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The Effects of Short-Time Solution Treatment and Short-Time Aging on Mechanical Properties of Ti-6Al-4V for Orthopaedic Applications

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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 result showed optimum heat treatments were solution treatment at 930 oC (1203 K) for 60 s and subsquent aging at 530 oC (803 K) for 40 s; 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 12%.**

***Keywords*—Ti-6Al-4V, short-time solution treatment, short-time aging, mechanical properties.**

I. INTRODUCTION

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],[3].

Research lately has been focusing on reducing Young's modulus 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-term use 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 also increased.

The yield strength and tensile strength of Ti-6Al-4V is significantly improved over the years by conducting aging treatment after solution treatment or thermo-mechanical processing including severe cold working followed by aging treatment. This 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 is not homogeneous when Young's moduli of the implant device and the bone are different (Stress shielding phenomenon). Stress shielding causes loosening of the implants such as artificial joints or bone re-fracture after extraction of the implants. [3]-[5].

In the previous study, Morita *et. al.* [7] 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 result, the STQ treatment 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 STQ-treated material. The most appropriate heat treatment conducted in this study was the STA treatment consisting of STQ treatment at 1203 K for 60 s and aging at 853 K for 40 s. With this 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%.

In the other study, Morita *et al.* [9] investigated the effect of duplex heat treatment on microstructure and fatique strength of Ti-6Al-4V, consisting of STQ treatment at 1203 K for 60 s and short-time aging at at 753, 803, 853 and 903 K for 40 s and air-cooled. As a result, the short-time duplex heat treatment greatly increased the tensile strength and fatigue strength of Ti-6Al 4V alloy without reduction in ductility. The most appropriate heat treatment was composed of STQ treatment at 1203 K for 60 s and short-time aging at 803 K for 40 s. Through this duplex heat treatment, the improvement rates of the tensile strength and fatigue strength reached 29 % and 22 %, respectively [9].

From the above back ground, this study comprehensively investigated the effects of the short-time solution treatment and subsequent short-time aging on mechanical properties of Ti-6Al-4V alloy at the lower aging temperatur then previous study. For the heat-treated materials, we carried out tensile tests.

II. Material and Methods

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

TABLE I
CHEMICAL COMPOSITIONS OF TI-6AL-4V ALLOY IN THIS STUDY (% MASS)

Al	V	Ti	Others
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) [13]. The material was supplied as round bars (diameter: 6 mm) and machined to the twenty two specimen shapes shown in Figure 1: (non-treated = 2 pieces, for solution treatment = 2 pieces, and for the series of solution annealing treatment and subsquent aging = 18 pieces). Specimens machined in CNC EMCO TU 2A type lathe machine.

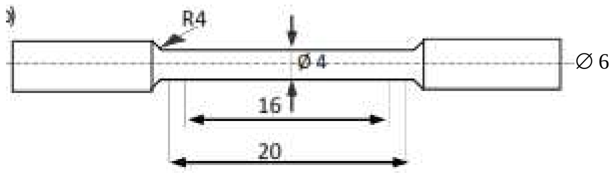

Fig. 1 Geometric and size for micro specimen tensile test (mm).

A. Short-time Solutions treatment and Subsquent Short-time Aging

For the short-time solution treatment, the specimens were kept at 1203 K for 60 s (heating time choosed 480 s) and quenched (quenching time choosed >20 s) [18]. These specimens were subsequent aged at temperatur 490, 510 and 530 ^{o}C (763, 783 and 803 K), for 40 s (heating time : 720 s) and air cooled (Fig. 2) [11],[12]. The specimen heat treated in electric vacuum furnace (NEY CERAMFIRE S, T_{max}= 1200 °C / 2292 °F).

