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The Effect of Surface Treatment and Rolling Direction on the Fatigue Behavior of Grade One Commercially Pure Titanium

by

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The Thesis of Shilong Tang for the degree of Master of Science in Mechanical Engineering is approved.

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ABSTRACT

Fully-reversed bending fatigue tests were conducted on both the as-received and finished grade one commercially pure titanium. Finishing is done by a process developed by TiMesh Inc., and known as TiMesh finishing. Results show that TiMesh finishing can not only increase material fatigue life at least by two times at the stress level of 25 Ksi, but also eliminate the anisotropic fatigue behavior observed in the as-received materials.

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CHAPTER 1

INTRODUCTION

The purpose of this work is to study the fatigue behavior of grade one commercially pure titanium as a function of material surface treatment and rolling direction.

Titanium was discovered in 1871 but was not commercially produced until 1950's. Although expensive, the high strength-to-weight ratio and corrosion resistance at room and elevated temperatures make titanium attractive for the applications such as aircraft, jet engine, chemical, petrochemical, marine components, and biomaterial, such as prosthetic devices.[1] At present, titanium and its alloys represent one of the major structural materials in a variety of engineering applications.

The inertness of titanium and its alloys to human body environment is probably the most important reason to use them as superior implant materials. Under some circumstances, the choice is even unique. For example, a group of investigators studied[2] the corrosion fatigue property of Type 316L stainless steel, Co-Cr-Mo alloy, and an annealed titanium alloy ELI Ti-6Al-4V, all of which are adopted by American Society for Testing and Materials (ASTM) as human implant

materials. The results showed that in both Hank's and Ringer's physiological solution at temperature of 37° and PH=7.4 (corrosive environment which mimics human body fluid, titanium alloy had the longest fatigue life.

In the past few decades, titanium based alloys received extensive study[3-8] due to the fact that their properties are extremely sensitive to small variations in both alloying and residual elements. Aluminum, vanadium, molybdenum, manganese, and other alloying elements are added to improve properties such as strength, workability and hardenability of the final alloys[9-12]. By controlling the chemical composition as well as selecting manufacturing processes, engineers have successfully developed a wide range of titanium alloys of specific functions.

At temperatures below 880°C (1600°F), titanium possesses a hexagonal close-packed structure (alpha-titanium) and transforms to body-centered cubic structure (beta-titanium) above this temperature. Beta-titanium is more ductile than alpha-titanium. The strength and ductility are greatly affected by both the impurity level and alloying. Some interstitial elements, such as oxygen, nitrogen, and carbon, will generally increase the strength of matrix and reduce its ductility[13]. Titanium alloys, on the other hand, can have a variety of microstructure such as alpha, near alpha, alpha-beta, and beta, depending on alloying elements and heat treatment.

Unlike its alloys, unalloyed titanium, known as commercially pure titanium, has received much less attention because of its relatively low strength to be generally accepted as a constructural material. Commercially pure titanium is classified in four grades according to its tensile strength[14]. Grade one is the softest and therefore, the most ductile with the highest purity. Research work in the past few decades on commercially pure titanium was concentrated on the higher strength grades (70 KSI or higher). From a practical point of view, if strength is crucial, higher grades are more likely to be used; on the other hand, if ductility is the number one consideration, cheaper materials such as aluminum can be used in stead of grade one titanium provided that the corrosion resistance of those materials can be improved by proper surface techniques. Grade one commercially pure titanium turns out to be of little importance in application.

In recent years however, commercially pure titanium has begun to be used by some maxillofacial implants manufacturers including Timesh[15], as the constructual materials for implant hardware such as screws, plates, meshes, cribs, and straps. From service point of view, a number of material properties have to be taken into account for implants: chemical inertness, strength, ductility, and fatigue properties. The majority of these components are subjected to load bearing from body motion and a corrosive environment.

A proprietary surface treatment was developed by Timesh Inc. and is successfully used as a standard procedure for all Timesh products. This process, known as Timesh finishing, has been proved to be able to enhance surface smoothness, increase corrosion resistance, and workability.

This study will first discuss the anisotropic fatigue behavior observed in grade one commercially pure titanium cold-rolled and annealed sheet as a result of cold rolling direction, and then, will show the effect of Timesh finishing as a beneficial surface treatment on material fatigue performance.

Concerning the testing philosophy in the fatigue experiment, it would be advisable to point out the two different approaches used in fatigue-related problems.

Classical approaches to fatigue design involve the characterization of the total life to failure in terms of the cyclic stress range (the S-N curve approach)[16] or the (plastic or total) strain range[17,18]. In these methods, the number of stress or stain cycles necessary to induce fatigue failure in initially uncracked (and nominally smooth-surfaced) laboratory specimens is measured under controlled amplitudes of cyclic stress or strain. The resulting fatigue life incorporates the number of fatigue cycles to initiate a dominant crack (which can be as high as some 90% of the total fatigue life) and to propagate this dominant flaw until catastrophic failure occurs. Various techniques are available

to account for the effects of mean stress, stress concentrations, environments, multiaxial stresses and variable amplitude stress fluctuation in the prediction of the total life using the classical approaches. Since the crack initiation constitutes a major component of the total fatigue life in smooth specimens, the classical stress-based or strain-based methods represent, in many cases, design against fatigue crack initiation. Under high-cycle, low stress fatigue situations, the material deforms primarily elastically; the failure time or the number of cycles to failure under such high-cycle fatigue has traditionally been characterized in terms of the stress range. However, the stresses associated with low-cycle fatigue are generally high enough to cause appreciable plastic deformation prior to failure. Under these circumstances, the fatigue life is characterized in terms of the strain range. An example of a situation, where the classical (short-life) strain-based approach (also referred to as the low-cycle fatigue approach) has found much appeal, involves the prediction of fatigue life for the initiation and early growth of a crack within the strain field associated with the fully plastic region ahead of a stress concentration[19]. The low-cycle approach to fatigue design has found particularly widespread use in ground-vehicle industries.

