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Research Article

Effect of Heat Treatment on the Mechanical Properties of a 3 mm Commercially Pure Titanium Plate (CP-Ti Grade 2)

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Titanium is seen as a good material for application in many fields due to its compatibility with different environments. However, it remains unclear whether what happens when this material is exposed to certain high temperatures for longer periods of time. The primary objective of this study was to investigate the effect of heat on a 3 mm commercially pure titanium grade 2 plate at a constant temperature of 900°C at different heating times. Three different heating times were employed in this study: 30 minutes for the first period, 60 minutes for the second period, and 90 minutes for the third period. All heated samples were air cooled to room temperature after each heating period. Microhardness, microstructure, tensile strength, and scanning electron microscopy (SEM) tests were performed. All the results were analyzed and compared with the parent sample. It was observed that the heating period influenced microstructural arrangement of the material. The microstructural changes affected negatively the ultimate tensile strength while percentage elongation was improved. The microhardness of the heat treated samples were firstly negatively affected which later jumped and exceeded that of the parent material.

1. Introduction

The major stimulus for titanium to be used in various engineering fields is its high specific strength and temperature strength within a wide temperature range. Titanium and its alloys have been dominating aerospace, automotive, and marine industries [1–4]. It is an undeniable fact that the mechanical properties being exhibited by titanium and its alloys come from the microstructural arrangement. There are various factors that can influence or modify the microstructural arrangement of metals. This includes thermal treatments and mechanical treatments [4–7]. Titanium and its alloys are composed of three structural forms being alpha (α), beta (β), and alpha-beta (α, β). Within the titanium alloy, aluminium is the alpha-phase stabilizer, whereas vanadium is the beta-phase stabilizer [8–12]. Commercially pure titanium (CP-Ti) undergoes an allotropic transformation at 882.5°C and transforms from a hexagonal close pack (HCP) crystal structure to body-centered cubic (BCC) [13–16]. There are numerous studies that were conducted to understand the impact heat and mechanical treatments on various properties of titanium and its alloys. This includes the work by Milner et al. [17] where the influence of warm accumulative roll bonding on grains and mechanical properties of CP-Ti (grade 2) were studied. The grain refinement was observed from the second cycle of accumulative roll bonding (ARB) and this resulted to improved tensile strength with a significant drop in elongation. Najdahmadi et al. [18] have investigated changes in the mechanical properties of titanium-29 niobium-13 tantaium-4.6 zirconium (Ti-29Nb-13Ta-4.6Zr) alloy through heat treatment and different cooling techniques and discovered that heat-treated samples contained equiaxed beta grains. It was further discovered that samples quenched in the liquid nitrogen produced smaller grain sizes compared to the samples cooled in the heater. The samples cooled using other media exhibited higher tensile strength with the compromise in ductility. However, the samples cooled through nitrogen liquid exhibited high tensile strength without compromising ductility.

El-Hadad et al. [19] studied the influence of heat treatment on the mechanical properties of Ti6Al4V alloy. It was discovered that the heat-treated samples followed by water quenching resulted in an increased hardness compared to the air-cooled and aged samples. Wachowski et al. [20] have investigated the impact of heat treatment on the surface fracture of explosively welded commercially pure titanium grade 1 with carbon steel plates. They discovered that the application of heat treatment on the welded steel-Ti plates yielded positive and negative results due to the formation of intermetallic compounds. There was a notable decrease in hardness post heat treatment and this decrease was attributed to decarburization mechanism. Huang et al. [21] did an investigation on the impact of microstructures on the notch tensile strength of heat-treated Ti-6Al-6V-2Sn alloy. The supratransus and subtransus temperature was used in treating the solution followed by water quenching and aging. It was discovered that the water quenching of heat-treated samples resulted in the formation of titanium martensite which then decomposed into various sizes of alpha and beta phases during aging. It was further discovered that the increase in aging temperature resulted to an increase in notch tensile strength in all samples. Catherine and Abdul Hamid [22] studied the behaviour of the tensile strength and ductility of pure Ti grade 2 after heat treatment. The two annealing temperature were used, i.e., 700°C and 900°C, and all the samples were exposed to these temperatures for 1 hr. The formation of acicular martensite was observed on specimens treated with 900°C, and this type of martensite was triggered by higher level of oxidation occurring at the temperature above the beta transus. The decrease in tensile strength with an increase in ductility was also observed on the specimens treated at 700°C.