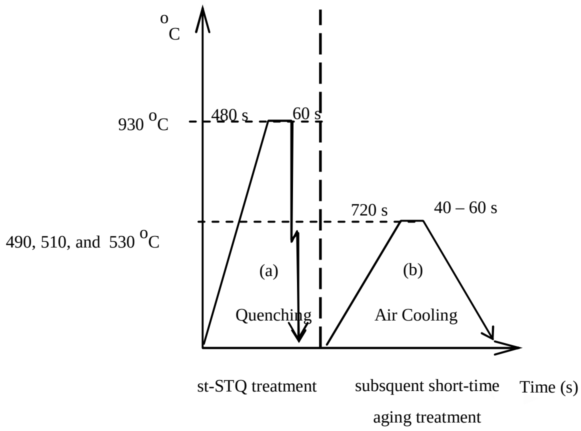

Fig. 2. Conditions of (a) short-time solution treatment and (b) subsquent short-time aging

B. Tensile Test

Tensile properties of nun-treated and solution annealing treated and subsquent 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%) environment.

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 (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.

III. RESULTS AND DISCUSSION

A. Short-time Solution Treatment And Subsquent Short-time Aging for 40 s

Tensile properties of the Ti-6Al-4V alloy obtain from tensile test on the longitudinal oriented specimens. Tensile test conducted to alloys were heat treated by shor-time solution treatment and subsquent aging at various temperature in vacuum furnace, they are 490, 510 dan 530 °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 II.

TABLE III
CHANGE IN MECHANICAL PROPERTIES OF TI-6AL-4V WITH SHORT-TIME SOLUTION TREATMENT AND SUBSEQUENT SHORT-TIME AGING FOR 40 S

No.	Type Treat-ment	σ_{ys}	σ_{ts}	ε	ϕ	$\frac{\sigma_{ys}}{\sigma_{ts}}$	E	Duc.
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 4.1 shown the changing in tensile properties of heat treated alloy by short-time solution treatment subsequent short-time aging treatment for 40 s. Representative changing in tensile properties alloy both untreated and heat treated shown in Figure 2.

The yield and ultimate tensile strength values of alloys after short-time solution treatment conform to the values of untreated one. The values of the yield ultimate tensile strength obtained in this study is 7,5 % and 8,5% higher than the values on untreated alloy respectly. 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 untreated alloy. It was increased from 34 to 47%. (as shown on Figure 3.1)

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

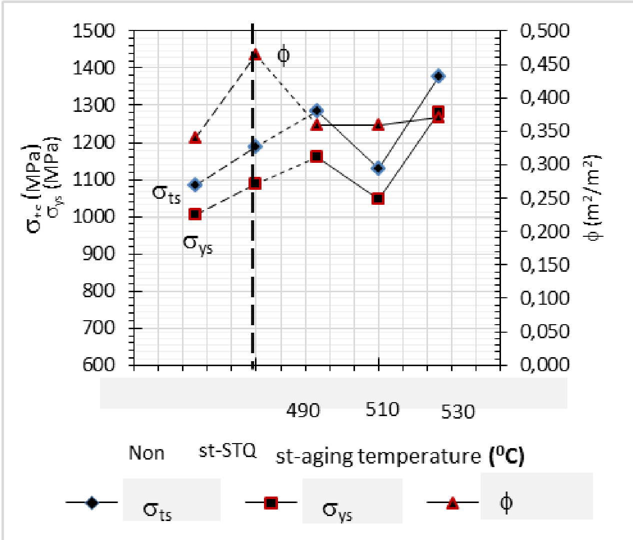

Fig. 3 Change in mechanical properties of Ti-6Al-4V with short-time solution treatment and subsequent short-time aging for 40 s.

Figure 3 shows the heat treated alloy by subsquent short-time aging, elongation determined in this study is noticeably higher, by as much as 6,6%, than the value obtained in the untreated alloy. It was increased from 14 to 15 %.

Also, ductility of subsquent short-time aging alloy determined in this study is noticeably higher, by as much as 6,6%, than the value obtained in the untreated alloy. It was increased from 14 to 15 %. The yield ratio of Solution treatment alloy decreased from 0,93 to 0,92 at temperature 510 °C (783 K).

