The Effects of Short-Time Solution Treatment and Short-Time Aging on Young's Modulus of TI-6Al-4V

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Abstract: The Ti-6Al-4V alloy is currently utilized as structural materials in artificial hip and knee joints, bone plates and screws, and artificial dental roots. It is mainly used in implants that replace hard tissue because has a high strength, good corrosion resistance, high biocompatibility compared to other conventional metallic biomaterials such as stainless steel and Co-Cr-Mo alloys. The Ti-6Al-4V alloy with low Young's modulus equivalent to that of the cortical bone is a simultaneously required in order to inhibit bone absorption. By short-time solution treatment and subsequent short-time aging, the mechanical properties of Ti–6Al–4V alloy can be improved while maintaining a low Young's modulus. The results shown that optimum heat treatments obtained in the alloys conducted the short-time solution treatment at 930 ^{o}C (1203 K) for 60 s and subsequent short-time aging at 530 ^{o}C (803 K) for 40 s. It was obtained the yield strength and tensile strength improved without reduction in ductility. Their maximum improvement rates of reached 21,6% and 21,1%, respectively and the Young's modulus reduced with maximum rates of reached 19%.

Key words: Ti-6Al-4V, short-time solution treatment, short-time aging, mechanical properties.

1. Introduction

With the development of economy and technology, the number of aged people demanding failed tissue replacement is rapidly increasing. Elderly people have a higher risk of hard tissue failure. It is estimated that 70%–80% of biomedical implants are made of metallic materials. Metallic implants are remarkably important for the reconstruction of failed hard tissue and the market growth rate remains at around 20% and 25% [1]. The population ratio of the aged people of representative countries is rapidly growing. With the increasing cases of fracture, the need for bone replacement (orthopedic implants) increased. More than 7 million implant system has been placed in the human body, more than 1,000,000 implantansi spinal rod has been carried out between 1980-2000. Not only replacement surgery is growing, but also implant revision surgery on the hip and knee. It is estimated that the number of hip revision surgery increased by up to 137% and knee revision surgery increased by 607% between the years 2005 to 2030 [2].

Metallic biomaterials have essentially three fields of use; these are the artificial hip joints, screw, plates and nails for internal fixation of fractures, and dental implants. Any of these devices must support high mechanical load and resistance of material against breakage is essential. High mechanical properties are needed for structural efficiency of surgical and dental implants [2], [3].The use of titanium alloys is due to their excellent corrosion resistance. Also, that is because of their tensile strength, a high strength to weight ratio and low elastic modulus. Titanium continues to be widely used in biomedical applications. Ti-6Al-4V alloy is the most frequently used these days [2]-[4].

Research lately has been focusing on reducing Young'smodulus and tensile properties of Ti-6Al-4V alloy.Since mechanical and tribological characteristics of Ti-6Al-4V alloy are most compatible with bone characteristics, in comparison with other biometallic materials such as stainless steels and Co-Cr based alloys [5].The strength as well as Young's modulus of titanium alloys is a very important factor for their long-termuse in implants for biomedical applications. However, it has been a problem that, there is a contradiction between the elastic modulus and other mechanical properties. When the elastic modulus is reduced, the strength of the titanium alloy is also decreased. Conversely, when the strength is enhanced, the elastic modulus is alsoincreased.

The yield strength and tensile strength of Ti-6Al-4V is significantly improved by conducting aging treatment after solution treatment or thermo-mechanical processing including severe cold working followed by aging treatment. These series of heat treatment is improved the mechanical biocompatiblity of alloy. With regard to the mechanical biocompatibility, Young's modulus is the major factor, and its value for the alloy should be equivalent to that of the cortical bone in order the stress transfer between an implant device and a bone tobe homogeneous. When the Young's modulus of the implant device and the bone are different, it will result stress shielding phenomenon. Stress shielding causes loosening of the implants such as in artificial joints or couses bone refracture after extraction of the implants. [3]-[8].

In the previous study, Morita *et. al.* [9] investigated the effect of *short-time duplex heat treatment* on the mechanical properties of the Ti-6Al-4V alloy, consisting of solution-treated at 1203 K for 60 s in air and water-quenched, and aged at 753–953 K for 40 s–16.2 ks. As a results, the heat treatments consisting of solution treatment at 1203 K for 60 s and water-quenching, the tensile strength of Ti–6Al–4V alloy was improved with an increase of ductility and subsequent aging at 753–953 K for 40 s further improved both the yield strength and tensile strength of the solution treated materials. The most appropriate heat treatment conducted in this study was the heat treatments consisting of short-time solution treatment at 1203 K for 60 s and aging at 853 K for 40 s. With these series of heat treatment, the yield strength and tensile strength were each increased by about 25% and the reduction of area was slightly increased, by about 9%.

