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ORIGINAL PAPER

Investigation of Adding Silicon on Fatigue Properties of Aluminum Based Alloys

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Abstract

Presence of impurities in a mechanical system have a great effect on its mechanical properties, some impurities can defeat fatigue life, while others may exert a highly careful effect. The principal usage of Aluminum alloys is in the production of plane light structures, panels, and metallic frameworks. The second largest consumer is the industrial vessels; this shows clearly the fastest growth with aluminum alloys as an alternative solution instead of steel and cast iron in industry. Two aluminum alloys were used to study effect of adding alloying element such as Silicon (Si) on mechanical dynamical properties (fatigue life) of these two selected alloys, they are Al-5Si (4043) and Al-12Si (4047). Fatigue tests are carried out on these specimens under rotating bending conditions to get the S-N curves. The S-N curves show fracture at around over 10^8 cycles without certain endurance limit for both alloys where the two employed specimens are aluminum based alloys, hence, each one will not exhibit a specific value of endurance limit. The final results showed that, for the first alloy, cracks initiate in the medium of aluminum and then rapid progress towards the alloying element (Si), so this means crack initiation is the governing factor for fatigue life for this aluminum alloy. For the second alloy, cracks start from alloying element (Si) at first and then directed towered the aluminum matrix, also. Al-12Si (4047) shows best largely fatigue resistance than the other alloy, sure this depends on the so small volume occupied by alloying element comparing with aluminum matrix.

Keywords Aluminum alloys 1 · Silicon 2 · Fatigue life 3 · Alloying elements 4

Abbreviations

ATU	Al-Furat Al-Awsat Technical University
Al	Aluminum
ASTM	American Standard for Test and Materials
Cu	Copper
da/dN	Crack growth to number of cycles
FCC	Face Centred Cubic
Fe	Ferrous
Mg	Magnesium
Mn	Manganese
MPa	Mega Pascal
S-N	Stress–Cycles Diagram
SCMI	State Company for Mechanical Industries
UTS	Ultimate Tensile Strength

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Wt.	Weight
Si	Silicon
K_{fc}	Fracture Toughness
$_{Prof.}$	Proof Stress (MPa)
$_{ult.}$	Ultimate Tensile Stress (MPa)

1 Introduction

In 1827, Sir Wohler is mostly attributed with having extracted the metal, while Sir Oersted prepared a contaminated formula two years or earlier. In addition, Sir Davy is the first scientist who proposed the name Aluminum for that nonferrous metal, where it is undiscovered at that time [1], and later he decided to name it as Aluminum. Aluminium nonferrous metal extracted by using the electrolysis of alumina dissolved in cryolite [2], this particular chemical process was discovered in 1886 by the scientist Sir Hall in the United States of America and at approximately the same year by the chemist Heroult in France. Cryolite is defined as a natural raw material founded in Greenland. [3, 4]. Today Aluminum can be manufactured from ore and clays; however, this process is not economically possible so the wide range of producing aluminum is by melting recycled raw materials [5], Aluminum is the richest metal founded in the Earth's layers which represent about (8.1%), but is certainly not found as a free and pure formula in the Earth layers, it is found in the natural granite and in many other natural mineral deposits [6]. Pure aluminum, has a grayish, snowy metal color and holds too many desired features such as it is light in weight; non-magnetic and non-sparking, malleable, and ductile to some extent. Pure aluminum is so soft metal and its alloyed with small percentage quantities of Silicon [7], copper, manganese, magnesium and other chemical elements to get a variety of beneficial mechanical and chemical properties [8], so these special alloys are important in the construction of modern aircraft and external and internal furniture of airspace rockets [9].

Silicon represents of 25.7% of the surface layers of the Earth's cortex, by weight, and is representing the second most available metal, being exceeded only by the Oxygen. Silicon is not founded in a free formula in nature, but appears as the oxide or silicates [10]. There are many chemical forms of Silicon such as Sand, quartz, and rock crystal; also the Silicon oxide appears in other formulae like the most spreading one named as coloured Granite, hornblende, asbestos substrate, feldspar, some specific kind of clay, or Mica, etc. [11]. Highly unalloyed Silicon could be extracted based on the thermal breakdown process of utterly pure tri-chloro-silane in a hydrogen atmospheric conditions, and by employing a vacuum float region process [12]. Silicon is representing an important constituent in steel; plus, Silicon carbide is also generally used as one of the most important abrasives sheet material. Crystalline Silicon has a metallic shine and darkish color. Silicon is an inert element [13].