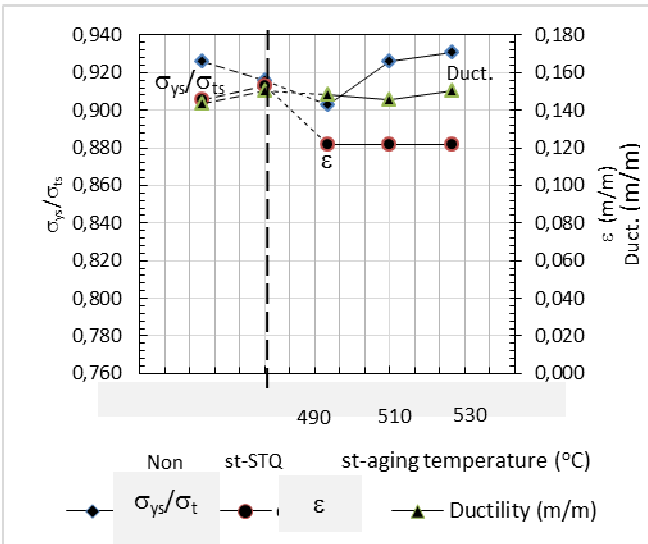

Fig. 4 Change in yield ratio, elongation and ductility of Ti-6Al-4V alloy with short-time solution treatment and subsequent short-time aging for 40 s.

B. Short-time Solution Treatment And Subsquent Short-time Aging for 50 s

Results of tensile test conducted to alloys which is heat treated by Solution treatment and subsquent aging at various temperature in vacuum furnace, they are 490, 510 dan 530 °C for 50 s is shown in Table III.

TABLE III
CHANGE IN MECHANICAL PROPERTIES OF TI-6AL-4V WITH SHORT-TIME SOLUTION TREATMENT AND SUBSEQUENT SHORT-TIME AGING FOR 50 S.

No.	Type Treat-ment	σ_{ys}	σ_{ts}	ε	ϕ	$\frac{\sigma_{ys}}{\sigma_{ts}}$	E	Duc.
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	1253	1363	0,127	0,37	0,92	93	0,14
4	510 °C	1096	1203	0,127	0,34	0,91	99	0,15
5	530 °C	1044	1183	0,113	0,33	0,97	81	0,14

By subsquent short-time aging treatment, both yield and tensile strength increased higher than those only sohor-time solution treatment. The highest yield and ultimate tensile strength value in this study are in the heat treated alloys by subsquent Short-time aging at temperature, T = 490 °C (783 K). They are 19,8 and 20,3%, respectively. The yield strength increased from 1005 to 1253 MPa and ultimate tensile strength increased from 1086 menjadi 1363 MPa. Whereas, the lowest yield and ultimate tensile strength are on heat treated alloys by subsquent 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 (Figure 5).

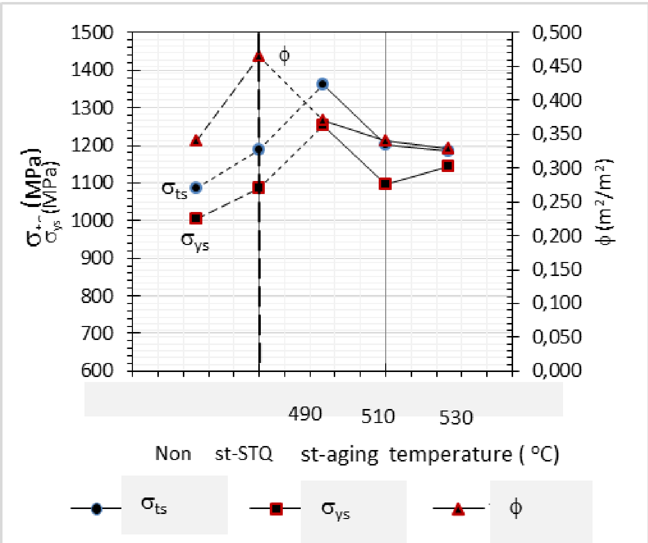

Fig. 5 Change in mechanical properties of Ti-6Al-4V with short-time solution treatment and subsequent short-time aging for 50 s.

Also, on the heat treated alloy by subsquent short-time aging at temperature T = 490 °C (783 K), reduction of area determined in this study is noticeably higher, by as much as 8,1%, than the value obtained in the untreated alloy. It was increased from 34 to 37 %. Except at the aging temperature 510 °C, the reduction of area not changed, same as untreated alloy. Whereas, at the aging temperature 530 °C in this study decreased to 33% (as shown on Figure 6 or explained in Table III) .