Zheng et al. [23] examined the impact of heat on tensile properties of thin pure titanium foils. The tensile tests were conducted on specimens at different temperatures and those temperatures were induced through the resistance heating method. It was discovered that the increase in temperature during tensile tests resulted in the decrease in tensile strength for foils with larger grains. However, this inverse relationship was valid at the temperature below 300°C. Different patterns were observed at the temperature above 300°C, i.e., an increase in tensile strength was observed on specimens comprised of larger grains. Wang et al. [24] have investigated the impact of heat treatment on the microstructure and mechanical properties of Ti-6Al-4V alloy. The microstructural observations did not show much difference for various temperatures. However, different phases were observed from different heat treatments, and those phases contributed to the enhancement of mechanical properties of Ti-6Al-4V alloy. The effect of different heat treatment on the mechanical properties of Ti-6Al-4V was investigated by Wanying et al. [25]. The heat treatment occurred at above 900°C which resulted in the formation of lamellar beta phase and alpha structures which in turn contributed to the enhancement of mechanical properties. A similar observation was also reported by number of researchers [26–32].

It has been observed that the majority of the works deals with heat treatment on titanium alloys. However, there are very few reports on the application of heat treatment on commercially pure titanium grade 2. Some of the works that reports on heat treatment of titanium and its alloys focused on heating the specimens and then employing aging technique. This paper presents the effects of constant heat treatment at different heating times on the mechanical properties of commercially pure grade 2 titanium plates. This is aimed at studying the microstructure in correlation with the mechanical properties of CP-Ti grade 2.

2. Materials and Methods

Commercially pure titanium (CP-Ti) grade 2 was utilized in this study. The mechanical properties and chemical composition are shown in Tables 1 and 2. The as-received CP-Ti grade 2 was prepared for various shapes suitable for various mechanical tests. The waterjet technology was used to cut 25 mm × 12 mm × 3 mm samples for microstructural analysis and microhardness tests (see Figure 1). Kroll's reagent (2 mL HF, 3.2 mL HNO_3, and 90 mL H_2O) was used in revealing the microstructure of the samples. The Motic AE2000 microscopy was employed in conducting the microstructural analysis [33–35].

The tensile samples were prepared according to the ASTME646-98, and the performance of tensile tests was also based on the same standard. The Hounsfield tensile testing machine was employed in conducting tensile tests and the constant strain rate of 3 mm/min. The samples fractured post tensile tests were then prepared for scanning electron microscopy in order to study the fracture morphology (see Figure 2).

The prepared samples were then inserted to the furnace for heat treatment. There were four sets of samples that were prepared for the entire study and each set was comprised of three samples, i.e., one sample for microhardness, one sample for tensile test, and one sample for microstructural analysis. The first set of samples was inserted to a room temperature furnace (see Figure 3) which was then heated up until the intended temperature (900°C). The stopwatch was only started when the temperature reads the intended temperature. The set of samples were allowed to cool down when the set time had elapsed.

The first set of samples were kept at 900°C for 30 minutes which was then followed by the set which was kept at the same temperature for 60 minutes and then last the samples that were exposed to 900°C for 90 minutes.

After heat treatment was concluded, all the samples were then subjected to different tests as mentioned earlier. The results from various tests are presented in the subsequent section.

3. Results and Discussion

3.1. Microstructural Analysis. Figure 4 shows the microstructure of the samples used in this investigation. The microstructure of the parent materials is shown in Figure 4(a), while Figures 4(b)–4(d) show the microstructure of the samples heat treated for 30 minutes, 60 minutes, and 90 minutes, respectively. The average grain size

Table 1: Mechanical properties of pure titanium grade 2.

Properties	Value
Tensile strength	275–410 MPa
Elongation	20%
Modulus of elasticity	105 GPa

Table 2: Chemical composition of pure titanium grade 2 (wt. %).

Fe	O	C	H	Ti
0.30	0.25	0.08	0.015	Bal

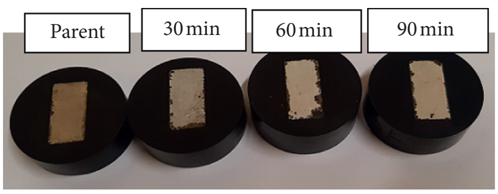


Figure 1: Mounted samples for microstructure and microhardness.

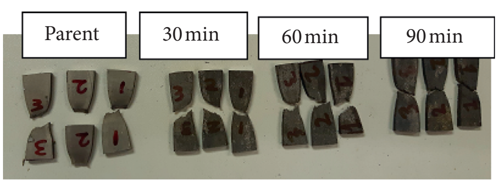


Figure 2: Prepared SEM samples.