Aluminum as a non-ferrous metal has been used in both commercial and scientific fields for more than tens of years due to its relatively excellent mechanical, chemical [14], and physical properties where the most important feature is its corrosion resistance in different ambient and boundary conditions furthermore, its low production cost per unit volume comparing with other metals of course after steel production cost. On the other side Aluminium has disadvantages, such as short fatigue life and variation in mechanical properties as its temperature rising in addition Aluminium has no clear or exact endurance limit (value) [15], where the recorded fatigue strength of the this unalloyed metal at dynamic load of about 10^8 cycles is merely of about 60% of its tensile strength and this ratio is lower, the higher the tensile strength of the alloy." because of its relatively low melting temperature, plus high levels temperature circumstances ability is utterly limited and the tensile strength of produced alloys will fall in a rapid manner over 220 °C and that situation of cast alloys will be beyond 270 °C [16], besides that, environmental corrosion resistance in an ordinary atmospheric conditions is very respectable and noticeable with time [17].

As it is scientifically well known fact that alloying additives for casting alloys differs considerably from those for ore alloys so that due to the principal contribution of adding Silicon in enhancing casting ability in addition greatly reducing thermal expansion and the induced thermal stresses, means thermal expansion coefficient will be reduced by approximately of about 32% for a Silicon content of 23%. The eutectic phase composition of altered Aluminium-Silicon mixture is around 12.6%, so if, to decrease the induced thermal expansion coefficient, the Silicon content is raised up over this specific rate, furthermore, the elongation percentage ratio will become extremely low because of the existence and formation of hyper eutectoid Silicon phase, in other words, adding Silicon will significantly reduce elongation and adding of alloying elements is considered as a key factor of enhancing both static and dynamic properties of alloys in general so in case of Aluminium based alloys adding Manganese or Silicon (up to 12%) will increase the ultimate tensile strength of this new alloy till specified value of 170 MPa without any specific thermal treatment, so that leads to the fact that Aluminium-Silicon alloys are employed where casting ability is considered as the control factor in the assigned application(s) with moderate strength is required [18].

Based on the criteria of the fatigue crack growth and propagation as a function of the applied cyclic load (da/dN), such factor for Aluminium alloys is reaching to 40 times that for steel. The situation for the Titanium alloys of double yield stress, this factor (da/dN) for Aluminium has become about 20 times that of the Titanium alloys, but in case of the other important cyclic property, fracture toughness, K_{fc}, where the value of this parameter for aluminium alloy is normally of about 20 MPa in a comparison with 160 MPa and 60 MPa for the steel and the titanium alloy respectively [15], that makes Aluminium alloys are the best selected alloys for manufacturing many mechanical components rather than other low and medium carbon steels. Aluminium alloys does not exhibit a clear defined endurance limit (value), but this does not consider as a disadvantages of using Aluminium alloys in industrial manufacturing because Aluminium alloy products are frequently employed and suggested to endure a periodic loading over of the level of 10^8 cycles.

2 Materials and Methods

Strength of a material acts on behalf of fatigue loads can be specified by conducting a fatigue life test by employing the HI-TECH machine, during this specific dynamically mechanical test, the already prepared sample(s) is subjected to a completely reversed bending stresses by applying different weights and rotated around a central axis of the employed specimen under invariable angular rotation. For a precise magnitude of the weights, one has to record the total number of revolutions at which the specimen under consideration broken. Again, the total number of revolutions at which the fatigue failure occurs in the assigned specimen is recorded too. The process is repeated many times with same experimental procedure and suitable miscellaneous weight of course in accordance with the employed mechanical rig for checking a repeatability as it actually gained. Finally, the obtained fatigue strengths for each specimen tests are plotted against the associated number of revolutions. The resulting curve is well-known and called the S-N curve. Previous experimental tests have proven that a metallic substances have an endurance limit defined as the highest value of alternating stress that can be withstood indefinitely by a test specimen without such kind of failure [19, 20]. Figure 1a, b below indicates a diagram for experimental steps:

2.1 Tensile Test

Theoretical and experimental calculation are completely depending on a mechanical properties of the employed alloys Al-5Si (4043) and Al-12Si (4047); these can be acquired from a tensile test of standard specimens based on the recommendation of ASTM A370 [19]. Figure 2 shows in details the standard prepared specimen sketch.