Figure 6 shows the change in tensile properties of alloy due to subsquent short-time aging treatment. Elongation determined in this study is noticeably lower, by as much as 13 to 27%, than the value obtained in the untreated alloy. It was decreased from 15 to 13 % in the subsequent aging temperature of 490, 510 °C and 15 to 11% at 530 °C.

Also, ductility of subsquent Short-time aging alloy determined in this study is noticeably higher, by as much as 6,6%, than the value obtained in the untreated alloy. It was increased from 14 to 15 %. Also, the yield ratio determined in this study is higher, by as much as 4,1%, than the value obtained in the untreated alloy. It was increased from 0,93 to 0,97 only at temperature 530 °C (803 K) on this study.

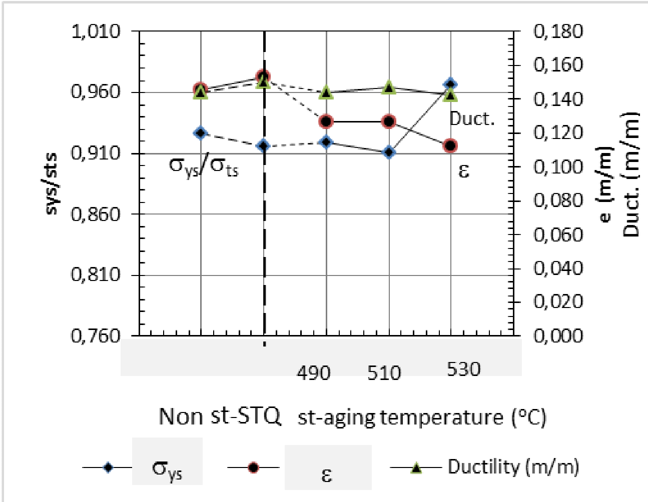

Fig. 6 Change in yield ratio, elongation and ductility of Ti-6Al-4V alloy with short-time solution treatment and subsequent short-time aging for 50 s.

C. Short-time Solution Treatment And Subsequent Short-time Aging for 60 s

Results of tensile test conducted to alloys which is heat treated by Short-time solution and subsquent short-time aging at various temperature in vacuum furnace, they are 490, 510 dan 530 °C for 60 s is shown in Table IV.

TABLE IV
CHANGE IN MECHANICAL PROPERTIES OF TI-6AL-4V WITH SHORT-TIME SOLUTION TREATMENT AND SUBSEQUENT SHORT-TIME AGING FOR 60 S.

No.	Type Treat-ment	σ_{ys}	σ_{ts}	ε	ϕ	$\frac{\sigma_{ys}}{\sigma_{ts}}$	E	Duc.
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	1142	1205	0,127	0,36	0,95	98	0,14
4	510 °C	1013	1084	0,134	0,35	0,93	111	0,14
5	530 °C	1064	1125	0,117	0,35	0,95	108	0,14

By subsquent short-time aging treatment, both yield and tensile strength also increased higher than those only Short-time solution treatment in this study. The highest increasing yield and ultimate tensile strength values in this study are in the heat treated alloys by subsquent Aging at temperature, T = 490 °C (783 K). They are 12 and 10%, respectively. The yield strength increased from 1005 to 1142 MPa and ultimate tensile strength increased from 1086 menjadi 1205 MPa. Whereas, the lowest yield and ultimate tensile strength are on heat treated alloys by subsquent Aging at temperature T = 510 °C (783 K). The yield and ultimate tensile strength increased only from 1005 to 1013 MPa and 1086 MPa to 1094 MPa, respectively (Figure 7).

Also, on the heat treated alloy by subsquent short-time aging at temperature T = 490 °C (763 K), reduction of area determined in this study is higher, by as much as 5,5%, than the value obtained in the untreated alloy. It was increased from 34 to 36 %. Except at the aging temperature 510 °C and 530 °C in this study increased from 34 to 35% only (as shown on Figure 7 or as explained in Table IV) .