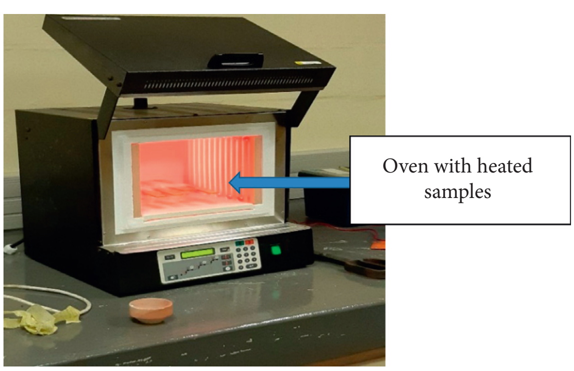


Figure 3: Furnace during heat treatment of samples.

(presented in Table 3) of each sample was measured by the use of linear intercept technique through ImageJ software [35]. The generic CP-Ti microstructure composed of alpha-phase was observed during microstructural analysis. However, the grain arrangement and grain boundaries started to be visible on the heat treated samples and this was due to the fact that there was grain growth (see Table 3).

The microstructural grains of the parent material are very fine due to high deformation that caused by forming procedure. Highly deformed grains are noticed when inhomogeneous deformation occurs between the outer and inner sheets because of the rolling procedure [22, 23]. In 30 minutes' microstructural image, signs of subgrains formed within the larger grains due to the introduction of heat were noticed. In 60 minutes' microstructural image, subgrains started to disappear but some areas showed finer grains, and this was due to the grain growth turning the subgrains in to new finer grains. With increase in heating period, fine equiaxed grains and dislocation densities are well characterised and huge amount of dislocations, shear bands, and subgrains appears (see Figure 4(d)) [25, 31, 32].

3.2. Tensile Test Analysis. Tensile tests were performed in all heat treated and untreated samples. The heat treated results were compared to the untreated samples. The summarized version of tensile test results is presented in Table 4. The stress-strain curves for parent material and heat treated samples are shown in Figures 5(a)–5(d). There was a significant drop in ultimate tensile strength (UTS) in all the heat treated samples compared to the parent material. The decrease in UTS is caused by the grain growth which is defined by the Hall–Petch relationship [26, 28, 35]. The decrease in UTS for the heat treated samples could be as the results of the annealing temperature which encouraged the transformation of alpha phase [13, 32, 36–38]. The decrease in UTS was however accompanied by the increase in percentage elongation for all the heat treated samples and this is normal in metals [13, 34–38]. The increase in percentage elongation suggests that the increase in ductility of the material [32–34].

3.3. Scanning Electron Microscope (SEM). The fractured surfaces from tensile tests were further analyzed to study the fracture mechanism of each sample. Figure 6(a) shows the fractured surface of parent material, while the heat treated samples are shown in Figures 6(b)–6(d).

The morphology of a tensile fracture surface of the parent sample (Figure 6(a)) appeared to be a bit flat without obvious cracks. There were few dimples and tiny shear lips on the surface. This then suggests that the fracture was semibrittle and semiductile. The morphology of the 30 minutes (Figure 6(b)) tensile fracture surface also showed dimples different in sizes with a large number of tearing ridges suggesting that the fracture was ductile. For 60 minutes' (Figure 6(c)) morphology, it portrayed deep shear lips and also noted ductile dimples; also, tiny cleavage facets were also noted and this is a clear indication of ductile fracture. The morphology of 90 minutes (Figure 6(d)) portrays deep shear lips, void with different sizes, facets, and also tearing ridges which indicate ductile fracture.

3.4. Microhardness. The microhardness was conducted using 500 g load and the dwelling time of 10 s with a spacing interval of 1.5 mm. The graphical presentation of microhardness results are shown in Figure 7. Figure 7(a) shows the microhardness profile of parent material, while the heat treated samples are shown in Figures 7(b)–7(d). There was a noticeable variation in microhardness points for all treated and untreated samples. The variation in microhardness values was attributed to the fact that all 15 points for hardness measurement were selected randomly on the surface of the