2.2 Fatigue Test

Fatigue of materials is a famous phenomenon whereby a huge number of cyclic stress variations at a particular point can cause a break or damage even though the maximum applied stress that is not as much of the proof or yield stresses for this loaded specimen with the same material. The formation of fracture is initiated by a tensile stress at a macro or microstructure cracks or flaw defects. Once started the edge of this micro crack acts as a stress raiser or sometimes named stress concentrating and thus assists in the propagation of the crack until the residual cross section can no longer carry out the applied periodic load. While it appears, the fatigue failure surely occurs in all substances, there are significant differences in the occurrence style of fatigue. The procedure of completely reversing the applied stress on an engineering component by using a reversed bending fixed-free ends beam was designated, therefore, the applied periodic stress at any point on the surface of the cantilever beam will vary according to sin wave or periodically. In the machine used here, the cantilever is specially designed to use a relatively simple specimen with a particular minimum cross-section area. The endurance limit and S-N curve are a powerful technique for the theoretical and numerical analysis. The specimens were manufactured by machining and preparation according to the machine standard; see Fig. 3a below, the total number of the prepared specimens is 50 specimens according to the standard [20].

All specimens are made from alloys Al-5Si (4043) and Al-12Si (4047), and the test was performed by HI-TECH [21] see Fig. 3b below. The proposed load is vertically applied to the free end of the employed cantilever specimen through a ball bearing. There is a specific cavity in the cantilever into which the test specimen is inserted, and by hiring a small cross section specimen, the stress on it will be much greater than in the rest of the cantilever. The apparatus is supplied based on the international recommendation of standard specimen ASTM E647 with the given dimensions in Fig. 3a [21].

3 Experimental Considerations

3.1 Chemical Composition

Chemical composition investigation is considered as a one of the most important experimental part of this research because this practical test will give a percentage composition of each chemical element in the employed alloy and consequently as it is well known that each element has its own effect on the overall mechanical properties of the assigned alloy including fatigue life prediction taking into account neglecting very small values equal or less than 0.005% and considering only significant values of these alloying elements so after checking the chemical composition for the two employed alloys, the following Table 1 shows in details the obtained results.

