. The size and density of these striations indicate the amount of plasticity that have undergone through the crack growth. It has been established that each striation is associated with the crack growth during one complete loading cycle. The crack propagation direction is generally normal to striations lines[17]. In region II, as shown in Figures 6.d and 6.e, the specimen was fractured in a different manner from that of region I, where the cross section was no longer able to withstand the applied

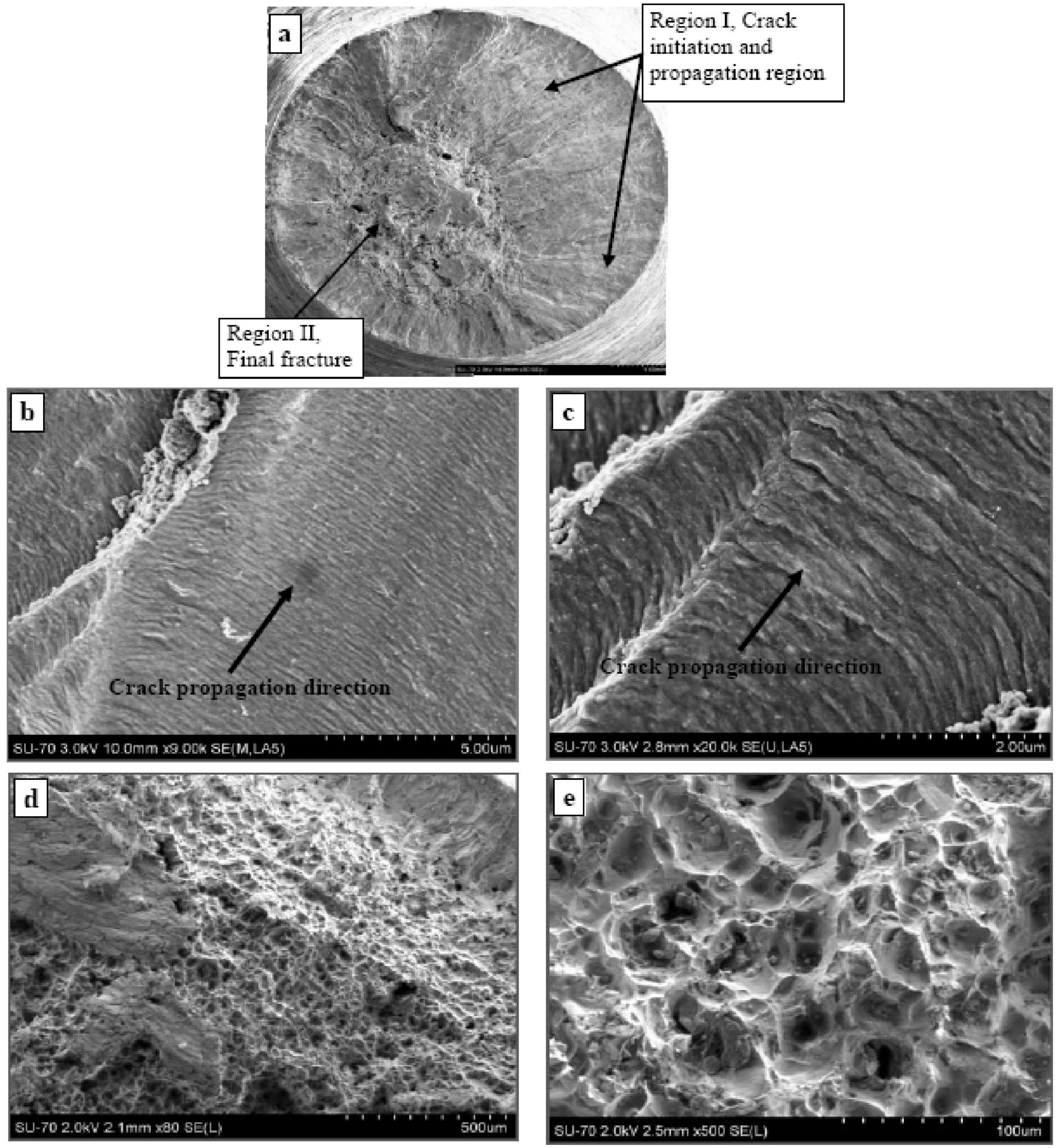

Figure 6 : SEM fractographs of burnished 7075-T6 Al ITF specimen tested under ~225 MPa at 623 K (a) Overview of fatigue fracture surface, 5X, (b) and (c) region I, fatigue striations, arrows point to crack propagation direction and (d) and (e) region II, final fatigue fracture.

stress. The fracture surface is covered with deep and thick walled dimples. The features of these dimples indicate that local strain softening mechanism has dominated the final stage of fatigue failure.