2. Materials and Methods

The chemical composition of Ti-6Al-4V alloy used in this study shown in Table 1(based on observation in SEM Hitachi S-3400N).

Table 1. Chemical Compositions of Ti-6Al-4V Alloys in this Study (% Mass)

Al	V	Ti	balance
5,76	3,91	88,58	1,75

The tensile tests were conducted on transverse oriented test specimens. The specimen for tensile properties test prepared conformance to ASTM E-8, the tension testing methods for metallic material at room temperature, (small-sizes specimen proportional to standard), Fig. 1. The material was supplied as round bars (diameter: 6 mm) and machined to the twenty two specimen shapes shown in Fig. 2. (non-treated = 2 pieces, for solution treatment = 2 pieces, and for the series of solution annealing treatment and subsequent aging = 18 pieces). Specimens machined in CNC EMCO TU 2A type lathe machine.

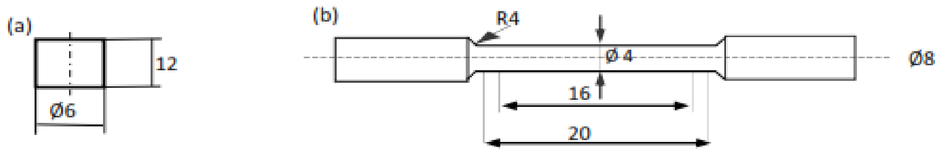

Fig. 1. Geometric and size for micro speciment tensile test (mm)

2.1. Short-time Solutions Treatment and Subsequent Short-time Aging

For the short-time solution treatment, the specimens were kept at 1203 K for 60 s (heating time was choosen 480 s) and quenched (quenching time was choosen>20 s) [11], [12]. Then, these specimens were subsequent aged at temperature 490, 510 and 530 ^{o}C (763, 783 and803 K), for 40 s (heating time was choosen : 720 s) and air cooled (Fig. 3.3) [11], [12]. All of these specimens heat treated in electric vacuum furnace (NEY CERAMFIRE S, T_{max}= 1200 °C / 2292 °F).

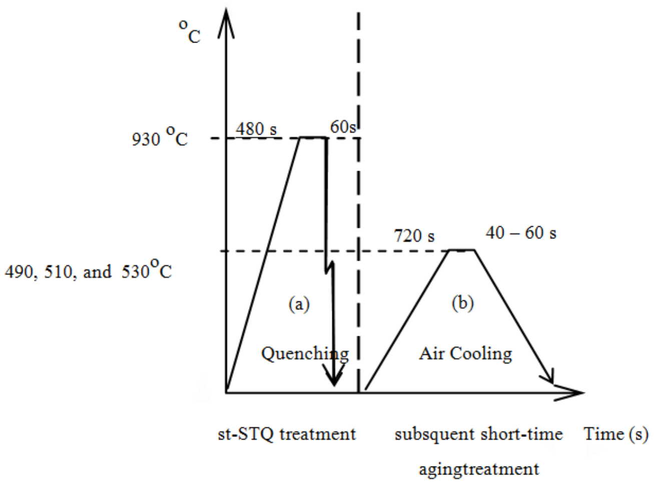

Fig. 2. Conditions of (a) short-time solution treatment and (b) subsequent short-time aging

2.2. Tensile Test

The tensile properties of non-treated, solution annealing treated and subsequent aging treated of Ti-6Al-4V alloy obtained from tensile test. Uniaxial tensile tests were performed on a fully-automated, closed-loop servo-hydraulic mechanical test machine [GALDABINI] using a 100 KN load cell. The tests were conducted in the room temperature, laboratory air (relative humidity of 55%) environtment.

The test specimens were deformed at a constant strain rate of 0·0001/sec. An axial 16.0-mm gage length hold-on specimen holder of machine. The stress and strain measurements, parallel to the load line, and the resultant mechanical properties of stiffness, strength (the yield strength and ultimate tensile strength), and ductility (quantified as strain-to-failure) was provided as a computer output by the control unit of the test machine.

3. Results and Discussion

3.1. Short-time Solution Treatment and Subsequent Short-time Aging for 40 s

Tensile properties of the Ti-6Al-4V alloy obtained from tensile test on the longitudinal oriented specimens. Tensile test conducted to alloys were heat treated by shor-time solution treatment and subsequent aging at various temperature in vacuum furnace, they are 490, 510 dan 530 ^{o}C for 40 s. It was used two heat treated and fully polished specimens for each temperature and the results of test shown in the Table 2.