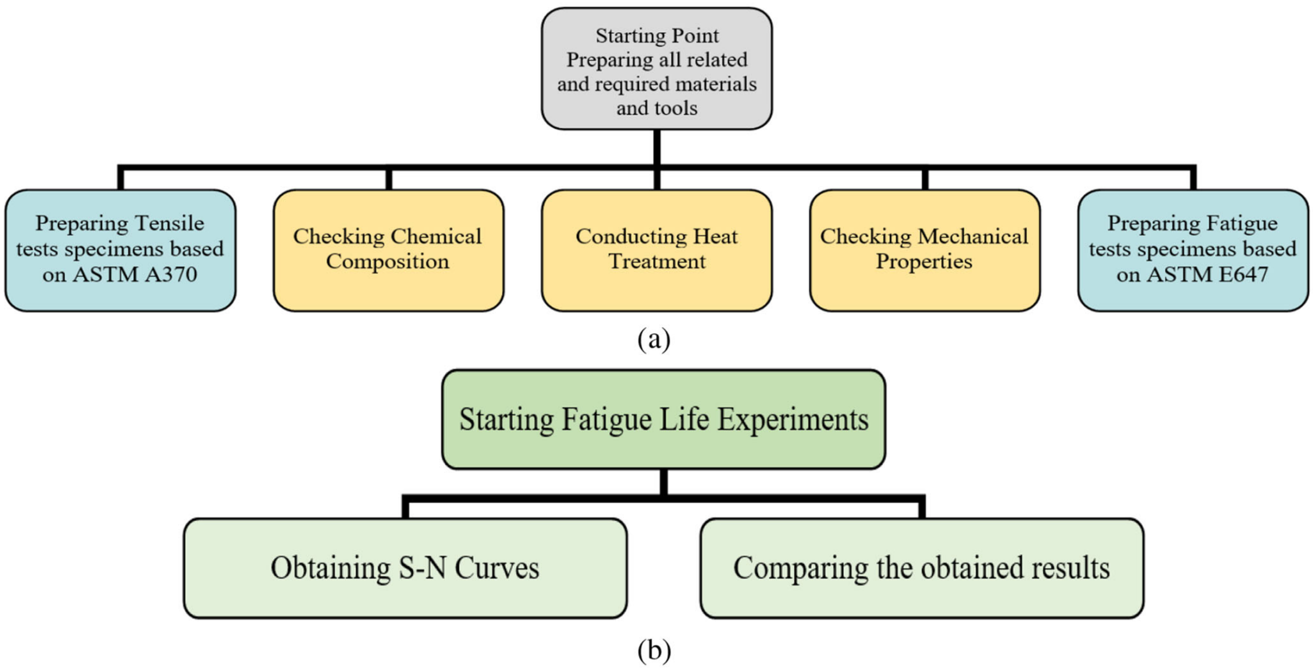


Fig. 1 **a** Preparing requirements; **b** Practical investigations

3.2 Heat Treatment

As a complementary and essential test that must be conducted is the so-called heat treatment of the alloys under consideration, because this specific kind of examination will relatively enhance specimens to sustain the coming compulsory surveys in other words, it will be a key factor in internal and residual undesired stresses so the nominated alloys will be relaxed and will smoothly respond to the proposed boundary conditions and loads, therefore, it was very crucial to pre-conduct this thermal tests. Heat treatment procedure for the hired samples explained in Table 2 below:

3.3 Mechanical Treatment

There is no doubt that mechanical tensile test is representing a backbone of almost of mechanical engineering studies including this research, where such principal test provides a full

