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Effect of shot peening and grain refinement on the fatigue life and strength of commercially pure Al and two of its alloys: Al-2024-T3 and Al-7075-T6

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Abstract. Aluminum and its alloys are widely used materials in automobile, aircraft and space craft industries due to their high strength- to- weight ratio and corrosion resistance beside their other useful properties. They are the second materials in use after steel alloys. Most of the failures in parts of aircrafts and space vehicles are mainly caused by fatigue and stress corrosion cracking. In this paper, the effect of shot peening on the fatigue life of commercially pure aluminumand two of its alloys namely:Al-2024 and Al-7075-T6 is presented and discussed. Furthermore, the effect of addition of vanadium to Al and Al grain refined by Ti and Ti+Bon Its fatigue life and strengthis also presented and discussed using scanning electron microscope, SEM. It was that shot peening and the addition of V toAl and Al onAl grain refined by Ti and Ti+B have resulted in enhancement of the fatigue life and strength. Ffinally, the effect of shot peening on the surface quality of the peened parts is also presented and discussed.

1. Introduction

Aluminum and its alloys are widely used materials in automobile, aircraft and space industries due to their high strength- to- weight ratio and corrosion resistance beside their other useful properties. They are the second material in use after steel alloys. Most of the failures in parts of aircrafts, space crafts and racing car axes are mainly caused by fatigue failure and stress corrosion cracking. Failure by fatigue is a progressive and localized structural damage which occurs when the part is subjected to cyclic loading. The stress values at which fatigue failures occur are much less than the ultimate tensile strength or even may be well below the yield strength of the material. The failure starts by initiation of cracks at the surface of the part which propagates and extends to cause complete failure of the part.


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The corresponding number of load cycles or the time during which the number is subjected to these loads before fracture occurs is referred to as the fatigue life of the member and the maximum stress which can be applied infinite number of cycles to the member without causing its failure,(in case of ferrous materials) is referred to as the endurance limit. However, in case of non-ferrous materials the no of cycles which defines the fatigue life, from which the maximum allowable stress to avoid fatigue failure is defined by the users and design engineers as indicated in Figure 1.

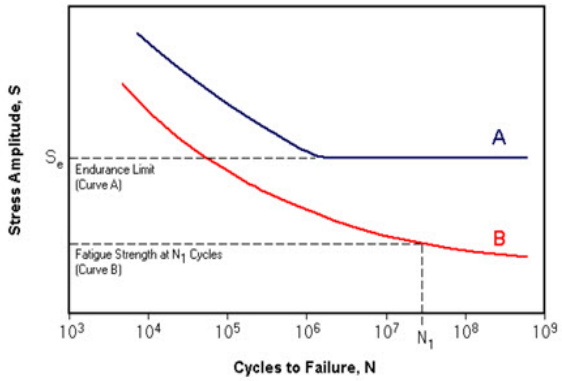


Figure 1. Fatigue S – N curve of A: mild steel and B: aluminum

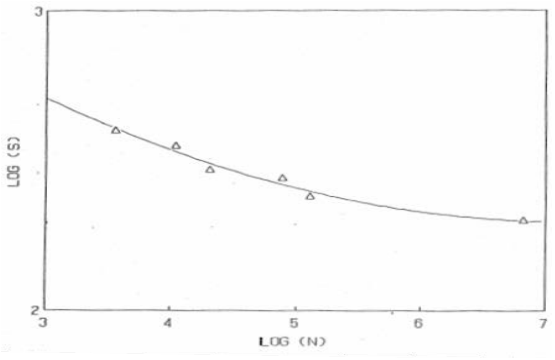


Figure 2. Log stress,(S) versus Log number of cycles to failure,(N)

Also fatigue data may be presented as Log S versus Log N; whereS is the alternating stress and N is the number of cycles.

The total period of fatigue life may be considered to consist of three phases:

i) Initial fatigue damage that produces crack initiation.
ii) Propagation of crack that results in partial separation of cross section of the member.
iii) The last phase when the remaining un-cracked cross section is unable to support the appliedload and then the complete fracture takes place.

1.1. Mechanismand mode of crack initiation and propagation

The position and mode of fatigue crack initiation depends on the microstructure of the material, the type of the applied stress and micro- and macro-geometry of the specimen. The crack initiation period may cover a large percentage of the fatigue life under high-cycle fatigue, i.e. under stress amplitudes just above the fatigue limit. But for larger stress amplitudes the crack growth period can be a substantial portion of the fatigue life. Detailed discussion of the different phases of the fatigue life and the relevant factors associated with them are beyond the scope of this paper.