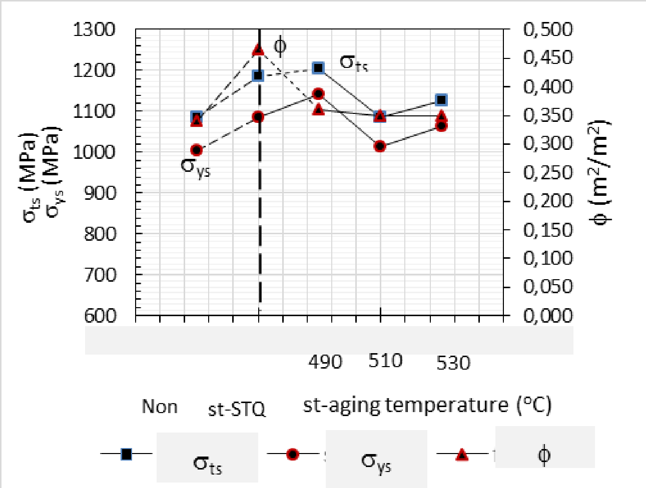

Fig. 7 Change in mechanical properties of Ti-6Al-4V with short-time solution treatment and subsequent short-time aging for 60 s.

Also, the yield ratio determined in this study is higher, by as much as 11 to 21%, than the value obtained in the untreated alloy. It was increased from 0,93 to 0,94 at aging temperature 490 and 530 °C (763 to 803 K) and not changed in aging temperature 510 °C.

Figure 8 shows the change in tensile properties of alloy due to subsequent short-time aging treatment. Elongation determined in this study is noticeably lower, by as much as 13 to 20%, than the value obtained in the untreated alloy. It was decreased from 15 to 13 % in the subsequent aging temperature of 490, 510 °C and 15 to 12% at 530 °C. Then, the ductility of subsquent short-time aging alloy determined in this study is not changed than the value obtained in the untreated alloy. It is as much as 15%.

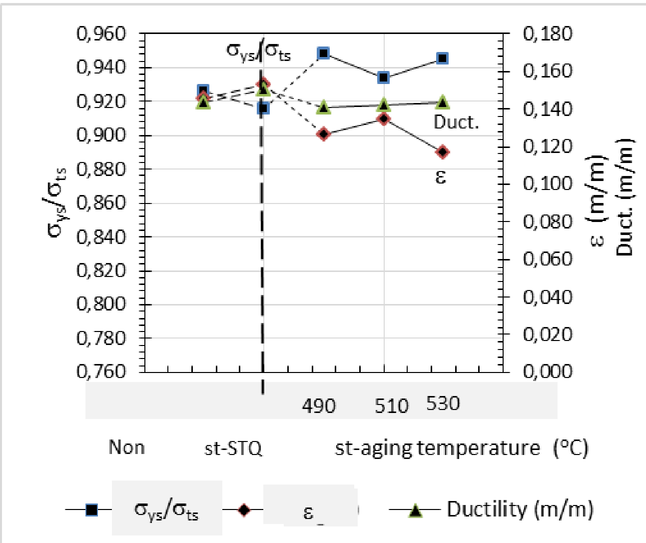

Fig. 8 Change in yield ratio, elongation and ductility of Ti-6Al-4V alloy with short-time solution tretment and subsequent short-time aging for 60 s.

Based on results of study known that static strength of solution treated materials in the *(α+β)* phase field were increased. The static strength increased higher at Short-time subsequent aging treatment materials. The highest increasing yield and ultimate tensile strength values in this study are in the heat treated alloys by subsequent aging at temperature 530 °C (803 K). They are 21,6 and 21,1%, respectively.

It is thought that the above remarkable strengthening 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 [7],[8].

IV. Conclusions

Based on results of study known that the most optimum changing in mechanical properties in the study were at Ti-6Al-4V alloy conducted heat treatment consisting of short-time solution treatment at 930 °C (1203 K) for 60 s and subsequent aging at 930 °C (803 K) for 40 s. With this heat treatment, the yield strength and tensile strength were each increased by about 21,6% and 21,1%. Then, the reduction of area and elastic modulus were each slightly increased, by about 8% and 12%.

Nomenclature

E	Young modulus	GPA
Duct.	ductility	m/m

Greek letters

σ	strength	MPa
ϕ	reduction of area	m^2/m^2
ε	elongation	m/m

Subscripts

ys	yield strength
ts	tensile strength

Greek letters with subscripts

σ_{ys}/σ_{ts} yield ratio

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