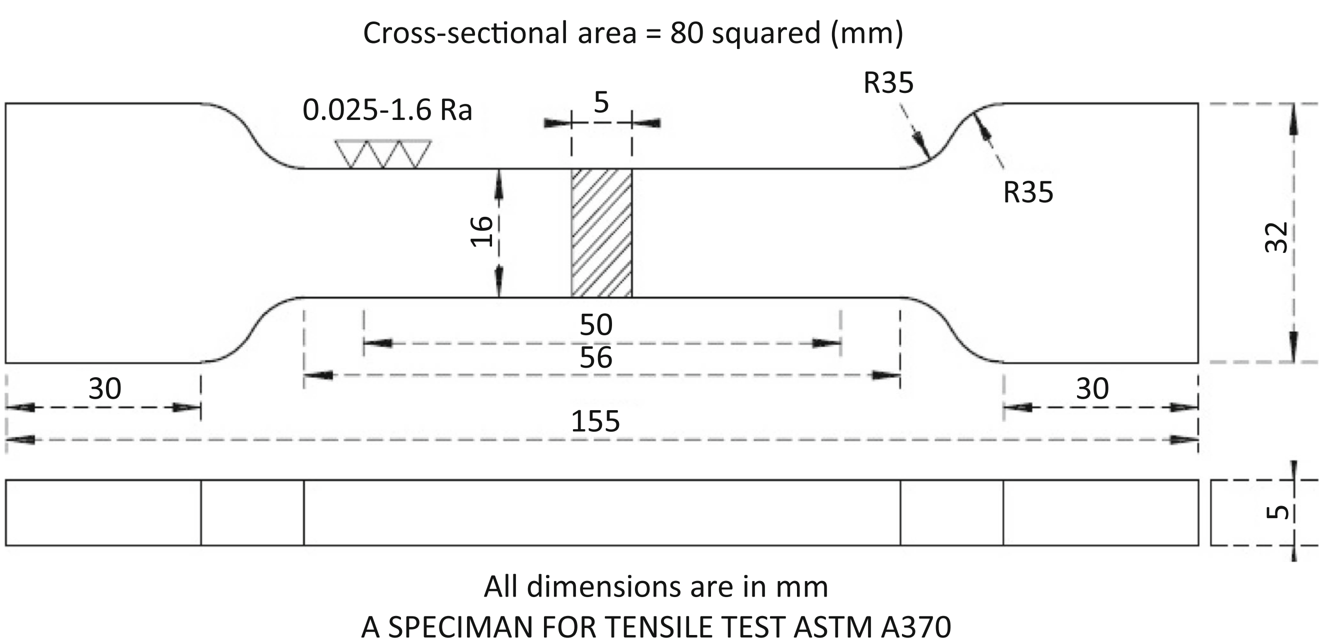


Fig. 2 Tensile test specimen

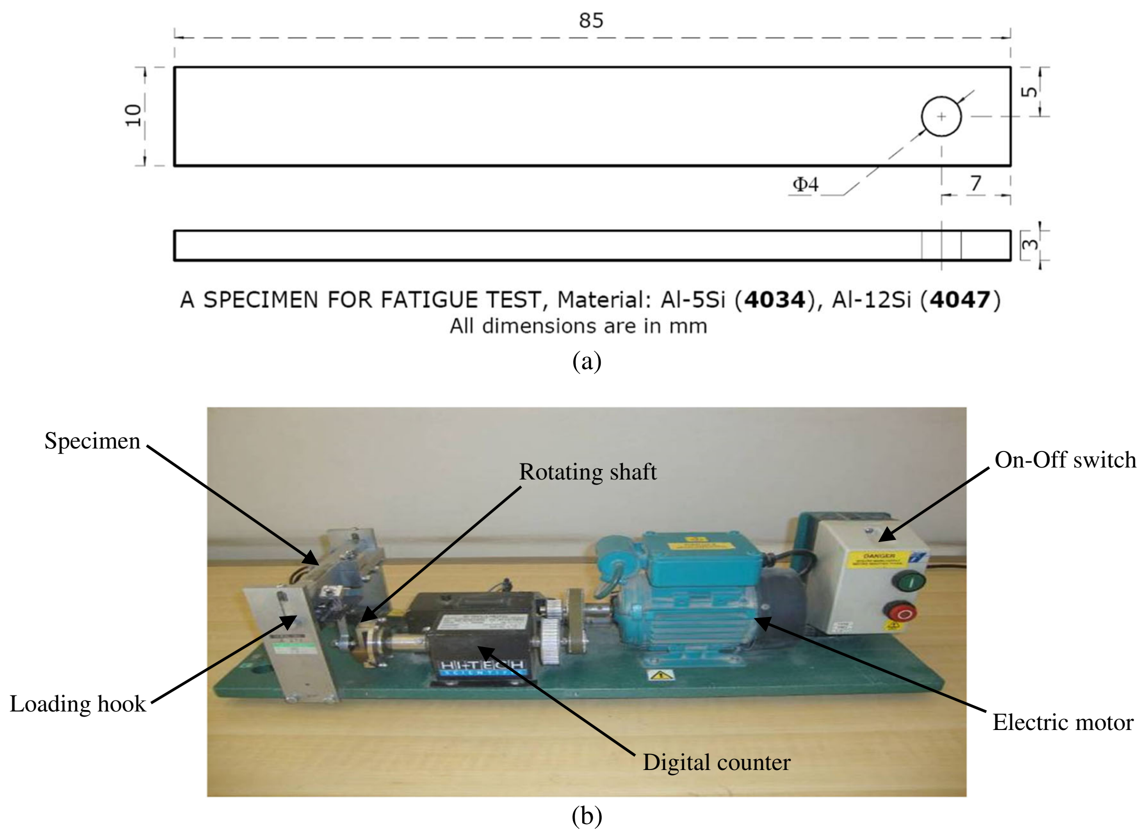


Fig. 3 **a** Fatigue test specimen; **b** Fatigue tester, S-N curve device

detail about the expected behavior of the material under investigation not only at the elastic region in the stress-strain diagram but also in the next plastic zone until reaching final fracture point, in addition, this traditional test will give a numerical precise values of the following parameters; Proof stress in MPa, Yield stress in MPa, Ultimate tensile stress in MPa, Reduction in area as a percentage ratio %, Young modulus (Modulus of Elasticity) in MPa. So to reduce diagrams in this paper, the gained results will be tabulated as indicated in Table 3 below; hence, the prepared samples as shown in Fig. 1 is used to check mechanical properties by using tensile test, which gives many important parameters that describe the mechanical behavior of these alloys. Table 3 below describes the gained values.