1.2. Methods of improving fatigue life and strength

In this section two methods (which are used for improving fatigue life and strength) will be dealt with. These are the shot peening and the grain refinement processes.

2. Shot peening

Shot peening is a surface cold working process in which the surface of the component is subjected to a multiple impact by a high velocity stream of hard particles in a defined and controlled manner. This multiple impact of the shots produces a dynamic compressive stress layer in the surface of the component which ranges from 0.25 to 1.2 mm, thereby effectively eliminates cracks and other imperfections; hence its mechanical behavior, fatigue life and strength are improved. Controlled shot peening is an operation which is largely used in the manufacturing of mechanical parts to increase their fatigue life and strength. The kinetic energy of the shot is transformed into plastic deformation of the work piece surface and the steel ball itself. The shot is reflected from the component surface with the remaining kinetic energy. The elastically deformed sub-surface layer tries to resist this surface

expansion, inducing a compressive stress at the surface, balanced by a tensile stress of lower magnitude. If a thin material is peened on one side, a curve will develop in the part and the shot peened side be convex [1,2]. Examination of the available literature on shot peening indicates that the trend has not changed over the subsequent years, [3-16].

2.1. *Parameters affecting shot peening process*

Like any other surface treatment process, the parameters involved in shot peening play a vital role in determining the efficiency, quality and reliability of the process to ensure that the part is correctly treated. From the available literature the main parameters which affect the shot peening process are: shots pressure and velocity, peening time and to a lesser degree the table rotational speed. Their increase will cause increase in peening intensity whereas, increase in the standoff distance results in decrease of the intensity. It is worth mentioning that it is very difficult to modify one of the parameters without having some effect on the others. The culminating effect in the shot peening process is the shot peening intensity and complete coverage of the surface by subjecting or exposing the part to the effect of the shots to a certain time. Hundred percent coverage is reached when the original surface of the material is entirely coveredby the overlapping peening dimples.

2.2. Peening intensity and saturation

Peening intensity is the term commonly used to describe the overall effect of shot peening on the treated work piece. Factors that influence the shot peening process are investigated through their effect on peening intensity. These factors include shot size, shape and hardness, shot pressure, velocity, standoff distance, projection angle and exposure time.The Almen strip test method is, so far, the only available non-destructive method for determining peening intensity.The deflection of the Almen strip when subjected to the shot peening process displays the resultant effect of all the process parameters. This deflection is taken as the height of the arc at the center of the strip in thou of an inch and is termed peening intensity provided saturation is achieved. Saturation is obtained when doubling the exposure time will not cause more than l0% increase in the intensity value. Figure 3 shows this variation for 7075-T6 aluminum alloy whereas Figure 4 shows the effect of shot peening on the fatigue life of the 2024-T3aluminum alloy. It can be observed from these two figures that their fatigue lives were enhanced.This is attributed to the grain refinement effect of these two elements on Al which increases the number of grain boundaries which will hinder the fatigue crack propagation; hence resulting in the improvement of their fatigue live and strengths.

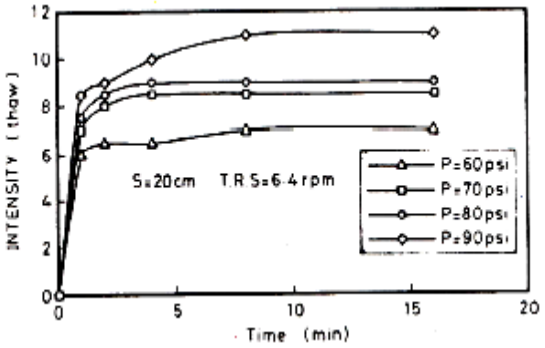


Figure 3. Variation of shot peening ntensity with time at different pressuresfor 7075-T6

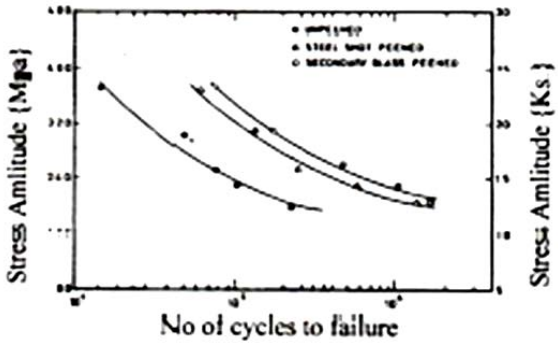


Figure 4. Effect of shot peening on the fatigue life of 2024-T3aluminum alloy

Shot peening intensity optimization to increase the fatigue life of a quenched and tempered structural steel was also investigated and reported in[9].