The fracture mechanics approach to fatigue design, on the other hand, invokes a "defect-tolerant" philosophy[20]. The

basic premise here is that all engineering components are inherently flawed. The size of a preexisting flaw is generally determined from nondestructive flaw detection techniques (such as visual, dye-penetrant or x-ray techniques or the ultrasonic, magnetic or acoustic emission methods). If no flaw is found in the component, proof tests are conducted whereby a structure, such as a pressure vessel, is subjected to a test at a stress level slightly higher than the service stress. If no crack is detected by the nondestructive test method and if catastrophic failure does not occur during the proof test, the largest (undetected) initial crack size is estimated from the resolution of the flaw detection techniques. The useful fatigue life is then defined as the number of fatigue cycles or time to propagate the dominant crack from this initial size to some critical dimension. The choice of the critical size for the fatigue crack may be based on the fracture toughness of the material, the limit load for the particular structural part, the allowable strain or the permissible change in the compliance of the component. The prediction of crack propagation life using the defect-tolerant approach involves empirical crack growth laws based on fracture mechanics. In terms of requirements of linear elastic fracture mechanics, the defect-tolerant method is applicable under conditions of small-scale yielding (i.e. away from the plastic strain field of any stress concentrators), where the crack tip plastic zone is small compared to the

characteristic dimensions of the cracked component (including the crack size) and where predominantly elastic loading conditions prevail. Various methods are available to incorporate the effects of mean stress, stress concentration, environments, variable amplitude loading spectra, and multiaxial stresses in the estimation of fatigue life. This intrinsically conservative approach to fatigue has been widely used in fatigue-critical applications where catastrophic failures will result in the loss of human lives; examples include the aerospace and nuclear industries.

The different approaches to fatigue also provide apparently different guidelines for the design of micro-structural variables for optimum fatigue resistance. These differences are merely a consequence of the varying degrees to which the role of crack initiation and crack propagation are incorporated in the calculation of useful fatigue life. For example, in many structural alloys the resistance to the growth of long fatigue cracks generally increases with an increase in grain size[21-24] (or a decrease in yield strength) at the early stage of the whole fatigue history (referred as stage 1) where a significant portion of subcritical crack growth life is expended. On the other hand, the total fatigue life estimated on the basis of the stress-life plots generally exhibits the opposite trend; higher strength materials and finer grained microstructure usually lead to a longer fatigue life. The apparent contradiction between the two approaches

can be reconciled by noting that the former approach to fatigue deals primarily the resistance to fatigue crack growth, while the latter approach based on nominally defect-free laboratory specimens focuses mainly on the resistance to fatigue crack initiation. The choice of a particular microstructural condition for improved fatigue life is then predicted upon the design philosophy for a specific application. Optimization of microstructural characteristics for improved resistance to both crack initiation and crack propagation requires a trade-off between the recommendations of the two approaches.

The stress-life approach is used in this study. Unlike other engineering components, for instance, aircraft part, from which we can obtain complete information of both crack initiation and crack propagation utilizing nondestructive detection techniques during their service, human implants, once embedded in, will provide us with little chance to detect even if a crack which approaches its critical condition is present in the structure. It has been known that during the growth of bones, those implants will bond to the bone basis. In this sense, all human implants have to be designed with 100% theoretical safety under normal conditions. In fact, only a small percentage, approximately 5 to 10 percent, of implant failures can be attributed to fatigue or corrosion fatigue.[2]

chapter Notes

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CHAPTER 2

MATERIALS AND PROCEDURES

The as-received material is grade 1 commercially pure titanium sheet. This material has been used as the principal construction material of TiMesh products. The manufacturing process consists of cold rolling to 0.026 inch followed by annealing at 1380°F for 3 minutes and then cooling in still air. Relative to the primary rolling direction, sheet fatigue specimens are classified in two categories, i.e., those with symmetric axis parallel to this direction are referred as L samples while those with axis perpendicular as T samples as shown in Figure 1. Observed by a metallurgical microscope, surfaces of the as-received material exhibit very dense and fine scratches with no signs of any readable microstructure at all. These scratches are the products of the rolling and the following annealing processes during which surface grains undergo a complex response such as elastic elongation, plastic deformation, break-down, and recovery. In chapter 3 it will be discussed about the role of the surface layer - a deformed layer in the fatigue performance of the bulk material. Material manufacturer's brochure shows that all surfaces are

free of contamination. The high purity and high strength is clearly shown in the chemical specification and mechanical properties listed in table 1 and 2 respectively.

Table 1 Chemical specilfication of Grade 1 Commercially Pure Titanium in Weight Percentage (ASTM F67)

element	w%	element	w%
Carbon	< 0.1	Oxygen	< 0.18
Iron	< 0.2	Hydrogen	< 0.015
Nitrogen	< 0.03	Titanium	balance

Table 2 Mechanical Properties of Grade 1 Commercially Pure Titanium Sheet (ASTM F67)

	Yield KSI	Tensile KSI	Elong %	Bending
L	> 25	> 35	> 24	1.5 TR
T	> 30	> 35	> 20	1.5 TR

(TR means thickness)

Specimens were cut to be standard fully-reversed bending test samples. During test, the left end is clamped to the

fixed body of the tester, while the right end is attached to an oscillating crank arm with controlled amplitude (and thus stress or strain). The sheet performs just like a cantilever beam. The tapered structure is used to keep the stress or strain constant all through the length.

Notice that fatigue crack always occurs roughly perpendicular to the maximum tensile plane (Figure 1 and 2).

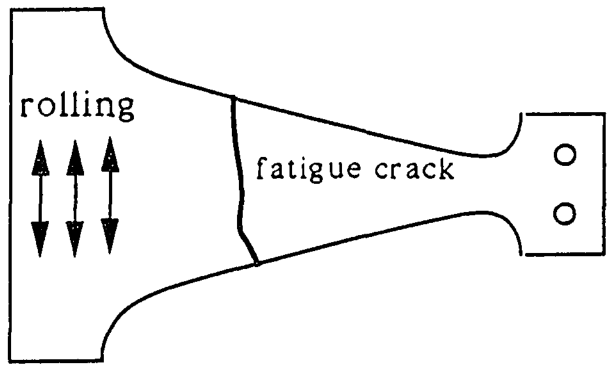
Program testing specimens are divided into 6 lots (A, B, C, D, E, and F).

Lot A contains 6 T-samples of as-received structure cut by the electrical-discharge machining (EDM).

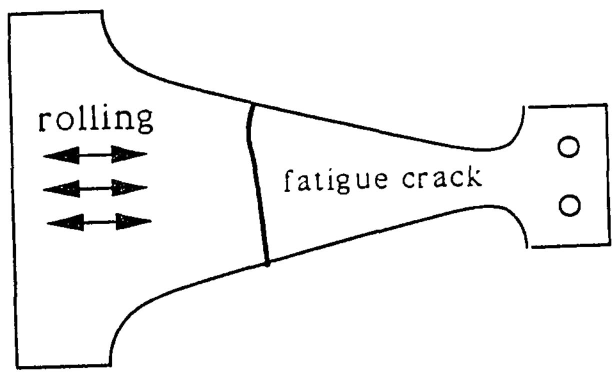
Lot B contains 6 L-samples of as-received structure cut by EDM.