Table 2. The Changing in Tensile Properties of Ti-6Al-4V with Short-time Solution Treatment and Subsequent Short-time Aging for 40 s

No.	Type of treatment	Yield Strength, $_{ys}$ (MPa)	Tensile Strength, $_{ts}$ (MPa)	Elongation (m/m)	Reduction of Area (m^2/m^2)	Yield Ratio $_{ys}/_{ts}$	Young Modulus, E (GPa)	Ductility (m/m)
1	Non	1005	1086	0,145	0,34	0,93	100	0,14
2	STQ	1087	1187	0,153	0,47	0,92	133	0,15
3	490 °C	1160	1286	0,122	0,36	0,90	96	0,15
4	510 °C	1045	1129	0,122	0,36	0,93	102	0,15
5	530 °C	1282	1377	0,122	0,37	0,93	87	0,15

The results of tensile test which summarized on Table 2, shown the changing in tensile properties of heat treated alloy by short-time solution treatment and subsequent short-time aging treatment for 40 s. Representative changing in tensile properties of alloys both non-treated and heat treated shown in Fig. 2.

The yield and ultimate tensile strength values of alloys after short-time solution treatment conform to the values of non-treated ones. The values of the yield and the ultimate tensile strength obtained in this study is 7,5 % and 8,5%,respectively,higher than the valueson non-treated alloys. The yield strength increases from 1005 to 1087 MPa, while the ultimate tensile strength increases from 1086 to 1187 MPa.

Also, the reduction of area determined in this study is noticeably higher, by as much as 28%, than the value obtained in the non-treated alloys. It was increased from 34 to 47%. (as shown on Fig. 2)

By subsequent short-time aging treatment, both the yield and the tensile strength increased higher than those only short-time solution treatment. The highest yield and ultimate tensile strength value were in the alloys that heat treated by subsequent short-time aging at temperature, T = 530 °C (803 K). They were increased untill 21,6 and 21,1%, respectively. The yield strength increased from 1005 to 1282 MPa and the ultimate tensile strength increased from 1086 menjadi 1377 MPa. Whereas, the lowest ones on alloys that heat treated by short-time subsequent aging at temperature T = 510 °C (783 K). The yield and the ultimate tensile strength increased only from 1005 to 1045 MPa and 1086 MPa to 1129 MPa, respectively.

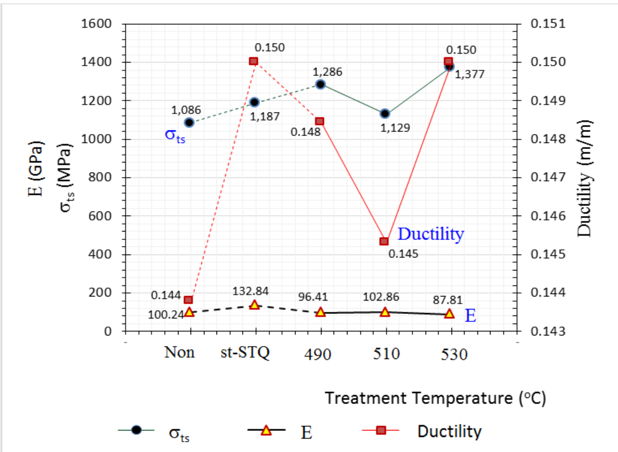

Fig. 3. The changing in tensile properties of Ti-6Al-4V with short-time solution treatment and subsequent short-time aging for 40 s.

Also,on the heat treated alloy by subsequent short-time aging at temperature 530 °C, Young's modulus determined in this study is lower, by as much as 12 %, than the value obtained in the non-treated alloys. It was decreased from 100 to 87 GPa. (as shown on Fig. 3). it is lower than Young's Modulus values on two others subsequentshort-time aging temperature in this study t hat decreased only as much as 96 and 103 GPa at aging temperature 490 and 510 °C, respectively. The ductility were not decreased for three of temperature of subsequent short-time aging treatments.

3.2. Short-time Solution Treatment and Subsequent Short-time Aging for 50 s

The results of tensile test conducted to alloys which was heat treated by short-time solution treatment and subsequent short-time aging at various temperatures in vacuum furnace, they were 490, 510 and 530 °C for 50 s shown in Tabel 3.

Table 3. The Changing in Tensile Properties of Ti-6Al-4V with Short-time Solution Treatment and Subsequent Short-time Aging for 50 s.