The fracture characteristics of a burnished TMF specimen tested at 225 MPa are shown in Figure 7. a-e. It is obvious in Figure 7.a that the fracture of TMF specimen has an irregular surface in comparison with that of ITF specimen. Fatigue striations have been formed in the outer ring on the fracture surface repre-

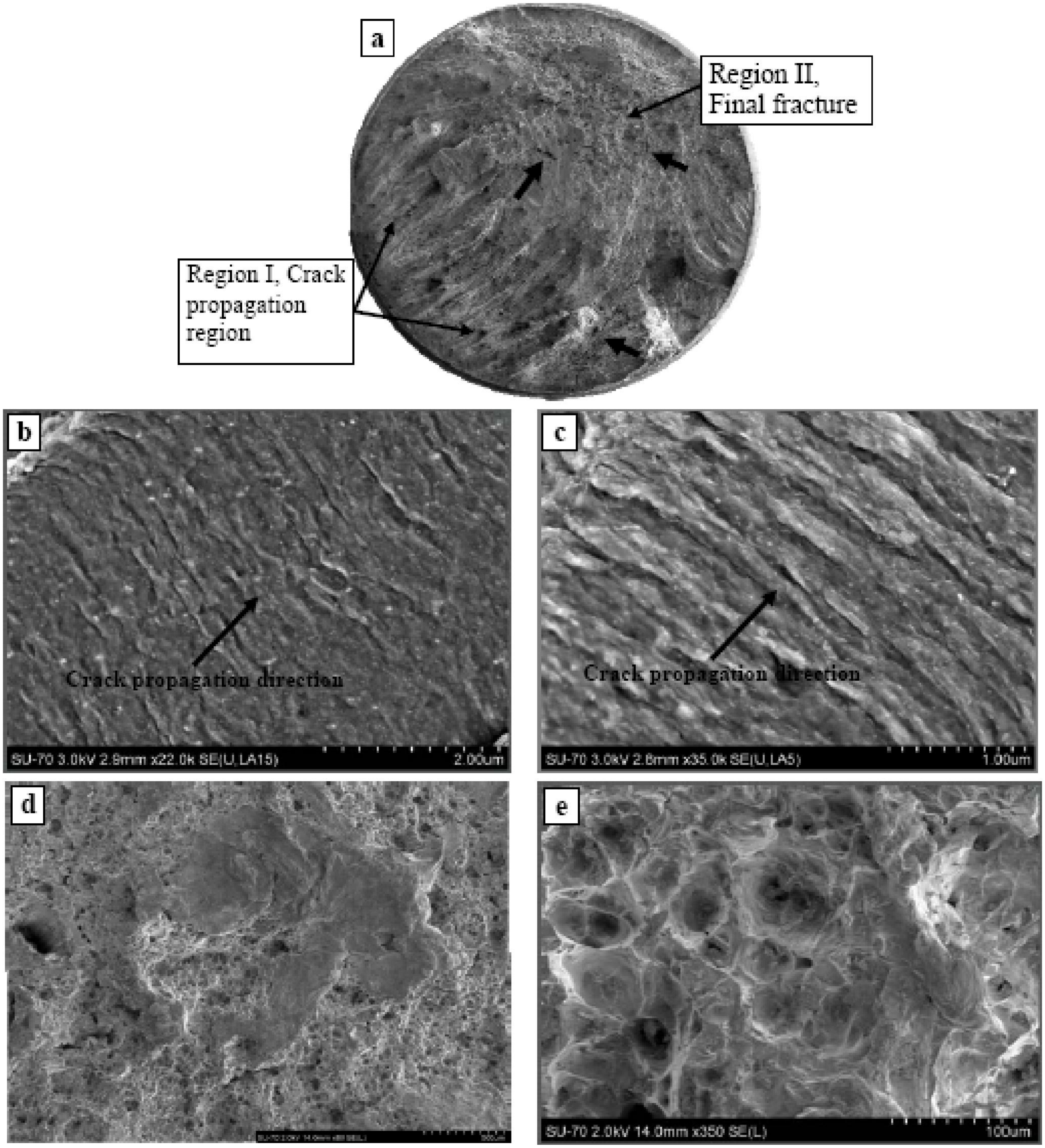

Figure 7 : Typical fatigue fracture surfaces of burnished TMF specimen failed under stress ~225 MPa, (a) Overview of fracture surface, 5X, (b) and (c) region I, fatigue striations, arrows point to crack propagation direction and (d) and (e) region II, final fatigue fracture