Table 1 Chemical composition results

Ref.	USA standard	Chemical composition (wt.%)				
		Si	Fe	Cu	Mn	Mg
Al-5Si	4043	10.8	0.19	7.33	0.012	0.58
Al-12Si	4047	17	0.3	4.2	0.23	0.61

There are other elements but neglected due to their very small values

3.4 Fatigue Test

In our ordinary daily life, many activities have related to dynamic loads or in other words cyclic and periodic loads as the time going on, and on another side, Aluminum is used in many applications and industries, so that leads to investigate how to improve aluminum products while they facing periodic loads? Hence based on the two previously mentioned factors, the rising mechanical investigation is fatigue test taking into account alternative suggestions to reach that goal, and one of the presented ideas is adding the Silicon with some specific percentage ratios to aluminum alloys, so this study focused on extending fatigue life of silicon-aluminum based alloys. The lateral cross-sectional dimensions are (3 mm*10 mm), so the resulted area will be $3*10^{-5}$ m^2 and the applied load at the free end of the employed specimen was varying from 0.1 kg up to 0.5 kg with increment step of 0.1 kg, so to get an accurate results, this fatigue test was repeated over than 50 attempt taking into account variation of the applied load in each time, and this is a principal point in fatigue test. In return to Fig. 3a and with the aid of the so called engineer equation $\sigma_{bending} = \pm \frac{M\ y}{I}$ where $\sigma_{bending}$ is representing bending stress(s), M is the maximum

Table 2 Heat treatment results

Ref.	USA standard	Heat treatment procedure
Al-5Si	4043	Heating up to 490 °C for 6 h then WQ, 170 °C for 8 h
Al-12Si	4047	Heating up to 500 °C for 6 h then WQ, 170 °C for 6 h

bending moment at the free end of the employed specimen, y is the half distance from the center line to the upper extreme point of the surface of the nominated specimen, and I is the second moment of area for the lateral cross-sectional area of this specimen, m is the applied suspended mass and w is the associated suspended weight at the free end of the specimen of length L, so Table 4 below summarizes the numerical values of the above mentioned effective parameters plus the induced stress range R.

Figure 4a–c below indicate the S-N curves obtained according to the standard mentioned above, these curves showed fracture occurred at over 10^8 cycles at room temperature and no distinct certain fatigue limit for both employed alloys but at the same time there are some differences in fatigue life in spite of all fatigue test for the two alloys are conducted under the same conditions also precise investigations of failed region or fatigued specimens shown that the shear cracks initiate and propagate in the aluminum matrix, that means the same for the two alloys but cracks beginnings exactly in the Silicon phase itself of at the interface between Silicon and aluminum, so this will lead to the following conclusion increasing percentage of Silicon will increase rapidly cracks initiations in the interfaces regions on the other side decreasing Silicon ration will decreasing cracks initiations but allow to shear cracks to grow in the aluminum matrix. From the obtained S-N curves, it is so easy to find the endurance limit for the 4043 alloy is about 10^7 cycles and for the 4047 is 10^8 cycles.

4 Micro Observations of Crack Initiation and Growth

After conducting many repeated tests on the prepared specimens until reaching first stage of the expected crack initiation and followed by local crack propagation at the boundaries of the molecules of the alloying element, silicon, a new local plasticized condensed zones have been created due to local brittle phases formation at these particular parting lines between the alloying element grains and the base metal matrix, aluminum, and there was a huge difference in behavior of the ordinary case at the first stage of loading Fig. 5a with the advanced stages of the loaded specimens Fig. 5b, so it is so clear to find under microscope the specific layers or parting lines at these additives element, exactly as shown in Fig. 5 below. In addition, it is important to compare the surface topography between the first stage(s) under relatively primary (low) loading case with the advanced topography situation as the loading time is going on for exactly the same specific zone, the initial peaks and asperities are completely deformed into valleys and formation of cracks via the scanning electromicroscopy images as clearly indicated in Fig. 5a, b.