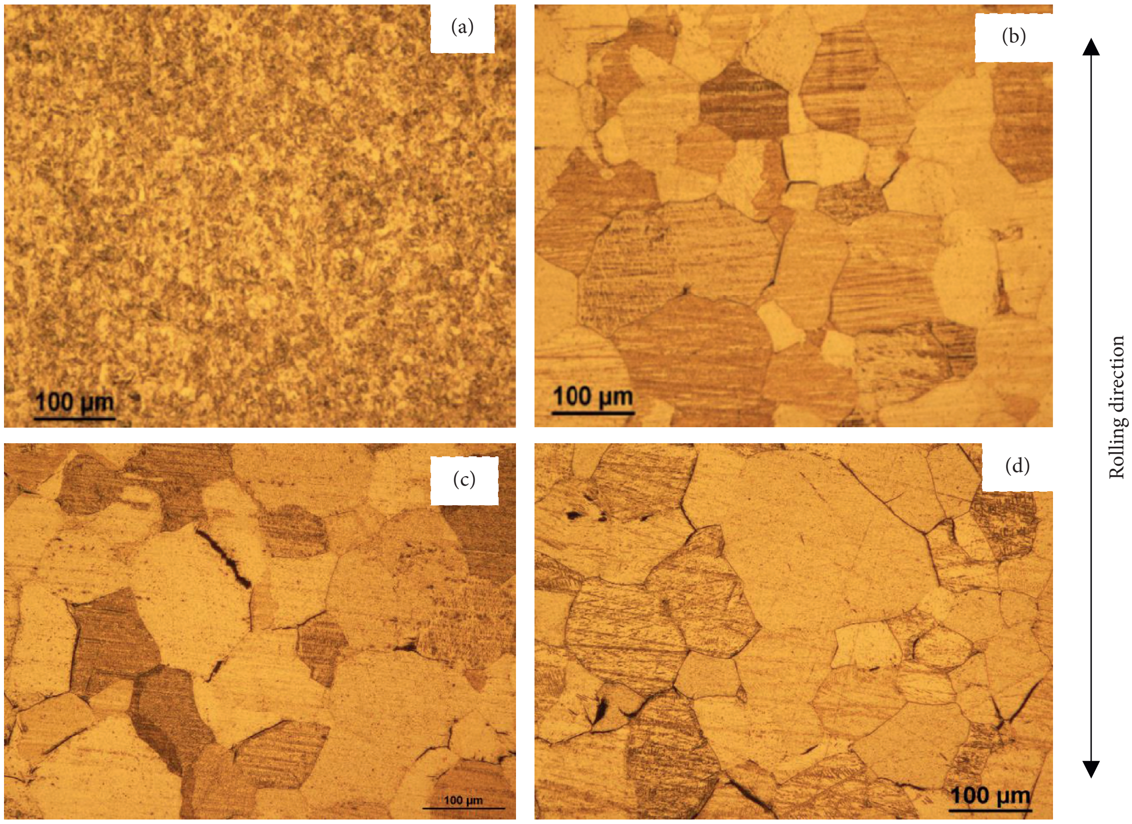


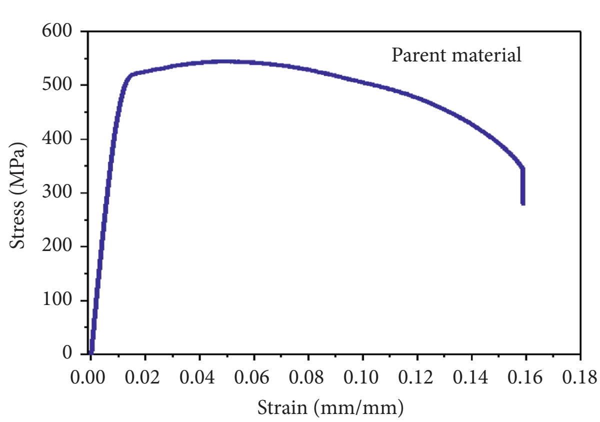
Figure 4: Microstructural images of different samples: (a) parent, (b) 30 mins, (c) 60 mins, and (d) 90 mins.

Table 3: Average grain size measurement for Cp-Ti grade 2 samples (μm).

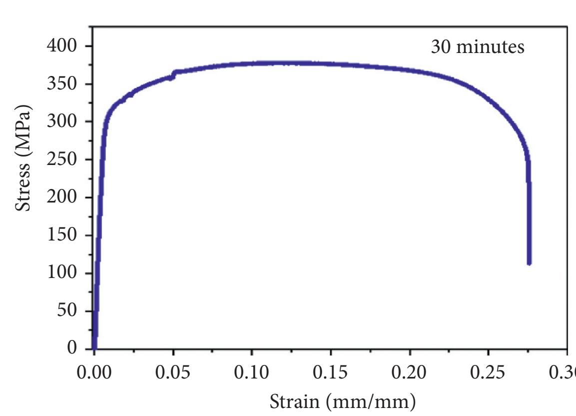
Item	Sample	Grain size
1	Parent	12.02
2	30 minutes	53.08
3	60 minutes	60.03
4	90 minutes	66.09

Table 4: Tensile results for all periods and parents.