2.3. *Effect of shot peening on the surface roughness of the peened surface*
Despite the advantages gained by shot peening; it has the disadvantage of increasing the surface roughness of the peened surface as illustrated in Figure 5.

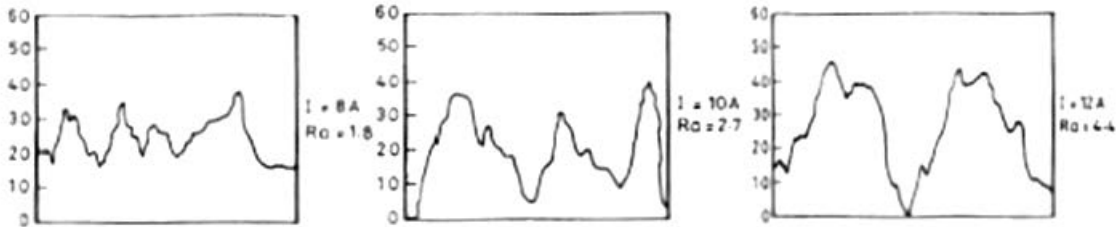


Figure 5. Variation of surface roughness with shot peening intensity

Also surface roughness and X-ray diffraction residual stress measurements were arried out on treated specimens made of X70 micro-alloyed steel (after severe shot peening) using microscopic examinations ann the results of their work is reported in reference [10].

3. Grain refinement
Aluminum and its alloys are the second in use in idustrial applications after ferrous alloys especially in the air craft and automobile industries due to their high strngth to weight ratio, their electrical and thermal conductivities in addition to their good corrosion resistance. However, against these advantages they have the disadvantage of solidifying in a columnar structure with large grains which tends to reduce their mechanical strength, surface quality and their fatigue life. Therefore, it became anecessity to grain refine their structure to overcome these disadvantages. Titanium and titanium + boron are the most widely used as effective refiners. The literature on the subject is voluminus from the metallurgical and mechanical aspects[17-24]. Review of this literature is given by the first author in reference[17].In this section, the effect of the grain refinement on the grain size, hardness, fatigue failure and fracture surface of the commercially pure aluminum is presented and discussed.

3.1. Effect of the different grain refiners addition to aluminum on its fatigue life
It can be seen from Figures 6 and 7 that addition of either Ti or Ti+B to commercially pure Al resulted in pronounced enhancement of their fatigue lives. Figure 8 shows comparison between the addition of vanadium to aluminum grain refined by Ti and Ti+B. It can be seen from this figure that the fatigue lives of both alloys had been improved by the vandium addition and is more pronounced in the case of its addition to Ti+B . This is attributed to the grain refinement effect of these two elements on Al which increases the number of grain boundaries which will hinder the fatigue crack propagation hence resulting in improvement of their fatigue lives and strengths.