A machining process developed in 1940s, the EDM (also called electrodischarge or spark-erosion machining) system[1] consists of a shaped tool (electrode) and the workpiece, connected to a dc power supply and placed in a dielectric fluid. When the potential between the tool and the workpiece is sufficiently high, a transient spark discharges through the fluid, removing a very small amount of metal from the workpiece surface. The discharge is repeated at rates of between 50kHz and 500kHz, with voltages usually between 50V and 300V, and currents from 0.1A to 500A.

Lot C contains 3 T-samples and 3 L-samples with EDM cutting followed by TiMesh finishing. After this process, the smoothness of the sheet is also improved, which can be

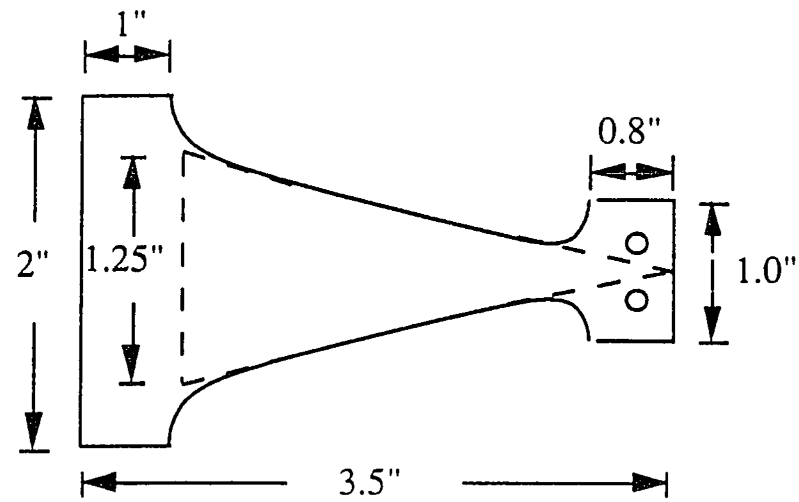


T specimen



L specimen

Figure 1 T specimen and L specimen. Notice that the orientation of the fatigue crack and rolling direction is different for T specimens and L specimnes.



Dimension of the sample

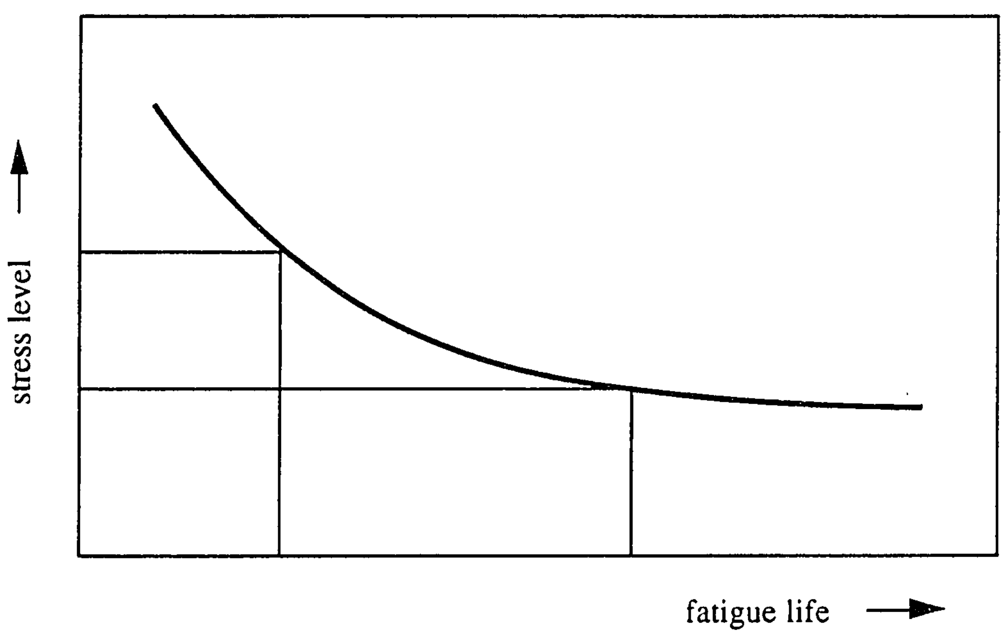


Figure 2 Illustration of S-N curve. The tapered contour of the specimen is to make stress constant throughout the length.

detected either visually or by systematic measurements.

Lot D contains 6 T-samples TiMesh finished.

Lot E contains 6 L-samples TiMesh finished.

Lot F contains 2 T- and 2 L-samples just like those in lot D and E. The difference is that, all samples in this lot are filed on edges. Filing will make the edge condition poorer than that of EDM.

The purposes of the lot classification are as follows:

1. measure the statistical fatigue lives of as-received L's and T's under a specific fatigue stress and determine if there is any difference. Since the only difference of the samples is their rolling direction (relative to the axial direction, or the tension/ compression direction), if any difference in fatigue strength is found, it should be contributed to the effect of rolling direction.
2. measure the fatigue lives of the TiMesh finished L's and T's at the same stress level and compare them to those of the as-received. Whether the TiMesh finishing process can improve the fatigue strength, in terms of the total fatigue life, should be seen.
3. determine whether there is any difference in the fatigue lives of TiMesh finished L's and T's, in an other words, whether the difference of fatigue behavior (if any) of the as-received L's and T's is

eliminated by the TiMesh finishing process.

4. determine if the improvement of the edge condition is the only factor that contributes to the improvement of the fatigue strength (if any) by using edge-filed samples.

A fully-reversed bending fatigue tester was employed in the study. Under normal conditions, i.e., with no corrosive evidence, pure titanium has a fatigue endurance limit around 24 ksi[2,3,4] (attention should be paid here since it has been shown that the fatigue strength of material is affected by a number of factors including the so-called size effect [5,6]). In our test, a fatigue stress with amplitude of 25 ksi and stress ratio of R=-1 was applied to lot A, B, C, and F. For lot D and E however, 25 KSI is not a good choice for the purpose of comparing the fatigue performance of TiMesh finished T and L samples, since it is close to the endurance limit of this materials which means the fatigue lives of both T and L are so long that they can be regarded as infinite. For this reason, the stress level in lot D and E was raised to 32 Ksi (it was after a few tests that this value was selected) to shorten the fatigue life (to a few hundred thousand cycles) which was appropriate for us to observe any difference in the fatigue performance of the two groups.