Sample	Ultimate tensile strength (MPa)	Percentage elongation (%)
Parent	545.21	15.88
30 minutes	378.58	27.55
60 minutes	372.56	27.88
90 minutes	375.57	35.03

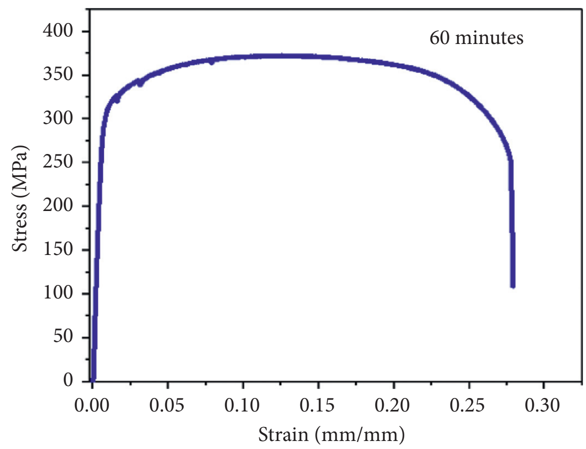


(a)



(b)

Figure 5: Continued.



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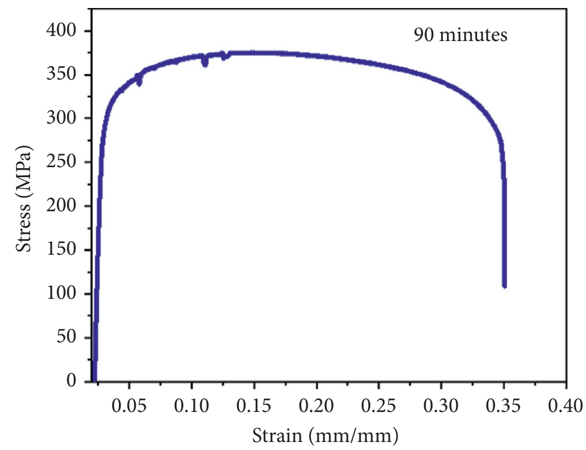
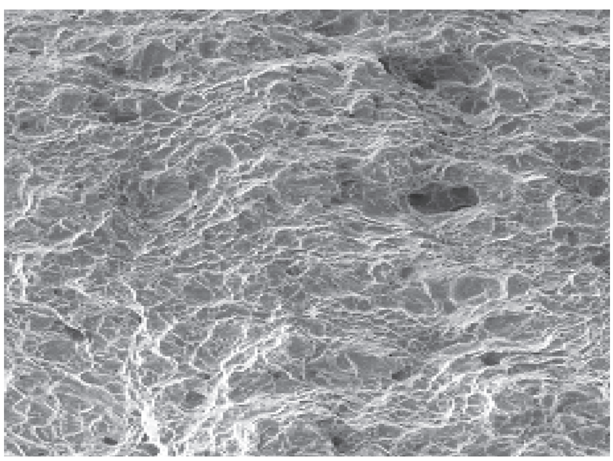
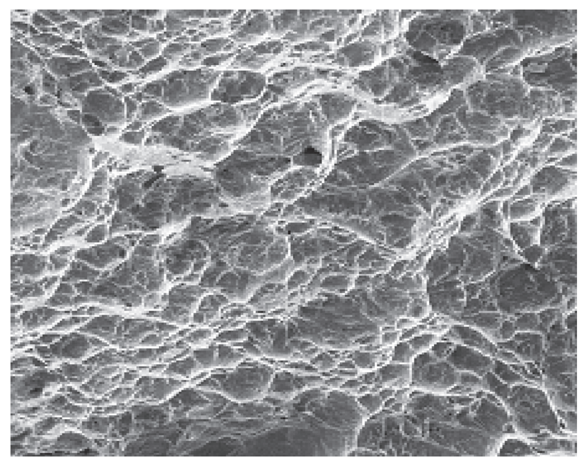


(d)

Figure 5: Stress-strain curve graph of different samples: (a) parent, (b) 30 min, (c) 90 min, and (d) 60 min.



(a)



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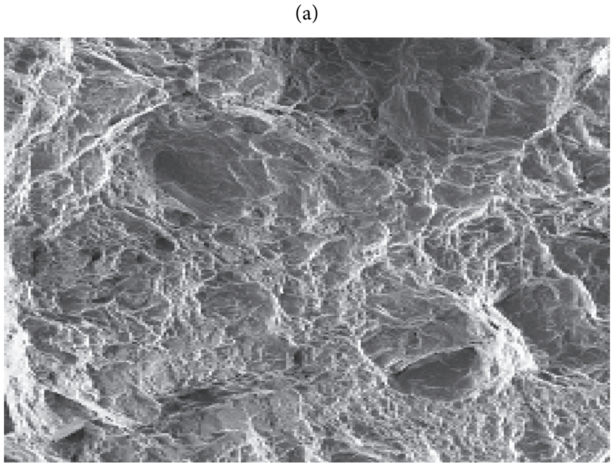
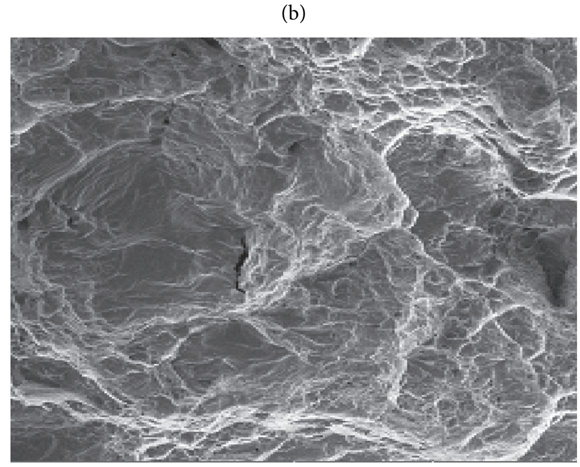