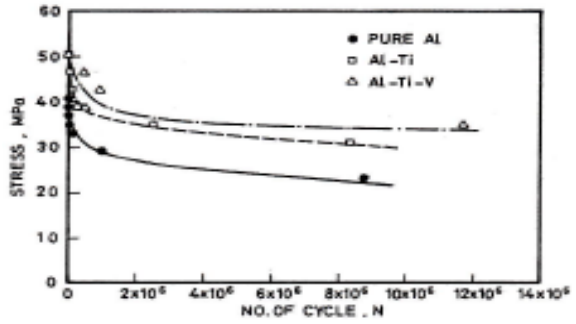


Figure 6. Effect of V on fatigue S-N curves grain refined by Ti

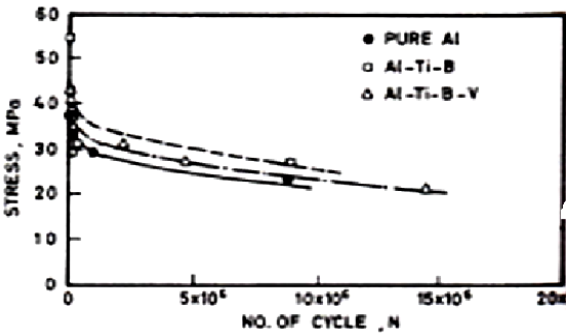


Figure 7. Effect of V on fatigue S-N curves grain refined by Ti+B

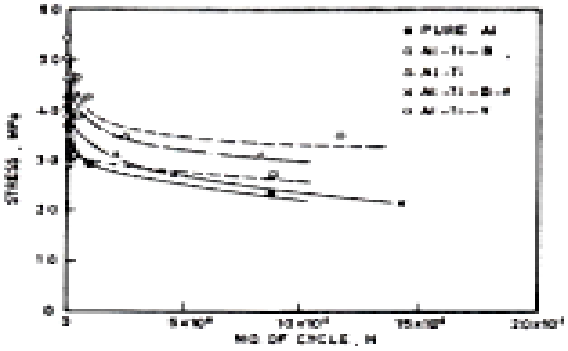


Figure 8. Effect of V on fatigue S-N curves grain refined by Ti and Ti+B

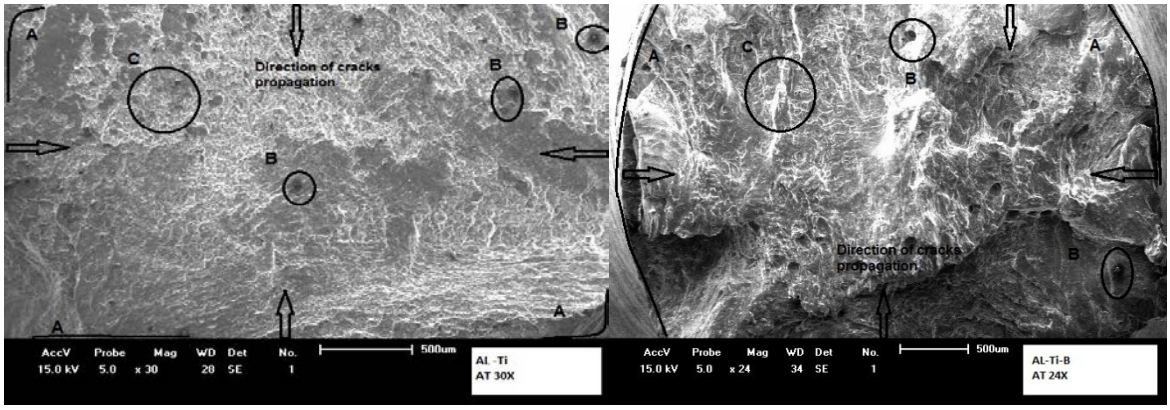


Figure 9. Photo-scans showing fractured surfaces of a).AL-Ti micro-alloy, b). AL-Ti-B micro-alloy

In all the previous photo-scans, it can be seen that there is two stages for the fatigue cracks, first stage is the crack initiation which starts at the surface of the specimen (region A), where it is initiated at a defect like pore or cluster pore located at or below the surface which is described as (region B) in the photo-scans. After the first stage when the micro-cracks have been nucleated, cracks growth starts but very slow and the erratic process occurs, due to the effect of the grain boundaries. Until this moment, fatigue is still material surface phenomenon. However, after some micro-cracks growth has occurred away from the nucleation site, a more regular growth is started, then the initiation period is expected to be completed and a real crack growth begins and the crack propagation takes place through the material until fracture occurs. Consequently, it was observed that the cracks have propagated within the grains (trans-granular), these cracks generate due to the cyclic slip deformation. Or at the grain boundaries (inter-granular) which have a certain angle against the grain boundaries. This may indicate the slip bands blocked by the grain boundary, leading to inter-granular cracks, and both of trans-granular and inter-granular modes occurred consequently.