5 Results and Discussions

As a results of the above mentioned experimental results and analysis, the Silicon alloying element changes the overwhole mechanical properties of the nominated alloy, in other words, with respect to dynamical fatigue properties, the Silicon has a significant effect on the fatgiue strength and this is due to creating a huge grid of specific boundaris within the microstructure of the employed alloys, where these boundaries may be considered as a weak zones comparing with other alloys. Crack initiation and propagation are representing a backbone of fatigue phenomonon, hence, in this case cracks will initiate and expandibly propagate early formed at the so called critical transformation boundaries, exactly like this one between aluminum and silicon, in a rapid progree towards the more brittle region(s) in all directions, so that means,

Table 3 Mechanical gained results

Ref.	USA standard	Mechanical properties				
		Prof· (MPa)	*ult.* (MPa)	*TFS* (MPa)	Red. in area (%)	Young modulus (MPa)
Al-5Si	4043	409	440	453	2.5	68
Al-12Si	4047	378	410	423	3.6	73

Table 4 The induced stress range values

m (Kg)	W (N)	L (m)	$M_{max.}$ (N.m)	y (m)	I (m^4)	$\pm\sigma_{bending}$ (MPa)	R (MPa)
0.1	0.981	0.078	0.076518	0.0015	$22.5*10^{-12}$	5.1012	10.202
0.2	1.962	0.078	0.153036	0.0015	$22.5*10^{-12}$	10.202	20.404
0.3	2.943	0.078	0.229554	0.0015	$22.5*10^{-12}$	15.303	30.607
0.4	3.924	0.078	0.306072	0.0015	$22.5*10^{-12}$	20.404	40.809
0.5	4.905	0.078	0.382595	0.0015	$22.5*10^{-12}$	25.505	51.012

there is a limitation in adding silicon to the aluminum alloys with maximum value of not more than 17 wt.% to get an acceptable mechanical properties. Many of other aluminum alloys investigations were about examining mechanical properties rather than effect of the percentage ratio(s) of adding alloying elements and the associated mechanical properties including fatigue test under different boundary conditions, plus previous conducted research papers were focusing on comparing for example aluminum alloys with another steel alloys to find the best one the comply with the assigned function of the manufactured components in many industrial application, so the novility in this paper is showing an exact value of an alloying element (Silicon) to the Aluminum based alloys to keep mechanical properties in a satisfies level, and the recommendation for more and future investigations is studying other factors including adding other alloying elements, creating initial cracks to simulate fatigue loading case(s), or checking rotating bending fatigue test for the same alloys taking into account the above obtained results.

6 Conclusions

The conclusions that can be drawn from this work largely depend on the type of the alloying element added to the aluminum matrix, so in this paper two alloys are selected with different percentage ratio of Silicon as an alloying element and neglecting the presence of other elements due to its very small quantities and limited side effect on mechanical properties of these alloys. Therefore, adding Silicon element will reduce fatigue strength of the modified alloys and vice versa, plus micro-cracks could be a starting local point to fatigue failure so it is essential to avoid forming flows not only in the alloying element but also in the substrate matrix of aluminum. Cracks and micro-cracks are observed initiate at Silicon phase always as clearly indicated in Fig. 5, which means that granule of silicon will be a starting local point to growth and initiation of cracks extending along the substrate matrix and conversely aluminum matrix showed acceptable resistance to cracks growth, so final conclusion is to add silicon as an alloying element to some restricted level (up to 17 wt.%) exactly as indicted in Fig. 4. In addition, at the same time silicon has a considerable positive effect on other mechanical properties, as numerically indicated in Table 3. Finally, the obtained overall results has confirmed the already expected hypothesis and guided this research line towards more investigation to get more confirmed results in association with the world of effect of alloying element on mechanical properties.