No.	Type of treatment	Yield Strength, σ_{ys} (MPa)	Tensile Strength, σ_{ts} (MPa)	Elongation ε(m/m)	Reduction of Area ϕ (m^2/m^2)	Yield Ratio σ_{ys}/σ_{ts}	Young Modulus, E (GPa)	Ductility (m/m)
1	Non	1005	1086	0,145	0,340	0,926	100	0,144
2	STQ	1087	1187	0,153	0,465	0,915	133	0,150
3	490 °C	1253	1363	0,127	0,370	0,919	93	0,144
4	510 °C	1096	1203	0,127	0,339	0,911	99	0,147
5	530 °C	1044	1183	0,113	0,330	0,966	81	0,142

By subsequent short-time aging treatment, both the yield and tensile strength increased higher than those only short-time solution treatments. The highest yield and ultimate tensile strength values in this study were in the heat treated alloys by subsequent short-time aging at temperature, T = 490 °C (783 K) for 50 s. They were increased untill 19,8 and 20,3%, respectively. The yield strength increased from 1005 to 1253 MPa and the ultimate tensile strength increased from 1086 menjadi 1363 MPa. Whereas, the lowest yield and ultimate tensile strength were on heat treated alloys by subsequent short-time aging at temperature T = 510 °C (783 K). The yield and ultimate tensile strength increased only from 1005 to 1044 MPa and 1086 MPa to 1183 MPa, respectively (Fig. 4).

Also, on the heat treated alloy by subsequent short-time aging at temperature T = 530 °C (803K) for 50 s, Young's modulus determined in this study is noticeably lower, by as much as 19 %, than the value obtained in the non-treated alloys. It was decreased from 100 to 81 GPa. But in this condition of treatment, the ductility of material was slightly decreased from 14,4 to 14,2 %. It was different from two others short-time subsequent aging temperature of treatment, the ductility were not changed at temperatur 490 °C, it was same as by non-treated alloy, it was 14,4%. Whereas, at the aging temperature 510°C, the ductility increased to 14,7%. Although the ductility is not decreased, but in this two subsequent short-time aging treatment, the Young's Modulus were higher. The were 93 and 99 GPa at temperature of treatment 490 and 510 °C, respectively (as shown on Fig. 3 or as they were explained in Table 3).

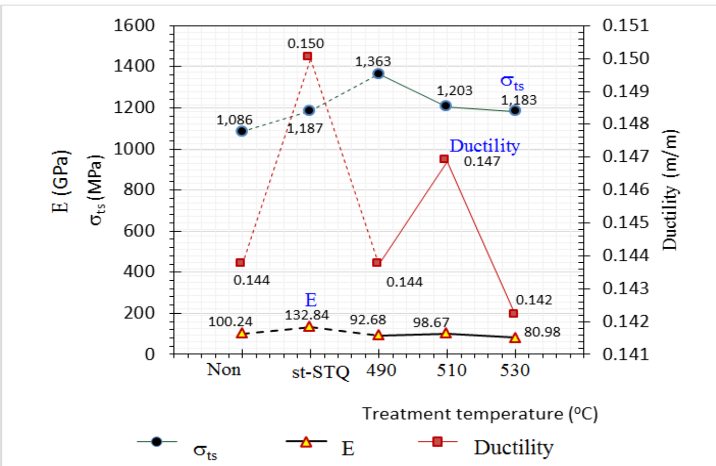

Fig. 4. The changing in tensileproperties of Ti-6Al-4V with short-time solution and subsequent short-time aging for 50 s.

3.3. Short-time Solution Treatment and Subsequent Short-time Aging for 60 s

The results of tensile test conducted to alloys which were heat treated by short-time solution treatment and subsequent short-time aging at various temperature in vacuum furnace: 490, 510 dan 530 °C for 60 s shown in Table 4.

By subsequent short-time aging treatment, both the yield and the tensile strength also increased higher than those only short-time solution treatment alloys in this study. The highest increasing in yield and ultimate tensile strength values in this study are in the heat treated alloys by subsequent aging treatment at temperature, T = 490 °C (783 K). They were increased 12 and 10%, respectively. The yield strength increased from 1005 to 1142 MPa and the ultimate tensile strength increased from 1086to1205 MPa. Whereas, the lowest yield and ultimate tensile strength were on heat treated alloys by subsequent aging treatment at temperature T = 510 °C (783 K). The yield and the ultimate tensile strength increased only from 1005 to 1013 MPa and 1086 MPa to 1094 MPa, respectively (Fig. 5).