The classification and preparation of samples and testing procedures are finally listed in the following table.

Table 3 Lot Classification and Testing Stress

Lot	KSI	Number of Samples	Description of Samples
A	25	6 T's	as-received structure EDM cutting
B	25	6 L's	as-received structure EDM cutting
C	25	3 T's and 3 L's	EDM followed by TiMesh finishing
D	32	6 T's	EDM followed by TiMesh finishing
E	32	6 L's	EDM followed by TiMesh finishing
F	25	2 T's and 2 L's	TiMesh finishing followed by edge-filing
stress frequency = 2 Hz still air environment			

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CHAPTER 3

Results and Discussion

I. Fatigue Life of the As-received Structure

The microstructure and surface condition are the two important factors to be considered in the process of fatigue crack initiation. Also, they continue to be influential in crack propagation. In the entire study, all the samples used are from the same grade of commercially pure titanium with an identified bulk microstructure but with different surface (including edge) condition. Shown in Figure 3 is the surfaces structure of the as-received materials. The most striking feature is all surfaces are fulfilled by uniform and fine scratches in the direction of rolling. Observation of its microstructure is shown in Figure 7.

For most samples in lot a and B, only one fatigue crack was observed for each sample. The location of cracks varies from sample to sample because no mechanical or metallurgical stress-concentration is present. During the tests, it has been observed that cracks always start from the edge of the sheet sample and propagate until catastrophic failure occurs.

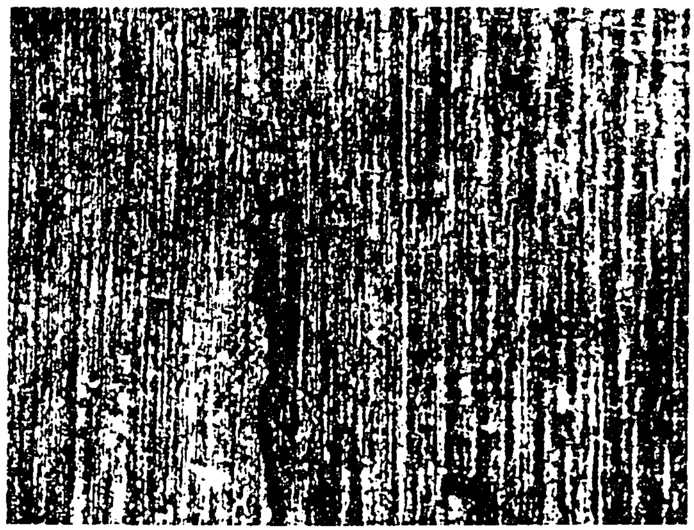

Figure 3 Surface condition of as-received T specimen, 50X.

Figure 4 Surface condition of as-received L specimen, 50X.

One L sample in lot B however, shows at least four cracks, the dominant of which is obviously a fatigue type of crack which runs through the sheet. The other three occur in the middle of the sheet plane but do not propagate to failure. The fatigue life of this sample (276,800 cycles), is much lower than those in the same lot (around one million cycles). It is likely that this sample had been pre-damaged or pre-cracked during either the rolling processes or the EDM cutting process.

The apparent difference in fatigue lives of T's and L's is shown in Table 4 and 5. No overlap of the two data sets appears except for the possibly pre-cracked sample strongly suggests that the difference can be only based on the rolling direction of the material. Under the experimental conditions (25 KSI), L samples have an average fatigue life 2 times longer than that of T samples. Notice that these lives (about three hundred thousand cycles for T samples and one million cycles for L samples) are still relatively short even though the stress is close to the estimated fatigue limit. This suggests that the surface layer is not beneficial. But at the present stage, the emphasis is on the effect of rolling direction on the fatigue behavior of the as-received material.

Fatigue properties are frequently correlated with tensile properties[1]. For example, the fatigue limit of cast and wrought steel is approximately 50% the ultimate tensile strength, the ratio of fatigue limit over tensile strength is

Table 4 Fatigue Lives of Lot A

(as-received T with EDM cutting)

Sample #	TiMesh Code	Fatigue Life (cycles)
1	506	599,400
2	506	205,200
3	506	518,300
4	506	531,500
5	506	252,100
6	506	141,800
Average life = 374,700 Standard Deviation = 68,500 stress level = 25 Ksi		

called fatigue ratio. Several nonferrous metals such as nickel, copper, and magnesium have a fatigue ratio of about 0.35. But our case can hardly be explained by the minor difference between the mechanical properties of L and T (tensile stress or elongation). As a matter of fact, this

difference in fatigue strength can only be understood as a result of different resistance of L and T to either fatigue crack initiation or fatigue crack propagation, or the combination of both, due to the anisotropic effect of surface and microstructure.

Table 5 Fatigue Lives of Lot B
(as-received L with EDM cutting)

Sample #	TiMesh Code	Fatigue Life (cycles)
1	182	276,800
2	182	1,427,600
3	182	1,092,100
4	586	891,800
5	586	1,843,700
6	586	1,120,400

Average life = 1,108,700

Standard Deviation = 195,900

stress level = 25 Ksi

The following discussion highlights several possible mechanisms:

The Anisotropic Structure of Fatigue Slip Bands Leads to the Different Resistance to Fatigue Crack Initiation

In recent years, advanced techniques allowed investigators to observe directly the sites of fatigue crack initiation. The topic received special interest because the initiation phase is critical to the process of fatigue. A huge number of experimental observations performed either by light or electron microscopy showed that microcracks in homogeneous materials always originate at a free surface. Observation of surfaces has shown that there are three types of nucleation sites[2]:

1. Fatigue slip bands. This is perhaps the most frequent type of nucleation.
2. Grain boundaries. Nucleation at grain boundaries is typical for high-strain fatigue, especially at high temperature.
3. Surface inclusions. This is typical for alloying containing large enough particles.

Common to all three types of nucleation is the local plastic-strain concentration at or near the surface.