senting the crack growth region, region I, as shown in Figure 7.b and 7.c. Another common feature associated with the formation of fatigue striations is the existence of secondary cracks on the fracture surface, pointed by arrows in Figure 7.a. The direction of main crack propagation depend on the nature of applied loading and microstructure features through which the crack is advancing and this causes the striations to alter orientation locally. Although, the temperature variation of TMF was not very large, 100 K, TMF tests have led to more dangerous fatigue fracture than that of ITF test specimens. The brittle character of the fracture surface appearance can be easily recognized by the typical cleavage facets presented on the fracture surface of specimen. This finding is supported by the nature of the surface dimples that were formed in final stage of fracture (region II). These dimples are shallow and have fine wall thickness indicating that they were formed in the very late stage of fatigue lifetime. This situation corresponds to the situation in which the material is subjected to periodically creep-fatigue interaction[7]. It is believed that crack initiation and further propagation tended to behave in a transgranular manner. These microstructural observations indicate also that failure of TMF specimens is dominated by fatigue damaging mechanism whatever the temperature situation.

It is well established that fatigue fracture is particularly insidious because it occurs without any obvious warning. This can be seen in the fractographs where the appearance of the fracture surface revealed a transgranular features with very limited plastic deformation. For bending fatigue loading, the maximum normal stress is parallel to the specimen axis and keeps varying from a tensile value on one surface to zero at the center to a compression value on the other surface. In this situation, the main crack occurs on a plane normal to the axis of the specimen and proceeds from the tensile side to the opposite side. This is very clear in Figures 6 and 7, where fatigue striations have been formed on the outer ring of the fracture surface and propagated across until separation occurred in the interior section of the specimens[14,18].

It is evident based on these findings that the fracture mechanism was characterized with a crack initiation and propagation region followed by a transgranular final region. In crack propagation region, many striations were found as shown in Figures 6.b, 6.c, 7.b and 7.c, indicating that the crack propagation, in this stage of fatigue life, occurred by fatigue fracture. In the transgranular region, no striations were observed but surface dimples, due to cavity nucleation and growth, Figures 6.d, 6.e, 7.d and 7.e. These surface dimples indicate that local strain softening has dominated the final stage of fatigue. The existence of strain softening caused ratcheting strain and the accumulated ratcheting strain can then produce additional damage[17]. As has mentioned in section 2.2, the average surface roughness has been improved due to the application of burnishing process to become ~1.14 μm. The main role of the burnishing process was to decrease the surface irregularities which minimize the potential sources of crack initiation and consequently delays the crack initiation stage. This process has affected only the fatigue lifetime and its effect on the fatigue fracture mechanism has less importance. Additional data on fatigue behavior of 7075-T6 Al should be obtained in order to cover wide range of TMF parameters, including the experiments of high and low cycle fatigue as well as a wide range of temperature intervals.

CONCLUSIONS

The experimental results and their discussions for burnished and unburnished 7075-T6 Al specimens tested under ITF and TMF have led to the following conclusions:

1. Roller burnishing processes have introduced a significant improvement in fatigue strength for both ITF and TMF specimens. The enhanced fatigue strength of the burnished specimens over the unburnished specimens was attributed to the overall increase in the surface layer strength which may delay fatigue crack growth from the surface. The relationship between fatigue stress, S, and lifetime, N, under ITF and TMF conditions can beexpressed using an empirical equation; $S = A.N^B$, where A and B are constants. It is found that the existence of both thermal and mechanical fatigue resulted in a significant decrease in fatigue strength of TMF specimens compared to ITF specimens. Small difference in the fatigue lifetime was obtained between the two kinds of ITF testes at 523 K and 623 K.
2. The fracture surface is characterized, for ITF and TMF cases, with two distinct regions: region I and region II. The fracture surface in the former region is associated with the formation of fatigue striations that were formed as the crack propagates through the specimen cross section whilst the specimen rotates. In the later region, fracture surface is covered with surface dimples indicating that local strain softening mechanism has dominated the final stage of fatigue failure.
3. It is believed that crack initiation and further propagation tended to behave in a transgranular manner.

For TMF specimens, fatigue cracks were observed on the fracture surface and final failure tends to be brittle. Microcracks were also observed and many of them were larger than those in the case of ITF specimens. Although, the temperature variation of TMF was not very large, 100 K, the TMF tests have led to more dangerous fatigue fracture compared to ITF tests. These microstructural observations indicate also that failure of TMF specimens is dominated by fatigue damaging mechanism.

ACKNOWLEDGMENT

The author is gratefully thanks *Dr. Robert Steffen*, Product Applications Manager at HITACHI Corporation, Hitachi High-Technologies Europe GmbH, 47807 Krefeld, Germany, for running SEM investigations at his Lab. Thanks are extended to the staff of the Materials Lab for their assistance in performing the burnishing processes. This work is partially supported by the deanship of scientific research at Qassim University, Project no. SRD-008-83.

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