(c)



(d)

Figure 6: Fracture morphology of different samples after the tensile test: (a) parent, (b) 30 min, (c) 60 min, and (d) 90 min.

samples; therefore, some points were in the center of the grain, some were next to the grain boundary, and some were exactly in the grain boundary. The average surface microhardness results are presented in Table 5, where 90 minutes' treatment shows a highest surface microhardness value compared to the parent and other treatments. The increase in surface hardness in 90 minutes' samples was attributed to the heating period of the samples that had an effect on the grain

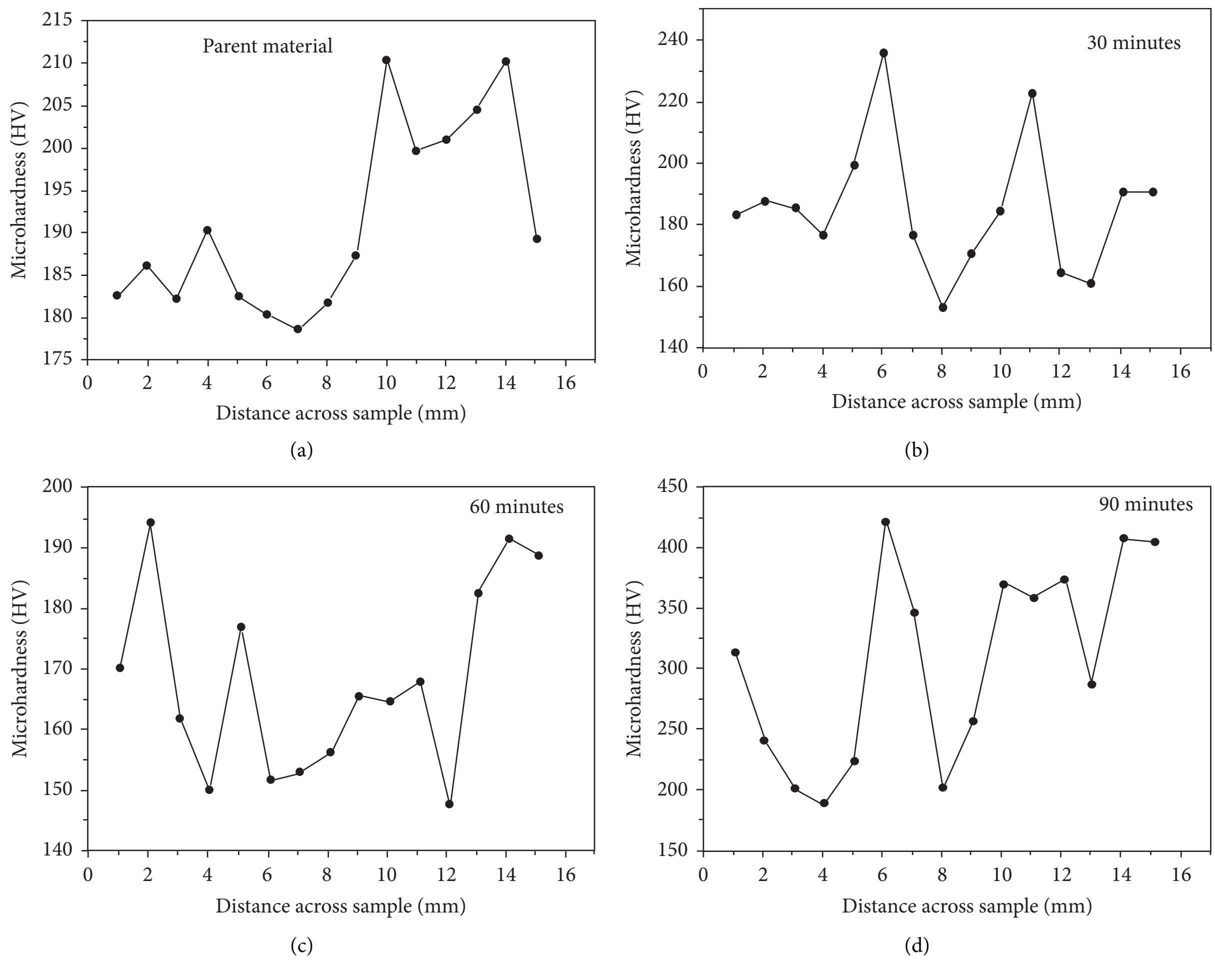


Figure 7: Measured microhardness point graph of different samples: (a) parent, (b) 30 min, (c) 60 min, and (d) 90 min.