Nucleation in the fatigue slip bands is a basic type of nucleation not only because this is the most frequent case, but mainly because the cyclic slip processes and formation of fatigue slip bands may also precede nucleation at grain boundaries or at surface inclusions. From this point of view, the inclusion-type of nucleation can be understood as cyclic slip concentration due to the stress-concentration effect of the inclusion, leading either to decohesion of the inclusion-matrix interface or to cracking of the inclusion. Both these microcracks were observed experimentally. There is strong evidence that grain-boundary-type nucleation is also conditioned by the cyclic slip process. Direct experimental observation on the formation of microcracks in the fatigue slip bands or along the interface of fatigue slip bands and matrix has also been made.[3,4,5]

In the light of the relationship of fatigue and slip characteristics of materials, it is possible to understand the nature of the fatigue limit of titanium. The extent of slip in a single crystal depends on the magnitude of the shearing stress produced by external loads, the geometry of the crystal structure, and the orientation of the active slip planes with respect to the shearing stresses. Slip begins when the shearing stress on the slip plane in the slip direction reaches a threshold value called the critical resolved shear stress. Table 6 shows this value for some metal single crystals.

Table 6 Critical resolved shear stress for single crystals

Metal	Structure	Slip plane slip direction	Critical Resol. shear stress (MPa)
Mg	hcp c/a=1.623	(0001) $[11\bar{2}0]$	0.77
Cd	hcp c/a=1.886	(0001) $[11\bar{2}0]$	0.58
Zn	hcp c/a=1.856	(0001) $[11\bar{2}0]$	0.18
Ti	hcp c/a=1.587	(0001) $[11\bar{2}0]$ (1010) $[11\bar{2}0]$	13.7 90.1
Cu	fcc	(111) [110]	0.65
Ag	fcc	(111) [110]	0.48
Fe	bcc	(110) [111]	27.5
Mo	bcc	(110) [111]	49.0

It can be seen from the table that the critical resolved shear stresses for fcc and high c/a ratio hcp structure are much lower than those for bcc structure. This can be correlated to the well-known engineering fact that fatigue limit, if defined at infinite fatigue cycles, does not exist in most fcc and high c/a ratio hcp metals such as aluminum and magnesium. The limit only exists in bcc metals such as steel. However, the critical resolved shear stress for titanium is far different from that of high c/a ratio hcp metals, in fact, it is comparable to the typical value of critical resolved shear stress for bcc metals. If the fatigue property of materials is governed by the microstructure and slip features, a real fatigue limit existing in bcc structure may apply to titanium. From a design point of view, a fatigue limit is defined to those metals without a real limit at a certain fatigue cycle, for example, one hundred million cycles.

A fatigue slip band is defined as a zone fulfilling the following two conditions: 1. its dislocation structure differs from that in the surrounding matrix and; 2. the zone ends on the specimen surface. It was established that after polishing a few microns from a surface covered with fatigue slip bands and after etching, the fatigue slip bands became visible again. This is why the fatigue slip bands are frequently called persistent slip bands (PSBs).

From micrographs in different sections, it is possible to construct a three-dimensional model of the overall dislocation

structure of the persistent slip bands. There are two types of PSBs: 1. ladder-like PSBs consisting of parallel walls perpendicular to the primary slip direction, and, 2. cell-like PSBs consisting of fully closed cells.

Despite some minor discrepancies between different experimental results concerning the details of PSB structure, there is agreement on the following points: 1. the PSBs lie along the slip plane and their structure is different from the surrounding matrix; 2. there are certain stress and strain requirements for the formation of PSBs. Below a threshold value of the plastic-strain amplitude, the PSBs have never been observed. This threshold[2] is typically of the order of 10^{-5}, for some materials it is slightly higher, but does not exceed $2x10^{-4}$. The corresponding threshold values for stress amplitude depend - in contrast to the plastic strain amplitude - very strongly on the material. These two values (threshold of the stress and strain) are connected directly through the cyclic stress-strain curve; 3. the formation of PSBs begins at surface. In the case of polycrystalline materials, they are mainly confined to the surface grains; in single crystals, their volume fraction increases both with the number of cycles and the loading amplitude. After a sufficiently high number of cycles even the entire crystal is filled with PSBs; 4. the plastic strain amplitude in the PSBs is higher than that in the matrix. For example, the shear-plastic-strain amplitude of single crystal copper is about $5x10^{-3}$ at the end of stable

stage of PSBs, while its matrix value is only about $5x10^{-5}$. Thus the local plastic strain amplitude in the PSBs is higher by a factor of 100 than the plastic strain amplitude in the surrounding matrix.

The probable preferred orientation of PSBs doesn't account for the difference of the fatigue lives of T and L, even if the rolling processes somehow changes the uniform distribution of slip systems (slip plane and slip direction) in the polycrystalline material. This is because the fatigue crack nucleation, whatever the mechanism it follows, is a single and independent event, while the orientation of PSBs however, is a statistical one. Rolling tends to orientate the primary slip systems in the sheet plane and in the rolling direction but is not capable of achieving 100% completeness. With the relaxation effect which follows the annealing process and possible formation sites other than the primary slip systems (this is especially true for titanium), it is hard to relate the preferred orientation with the complete lack of overlap of the fatigue lives measurements of L and T (except the pre-cracked one).

The most possible reason, if the large difference in fatigue lives of T and L was due to the crack initiation process, is that the as-received structure has different threshold plastic-strain and plastic-stress values along T and L. Unlike PSB orientation in a statistical sense, different threshold values would guarantee the time sequence of

the formation of PSBs and thus the fatigue crack initiation process.

Surface Texture

Texture is an alternative word for anisotropy. Materials develop anisotropy of both mechanical and physical properties after have been mechanically processed. The degree of anisotropy depends on how much it is deformed. Rolling, one of the most common manufacturing process for sheet metals, can introduce strong surface or interior texture, according to process parameters such as the radius of the rolls, reduction percentage, temperature, and others. There are two general types of texture[6]: preferred orientation and mechanical fibering. Preferred orientation is also called crystallographic anisotropy. This type of texture is produced when the crystal structure is subjected to tension or compression. Grains subjected to tension will rotate toward the direction of pulling, therefore, slip planes and slip bands tend to align themselves with the direction of deformation. Conversely, under compression the slip planes tend to align themselves in a direction perpendicular to the direction of compression. The detection of preferred orientation is accomplished by the X-ray diffraction techniques[7] (pole figures). Mechanical fibering results from

the alignment of impurities, inclusions (stringers), and voids in the metal during deformation. For example, if a spherical grain were coated with impurities and subjected to vertical compression, impurities would align themselves generally in a horizontal direction after deformation. Since impurities weaken the grain boundaries, this piece of metal would be weak and less ductile when tested in the sheet transverse direction. An analogy would be plywood, which is strong in tension along its planar direction, but peels off easily when tested in tension in its thickness direction.