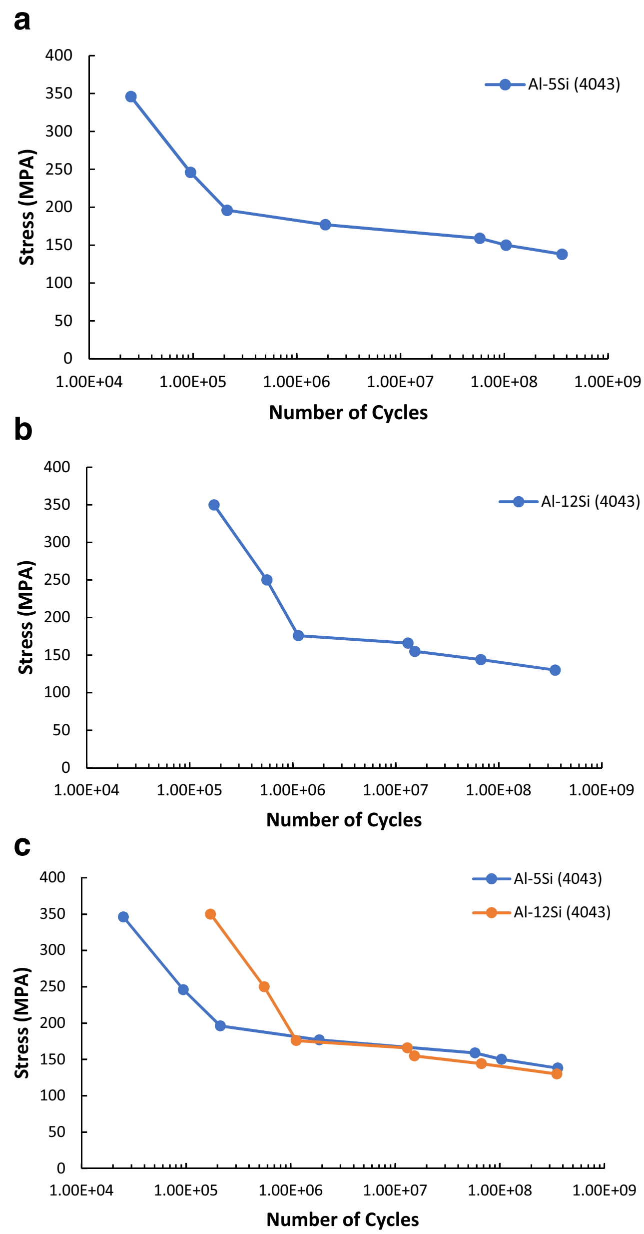
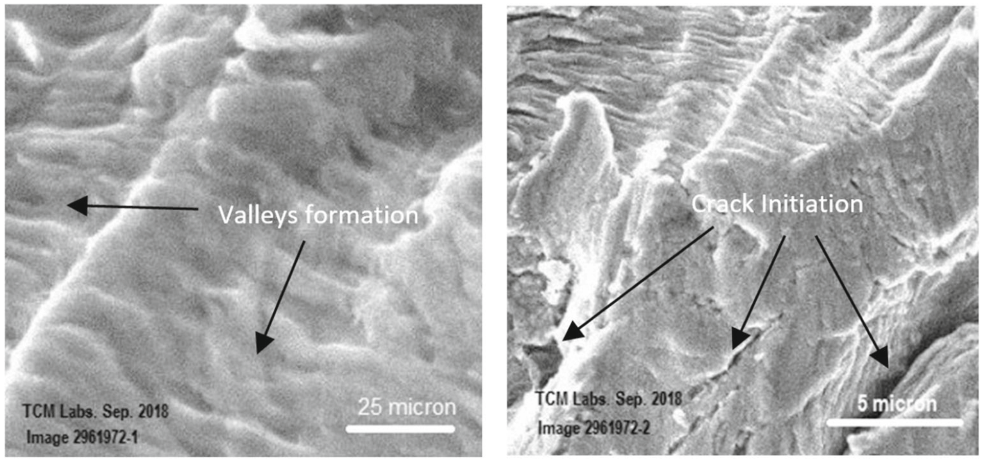


Fig. 4 **a** S-N curve obtained for the employed 4034 alloy; **b** S-N curve obtained for the employed 4047 alloy; **c** S-N curve obtained for the two employed alloys

Fig. 5 Micro observation of the gained crack initiation



a) First stage of loading **b)** Advanced stage of loading

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Compliance with Ethical Standards

Conflict of Interest The authors declare no conflict of interest.

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