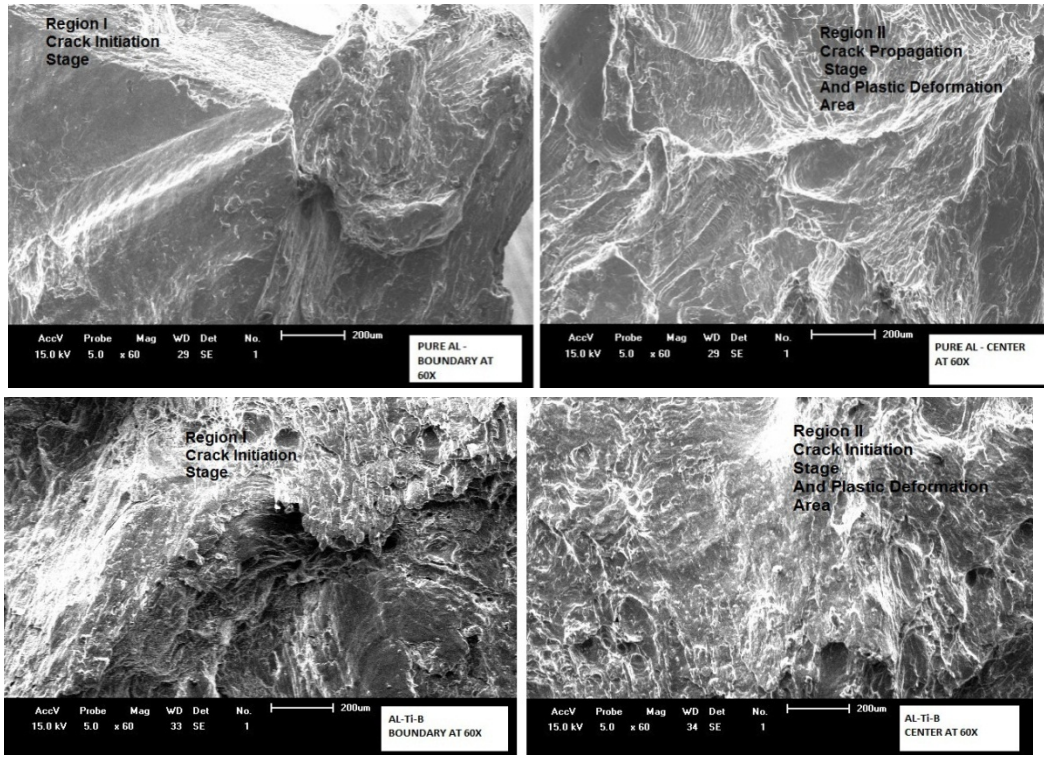


Figure 10. Photo-scans showing the crack initiation regions in Al and Al-Ti-B at 60X

The mode of fatigue failure in the different micro-alloy (to a great extent), alloys is almost identical.It indicates that the specimens suffer a certain amount of plastic deformation prior to fracture, and the amount of the plastic deformation varies with the added grain refiner. The SEM photo scans of Figures 9 and 10, show the fractured surface (At 60X) of pure Al, Al-Ti, Al-Ti-B, Al-Ti-V and Al-Ti-B-V respectively. On the whole, the fatigue failure in aluminum is not sudden as with other materials, e.g. steel, Since the total failure is proceeded with a state of plastic deformation. Examination of the fractured surface reveals that it consists of two regions regarding the crack propagation, which is denoted as (Region I and Region II). Region I contains the fatigue crack initiation as well as initial crack propagation,. It shows that the crack propagates almost is a trans-granular type. As the crack travels through the grains rather than at the grain boundaries. In addition, this region consists of a ductile region at the outer part. The area of the ductile fracture is reduced as the percentage of the hard particles increases in aluminum matrix this was observed in case of addition of vanadium to aluminum grain refined by titanium where a combination of TiAl3 and VAl3 particles exist in aluminum matrix. Both of them are hard particles. Region II is characteristic of higher rates of crack propagation observed as larger crack size, being much more irregular than Region I. Furthermore some trans-granular cracking is observed in this Region, II. The crack propagation in this region is primarily inter-granular, and the number of the trans-granular cracked grains of the fractured surface decrease as the crack length increases, resulting in more surface irregularity away from the initiation site. It is worth noting, that the fracture surface of the Al-Ti-B-V specimen reflected larger plastic deformation region due to existence of the borides TiB2 and VB2 which are soft particles. Also there is evidence of fatigue striations on the fractured surface of Al-Ti-V described as region D. This may be attributed to the existence of the hard particles TiAl3 and VAl3.

4. Conclusions

The following points are concluded:

4.1. Effect of shot peening:

i. Shot peening intensity increases with the increase of shot pressure and time, whereas the standoff distance has slight effect on intensity and the table speed has particularly no effect on the intensity.
ii. Shot peening resulted in pronounced improvement in the fatigue life and strength of Al and its two alloys7075-T6 and 2024-T3 provided that saturation has been achieved and no over peening has occurred. If over peening occurs it will cause adverse effect on the fatigue life and strength.
iii. Shot peening resulted in deterioration of the surface quality of the peened surface as it caused slight increase of its surface roughness. This can be reduced by decreasing the shots size and controlling the process parameters.

4.2 Effect of grain refinement:

i. Addition of any of the grain refiners Ti, Ti + B or V to Al resulted in reduction of its grain size from columnar structure into equi -axed one. Furthermore, their addition resulted in enhancement of its fatigue life and strength due to the strengthening caused by the increase of the number of grain boundaries.
ii. Addition of any of the used grain refiners used to aluminum resulted in modifying the mode of failure e.g. crack initiation and propagation, being a mixture of trans-granular and inter-granular of different percentages, due to the formation of the hard particles of the intermetallic compounds of titanium and vanadium alum ides within the main matrix.

5. Acknowledgment

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