Another important issue in texture problem is surface. Regardless of the method of production, all surfaces have their own characteristics, which are referred to as surface texture; roughness, and finish. The description of surface texture as a geometrical property is complex. However, certain guidelines have been established to identify surface texture in terms of well-defined and measurable quantities.

1) Flaws, or defects, are random irregularities, such as scratches, cracks, holes, depressions, seams, tears, and inclusions.
2) Lay, or directionality, is the direction of the predominant surface pattern and is visible to the naked eye.
3) Roughness, consists of closely spaced, irregular deviations on a scale smaller than that for waviness. Roughness may be superimposed on waviness. Roughness

is expressed in terms of its height, its width, and the distance on the surface along which it is measured.

4) Waviness is a recurrent deviation from a flat surface, much like waves on the surface of water. It is measured and described in terms of the space between adjacent crests of the waves (waviness width) and the height between the crests and valleys of the waves (waviness height). Waviness may be caused by deflections of tools, dies, and the workpiece, warping from forces or temperature, uneven lubrication, and vibration or any periodic mechanical or thermal variations in the system during the manufacturing process.

It is in the last past few years that researchers began to study the role of texture in material fatigue behavior for titanium and its alloys.[8,9,10] Preferred orientation of a single crystal or a polycrystalline sample is specified by means of pole figures[7], which are sterographic projections showing the density of crystallographic poles of selected planes as a function of orientation. It has been shown that rolling texture of close packed hexogonal metals depends on c/a ratio. For high c/a ratio metals, rolling tends to rotate the basal plane (0001) into the sheet plane and the easy slip direction $[11\bar{2}0]$ into the rolling direction. The texture of

low c/a ratio metals including titanium however, differs from this observation by a complex response of the slip systems to rolling. The problem becomes even more complicated when annealing processes follow working. Depending on annealing time, temperature, and working material, annealing can eliminate, alter, or even enforce the existing texture. Actually, the term "annealing texture" has been developed to describe this complex effect.

Lacking pole figure information, we can not take preferred orientation into consideration. In contrast, mechanical fibering, once aligned by rolling (such as a crack produced by pushing a steel ball against the metal surface), is less affected by the annealing process. If a catastrophic fatigue crack was developed on mechanical fibering (including mini-cracks) which act as stress-raisers, a parallel orientation of them (which is the case of T samples) is preferred.

Fatigue Crack Deflection

Fatigue crack deflection is the phenomenon that the path of crack is periodically deflected from its nominal growth plane.[11] Although crack deflection is viewed as one of the mechanisms for the toughening of brittle and ductile matrix composites, wherein the obstacles in the path of the crack (reinforcements) may cause apparently beneficial resistance to

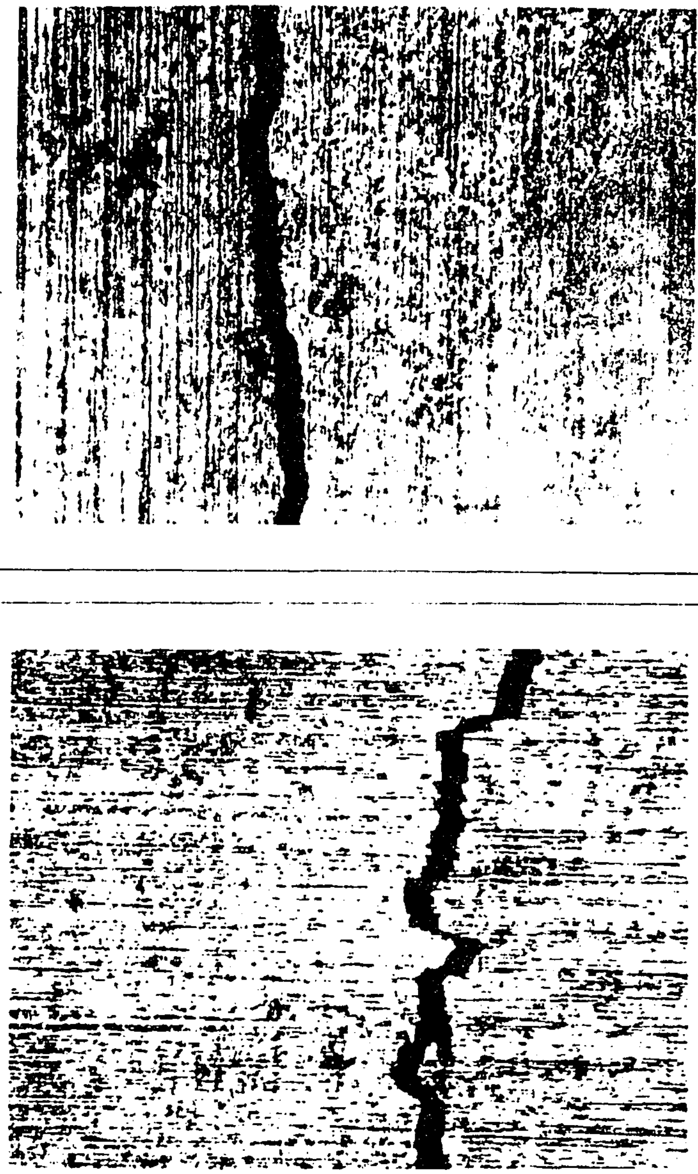

Figure 5 Early-stage fatigue crack profile of as-received T (upper) and L (lower). Notice the distinctive difference of the crack profile between these two specimens.

crack growth by tilting or twisting the crackfront[12], how the structure of material affects the fatigue crack path is still unknown. Many independent studies on 7xxx series aluminum alloys show that the over-aged (T7351) heat treatment condition leads to a predominantly straight (undeflected) fatigue crack profile over a wide range of growth rate (10^{-8} to 10^{-4} mm/cycle in vacuum); on the other hand, the under-aged treatment (of roughly the same yield strength) leads to a highly serrated or crystallographically deflected fatigue crack path. In fracture mechanics, the deflected crack is observed to be consistently associated with a higher crack growth resistance (or lower da/dN rate) and a higher fatigue threshold value than the straight path does. Shown in Figure 5 is the profile of two fatigue cracks of the as-received T and L samples respectively. They were removed for study before failure occured. Although the difference is not as striking as that for the over-aged and under-aged aluminum alloys, it is still distinguishable that the crack in the L sample is more serrated or deflected than that in the T sample. The difference, if somehow produced by the anisotropic surface properties as a result of the rolling process, may turn out to be the clue that L orientation has a higher fatigue crack growth resistance that T does, when pure geometrical effect is considered. This is more likely under high stress or strain conditions where crack growth rather than crack initiation is the controlling factor.