Table 5: Average microhardness results.

Sample	Microhardness (HV)
Parent	195
30 minutes	186
60 minutes	170
90 minutes	305

structure and on the titanium oxide. The thickness of the oxide layer expands with an increase in the heating timeframe of the surface; also, the greatest surface hardness expands with an increase in the heating timeframe and the hardness layer depth additionally expands [36–38].

4. Conclusions

The heat treatment was successfully employed to observe its influence on mechanical properties of CP-Ti grade 2. It was discovered that heat treatment influences the grain growth variation with different annealing periods. The increase in annealing time had a detrimental effect on UTS of CP-Ti grade 2. However, the increase in percentage elongation with an increase in annealing time was observed. There was also a notable decrease in hardness from 30 minutes period to 60 minutes period which was then followed by a high jump in microhardness. The high jump in microhardness value was attributed to the thickening of oxide layer with high annealing period.

Data Availability

The data used in producing this article can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] V. A. Kumar, S. V. S. N. Murty, R. K. Gupta, A. G. Rao, and M. J. N. V. Prasad, "Effect of boron on microstructure evolution

and hot tensile deformation behavior of Ti-5Al-5V-5Mo-1Cr-1Fe alloy," *Journal of Alloys and Compounds*, vol. 831, p. 154672, 2020.

[2] Y.-Q. Jiang, Y. C. Lin, X.-Y. Zhang, C. Chen, Q.-W. Wang, and G.-D. Pang, "Isothermal tensile deformation behaviors and fracture mechanism of Ti-5Al-5Mo-5V-1Cr-1Fe alloy in β phase field," *Vacuum*, vol. 156, pp. 187–197, 2018.

[3] F.-W. Chen, G. Xu, X.-Y. Zhang, K.-C. Zhou, and Y. Cui, "Effect of α morphology on the diffusional $\beta \leftrightarrow \alpha$ transformation in Ti-55531 during continuous heating: dissection by dilatometer test, microstructure observation and calculation," *Journal of Alloys and Compounds*, vol. 702, pp. 352–365, 2017.

[4] L. Ren, W. Xiao, W. Han, C. Ma, and L. Zhou, "Influence of duplex ageing on secondary α precipitates and mechanical properties of the near β-Ti alloy Ti-55531," *Materials Characterization*, vol. 144, pp. 1–8, 2018.

[5] R. Dong, J. Li, H. Kou, J. Fan, B. Tang, and M. Sun, "Precipitation behavior of α phase during aging treatment in a β-quenched Ti-7333," *Materials Characterization*, vol. 140, pp. 275–280, 2018.

[6] H. Zhang, H. Shao, D. Shan et al., "Influence of strain rates on high temperature deformation behaviors and mechanisms of Ti-5Al-5Mo-5V-3Cr-1Zr alloy," *Materials Characterization*, vol. 171, p. 110794, 2021.

[7] R. Dong, J. Li, J. Fan, H. Kou, and B. Tang, "Precipitation of α phase and its morphological evolution during continuous heating in a near β titanium alloy Ti-7333," *Materials Characterization*, vol. 132, pp. 199–204, 2017.

[8] Y.-Q. Jiang, Y. C. Lin, X.-Y. Jiang, D.-G. He, X.-Y. Zhang, and N. Kotkunde, "Hot tensile properties, microstructure evolution and fracture mechanisms of Ti-6Al-4V alloy with initial coarse equiaxed phases," *Materials Characterization*, vol. 163, p. 110272, 2020.

[9] G.-Z. Quan, Y.-Y. Ma, Y.-Q. Zhang, P. Zhang, and W.-Y. Wang, "Separation of dynamic recrystallization parameter domains from a chaotic system for Ti-6Al-4V alloy and its application in parameter loading path design," *Materials Science and Engineering: A*, vol. 772, p. 138745, 2020.

[10] Y. Chong, T. Bhattacharjee, Y. Tian, A. Shibata, and N. Tsuji, "Deformation mechanism of bimodal microstructure in Ti-6Al-4V alloy: the effects of intercritical annealing temperature and constituent hardness," *Journal of Materials Science & Technology*, vol. 71, pp. 138–151, 2021.