Table 4. The Changing in Tensile Properties of Ti-6Al-4V with Short-time Solution Treatment and Subsequent Short-time Aging Treatment for 60 s.

No.	Type of treatment	Yield Strength, σ_{ys} (MPa)	Tensile Strength, σ_{ts} (MPa)	Elongation ε(m/m)	Reduction of Area ϕ (m^2/m^2)	Yield Ratio σ_{ys}/σ_{ts}	Young Modulus, E (GPa)	Ductility (m/m)
1	Non	1005	1086	0,145	0,340	0,926	100	0,144
2	STQ	1087	1187	0,153	0,465	0,915	133	0,150
3	490 °C	1142	1205	0,127	0,360	0,948	98	0,141
4	510 °C	1013	1084	0,134	0,350	0,934	111	0,142
5	530 °C	1064	1125	0,117	0,350	0,946	108	0,144

Also, on the heat treated alloy by subsequent short-time aging treatment at temperature T = 490 °C (763K), Young's Modulus determined in this study is slightly lower, by as much as 2 %, than the value obtained in the non-treated alloy. It was only decresed from 100 to 98GPa. Except at the aging temperature 510°C and 530°C, the Young's modulus not decreased, but they were increased from 100 to 110 and 108 GPa, respectively (as shown on Fig. 5 or as they were explained in Table 4).

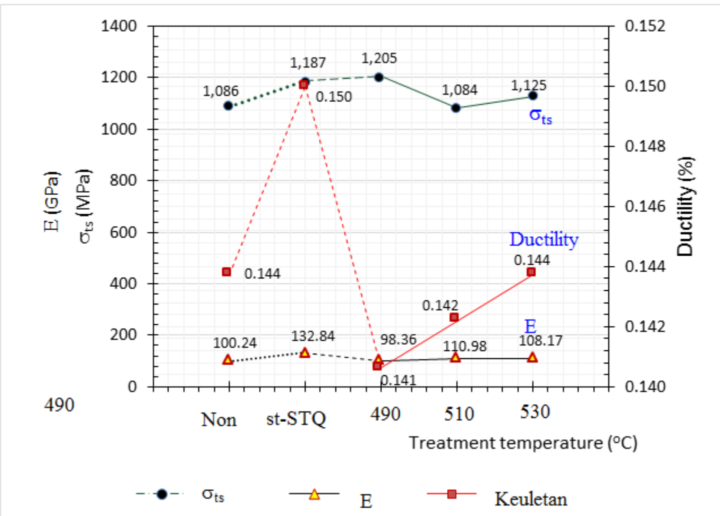

Fig. 5. The changing in the tensile properties of Ti-6Al-4V with short-time solution treatment and subsequent short-time aging treatment for 60 s.

Based on the result of the study known that static strength of solution treated alloys in the (α+β) phase field were increased. Then, the static strength increased higher at short-time subsequent aging treatment alloys. The highest increasing in the yield and the ultimate tensile strength values in this study were in the heat treated alloys by subsequent short-time agingtreatment at temperature 530 ^{o}C (803 K) for 40 s. They are 21,6 and 21,1%, respectively without decreasing in ductility. While the lowest Young's Modulus are in the heat treated alloys by subsequent aging treatment at temperature 530 ^{o}C (803 K), for 50 s, namely 19 %, althought, the decreasing in Young's modulus followed by slightly decreasing in ductility. But it was still recomended as optimum series of heat treatment to obtain Ti-6Al-4V alloy that compatible for orthopaedic implants.

It was concluded that the optimum series of heat treatment in for orthopaedic implant materials were in the Ti-6Al-4V alloys that heat treated by short-time solution treatment at 930 ^{o}C (1203K) for 60s and followed by short-time aging treatment at temperature 530 ^{o}C (803 K) for 50 s, which were the static strength increased, while the Young's modulus decreased from 100 GPa to 81 GPa without decreasing in ductility.

It is thought that the above remarkable strengthening and decreasing in Young's modulus is mainly due to the refinement of prior β phase resulting from the formation of α' phase and the precipitation of fine α phase through the short-time solution treatment and subsequent short-time aging treatment [9], [10].

4. Conclusion

Based on the results of this study known that the most optimum changing in tensile properties in the study were at Ti-6Al-4V alloy conducted heat treatment consisting of short-time solution treatment at 930 ^{o}C (1203 K) for 60 s and followed by short time aging treatment at 530^{o}C (803 K) for 50 s. With these series of heat treatment the Young's modulus were decreased, by about 19 %.

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