II. Fatigue Lives of Lot C

This lot consists of 6 TiMesh finished samples. After the TiMesh finishing, the interior structure of the as-received titanium sheet may be examined metallographically. The structure shown in Figure 6 has two phases: alpha-titanium and a small amount of intergranular beta-titanium. TiMesh finishing improves the smoothness of both surface and edge. This can be easily confirmed visually.

The fatigue lives of this lot are shown in Table 7.

Each sample in this lot has a fatigue life over 3 million cycles. Tests were interrupted if they were over 3 million cycles since the purpose of testing this group is only to determine the effect of TiMesh finishing. Comparing to those lives of as-received T (about 300 thousand cycles) and L (about 1 million), the fatigue life of TiMesh finished samples has significantly been improved. One sample running to the failure showed a fatigue life of 10,516,200 cycles. The data of this group confirms that 25 KSI is around the fatigue endurance of the material tested , i.e., Timesh finished grade 1 commercially pure titanium sheet.

We attribute this improvement to the beneficial surface effect of TiMesh finishing in removing the effects of rolling from the sheet surface.

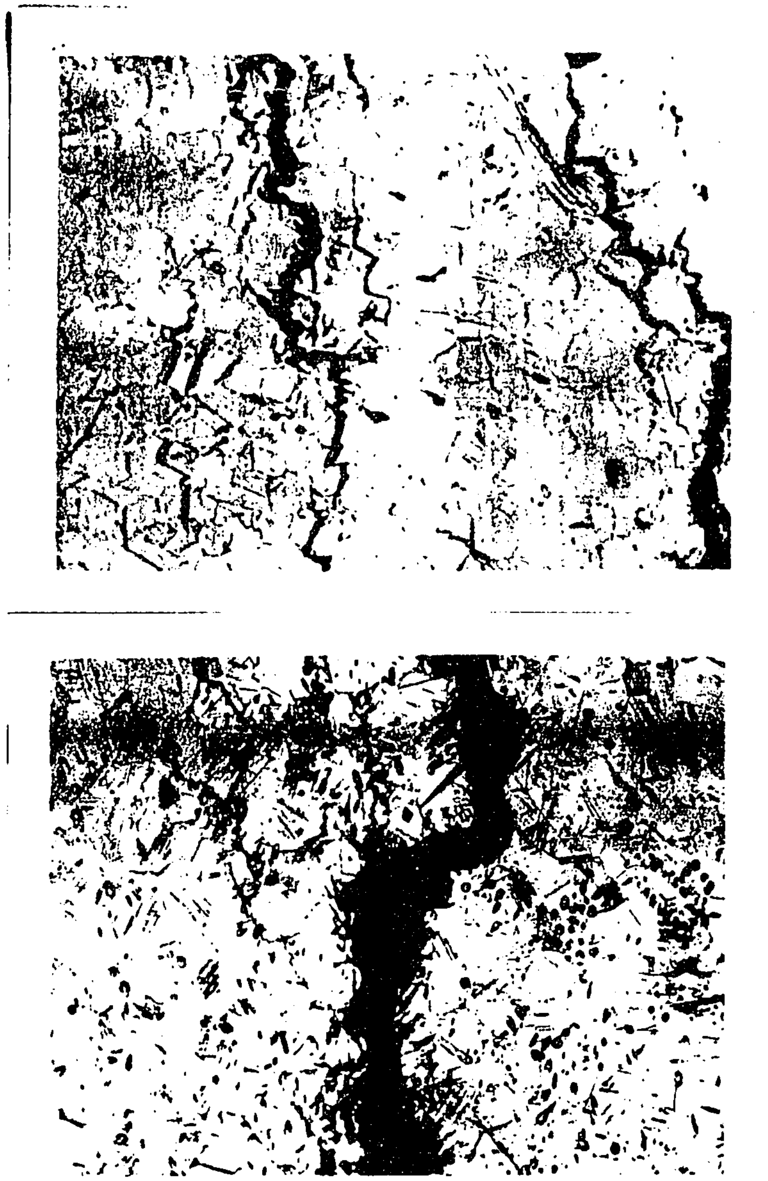

Figure 6 Microstructure of TiMesh finished T (upper) and L(lower) specimens. The right hand side crack shown on the upper picture is an in-plane crack while the left hand side ne initiated from the edge of the sample. A similar in-plane fatigue crack was shown in the right lower conner of the picture of L.

Table 7 Fatigue Lives of Lot C

(TiMesh Finished T and L)

Sample #	TiMesh Code	Fatigue Life (cycles)
1	T 506	> 3,085,100
2	T 506	> 3,053,900
3	T 506	> 3,830,300
4	L 182	> 3,053,800
5	L 182	>3,197,100
6	L 182	10,516,200
Average life over 3,000,000 stress level = 25 Ksi		

Surface has played such an important role in fatigue related problems that the phenomenon can even been regarded as two-dimensional. The manner in which the surface is prepared during manufacturing of a component has a decisive influence on dictating the life for fatigue cracks. Practically, all

fatigue failures start at the surface. For many common types of loading, like bending and torsion, the maximum stress occurs at the surfaces so that it is logical that failure should start there. However, even in axial loading where the stress is uniform throughout the cross section the fatigue failure nearly always begins at the surface.[11] There is ample evidence that fatigue properties are closely related to surface conditions. The factors that affect the surface of a fatigue specimen can be divided roughly into three categories, (1) surface roughness or stress raisers at the surface, (2) changes in the fatigue strength of the surface metal, and (3) changes in the residual stress condition of the surface. In addition, the surface is subjected to oxidation and corrosion.

Surface residual stress does not play a role in this investigation because it has been removed by the annealing process.

It has been recognized since the early days of fatigue study that different surface finish can appreciably affect material fatigue performance. The valleys on the rough surface serve as stress concentrations, which, in turn, induce different levels of resistance to fatigue crack nucleation. Some high-strength engineering materials, such as steel, are extremely sensitive to surface condition.

There exists a variety of surface treatments such as carburizing, nitriding, flame hardening, induction hardening, and shot-peening, which are designed to impart high strength,

wear resistance localized in the near-surface regions of the material. Since fatigue failure is so dependent on the surface conditions, anything that changes the property of surface will greatly alter the fatigue strength. Marked improvements in fatigue properties can result from the formation of a harder and stronger surfaces. On the other hands, a weaker and softer surface is detrimental to the fatigue performance. For example, the fatigue strength of aluminum-alloy sheet is reduced when a soft coating is applied to the stronger age-hardenable aluminum alloy. Also, electroplating or chromium plating of steel generally decreases its fatigue limit. Further, decarburization of steel surface greatly reduces the fatigue resistance.

It is concluded that the highly deformed rolling surface of the as-received titanium sheet has a negative effect on material fatigue strength that will lower the fatigue life, while the TiMesh finishing restores the original fatigue performance of the material.

III. Fatigue lives of Lot D and E (TiMesh Finished)

These two groups were tested under the raised stress of 32 KSI to investigate whether the anisotropic property of the as-received materials can be removed by TiMesh finishing process.

Although L samples show a slightly higher average fatigue life, it is hard to discern any significant difference of the fatigue properties between these two groups. Notice that the fatigue lives of L and T samples actually overlaped - quite

Table 8 Fatigue Lives of Lot D

(TiMesh Finished T)

Sample #	TiMesh Code	Fatigue Life (cycles)
1	506	316,600
2	506	95,300
3	506	303,500
4	506	113,300
5	506	110,500
6	506	111,800
Average life = 175,200 Standard Deviation = 39,000 stress level = 32 Ksi		

standard deviation is considered, their average lives become

statistically indistinguishable.

Fatigue at this stress level is clearly short-term fatigue according to the fatigue life observed. For the TiMesh finished samples, the long-term fatigue is actually measured in lot C where a stress of 25 KSI is used and no difference has been observed. We already know that 25 KSI can

Table 9 Fatigue Lives of Lot E

(TiMesh Finished L)

Sample #	TiMesh Code	Fatigue Life (cycles)
1	182	249,900
2	182	374,700
3	182	164,200
4	586	300,300
5	586	124,900
6	586	168,000
Average life = 230,300 Standard Deviation = 35,500 stress level = 32 Ksi		

different from those of the as-received samples. Also, if one be regarded as the fatigue limit of both TiMesh finished L and T.

If there is no significant difference between the TiMeshed L and T in short-term fatigue (or safely, the difference is small so that it can be practically disregarded) and long-term fatigue, two conclusions can be drawn: 1. the anisotropic fatigue behavior of the as-received materials is purely a surface effect. 2. TiMesh finishing process can eliminate the anisotropy.

It also comes to the investigators that preferred orientation is not effective for our testing materials, though it has to be carefully checked out in most rolling and drawing processes. More safely, if preferred orientation exists, it does not significantly affect the fatigue life. Once this type of texture is embedded in the material, it should cause intrinsically difference in fatigue performance which was not observed.

We treat the vanishing difference as the residual surface effect in cooperation with a longer fatigue life along L direction. During the tests we noticed that there existing roughly two types of fatigue cracks - one that initiates at the edge and the other that initiates at the interior of the sheet plane. This is shown in Figure 6. The later one can never happen if the samples are perfectly free of stress-concentration effect because all fatigue cracks of smooth

samples start from the edge. It was observed that the catastrophic fatigue cracks of most L samples originated from the interior rather than the edge. On the other hand, most T samples (where catastrophic fatigue cracks were more likely to start from the edge) showed extensive interior fatigue cracks. Under an optical microscope, these cracks generally were intergranular and may run to a few centimeters.

IV. Fatigue lives of Lot F (TiMesh Finished and Edge-filed)

It is seen from lot C that the fatigue performance of the as-received commercially pure titanium sheet can be improved by the TiMesh finishing process. The question that how much beneficial effect is introduced by the improvement in edge condition (roughness) which comes from the TiMesh finishing process automatically as well aseliminating surface effect still remains open.

Data in table 10 indicates that even under an edge condition poorer than that of the as-received samples, the TiMesh finished samples still show an improved fatigue performance than the as-received ones. Conclusion thus can be drawn that the major beneficial effect to fatigue property of the TiMesh finishing process is the surface treatment rather than edge-condition improvement.

No doubt that poorer edge condition (by filing) will

impair the fatigue life of materials. This suggests that the estimation of 3 million cycles as the fatigue life of TiMesh finished smooth samples is fairly conservative.

Table 10 Fatigue lives of TiMesh finished and edge-filed samples

Sample #	TiMesh Code	Fatigue Life (cycles)
1	T, 506	over 3,183,000
2	T, 506	over 3,094,700
3	L, 182	over 3,153,400
4	L, 182	over 3,078,100
Average lives over 3 million cycles stress level = 25 KSI		

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CHAPTER 4

CONCLUSION

The results of this study regarding the effect of TiMesh finishing on the fatigue performance of grade one commercially pure titanium sheet can be summarized in the following statements:

1. Anisotropic fatigue is observed in the as-received materials. At the stress level of 25 KSI, longitudinal fatigue life is longer than the transverse one by a factor of about two. The anisotropy is due to surface characteristics resulting from the rolling.
2. TiMesh finishing can significantly improve the fatigue performance of the as-received materials by producing a defect-free surface.
3. Anisotropy - difference in fatigue lives between the longitudinal and transverse direction, can be remarkably reduced, if not eliminated, by the TiMesh finishing process.

APPENDIX

Stress Calibration

An exact weight has to be calculated and scaled before calibrating the stress. To keep the stress constant all through the sample, the edge of the sample is cut to be linearly tapered. However, calibration is done on the extrapolation of the real sample to avoid geometrical edge effect. After the weight is loaded to the right end of the sample, the stress on the surface of the sample is given by the following expression:

$$\sigma=\frac{6W}{(b/L)T^2}$$

Where W is the weight, T is the thickness of the sample, b/L is the ratio of the root width over the length of the sample (extrapolated). b/L can be reasonably be taken as 0.5 for our samples shown in .

Now the stress can be calculated. For example, if a sample of 0.023in is used, a weight of 1.102lb has to be attached to result a stress of 25 KSI.

Next step is to take off the weight and adjust the fatigue tester so that the sample experiences exactly the same deflection. This is accomplished by placing an electronic detector under the sample. The stress is automatically adjusted to the same whenever the deflection is done.

The thickness of each lot is listed in the following table.

LOT	Thickness (in)
A	0.026
B	0.026
C	0.023
D	0.023
E	0.023
F	0.023

Notice the TiMesh finishing removes off about 0.0015in from each surface of the sample which corresponds to about 12% stress reduction.