[11] N. Jin, Z. Yan, Y. Wang, H. Cheng, and H. Zhang, "Effects of heat treatment on microstructure and mechanical properties of selective laser melted Ti-6Al-4V lattice materials," *International Journal of Mechanical Sciences*, vol. 190, p. 106042, 2021.

[12] J. Fan, J. Li, H. Kou, K. Hua, B. Tang, and Y. Zhang, "Influence of solution treatment on microstructure and mechanical properties of a near β titanium alloy Ti-7333," *Materials & Design*, vol. 83, pp. 499–507, 2015.

[13] A. M. Vemula, G. C. M. Reddy, and M. M. Hussain, "Comparative analysis of the orientation dependent tensile deformation of commercially pure titanium and titanium alloy OT 4-1," *Materials Today: Proceedings*, vol. 37, pp. 1743–1747, 2020.

[14] K. V. Mjali, "Fatigue life prediction of laser and mechanically formed commercially pure grade 2 titanium alloy plates," *Procedia Manufacturing*, vol. 48, pp. 256–266, 2020.

[15] T. Hama, A. Kobuki, and H. Takuda, "Crystal-plasticity finite-element analysis of anisotropic deformation behavior in a commercially pure titanium grade 1 sheet," *International Journal of Plasticity*, vol. 91, pp. 77–108, 2017.

[16] A. Mamedov, H. Ozturk, and T. Makas, "Investigation of mechanical and microstructural properties of Ti-6Al-4V alloy depending on hot forging process parameters," *Procedia Engineering*, vol. 207, pp. 2155–2160, 2017.

[17] J. L. Milner, F. Abu-Farha, C. Bunget, T. Kurfess, and V. H. Hammond, "Grain refinement and mechanical properties of CP-Ti processed by warm accumulative roll bonding," *Materials Science and Engineering: A*, vol. 561, pp. 109–117, 2013.

[18] A. Najdahmadi, A. Zarei-Hanzaki, and E. Farghadani, "Mechanical properties enhancement in Ti-29Nb-13Ta-4.6Zr alloy via heat treatment with no detrimental effect on its biocompatibility," *Materials & Design (1980–2015)*, vol. 54, pp. 786–791, 2014.

[19] S. El-Hadad, M. Nady, W. Khalifa, and A. Shash, "Influence of heat treatment conditions on the mechanical properties of Ti-6Al-4V alloy," *Canadian Metallurgical Quarterly*, vol. 57, no. 2, pp. 186–193, 2018.

[20] M. Wachowski, M. Gloc, T. Ślęzak, T. Płociński, and K. J. Kurzydłowski, "The effect of heat treatment on the microstructure and properties of explosively welded titanium-steel plates," *Journal of Materials Engineering and Performance*, vol. 26, no. 3, pp. 945–954, 2017.

[21] R.-T. Huang, W.-L. Huang, R.-H. Huang, and L.-W. Tsay, "Effects of microstructures on the notch tensile fracture feature of heat-treated Ti-6Al-6V-2Sn alloy," *Materials Science and Engineering: A*, vol. 595, pp. 297–305, 2014.

[22] L. Catherine and D. B. Abdul Hamid, "The effect of heat treatment on the tensile strength and ductility of pure titanium grade 2," *IOP Conference Series: Materials Science and Engineering*, vol. 429, p. 012014, 2018.

[23] Q. Zheng, T. Shimizu, and M. Yang, "Effect of heat on tensile properties of thin pure titanium foils," *Manufacturing Reviews*, vol. 2, no. 3, pp. 1–5, 2015.

[24] J. Wang, X. Lin, M. Wang, J. Li, C. Wang, and W. Huang, "Effects of subtransus heat treatments on microstructure features and mechanical properties of wire and arc additive manufactured Ti-6Al-4V alloy," *Materials Science and Engineering: A*, vol. 776, p. 139020, 2020.

[25] L. Wanying, L. Yuanhua, C. Yuhai, S. Taihe, and A. Singh, "Effect of different heat treatments on microstructure and mechanical properties of Ti6Al4V titanium alloy," *Rare Metal Materials and Engineering*, vol. 46, no. 3, pp. 634–639, 2017.

[26] N. Davari, A. Rostami, and S. M. Abbasi, "Effects of annealing temperature and quenching medium on microstructure, mechanical properties as well as fatigue behavior of Ti-6Al-4V alloy," *Materials Science and Engineering: A*, vol. 683, pp. 1–8, 2017.

[27] R. Julien, V. Velay, V. Vidal, Y. Dahan, R. Forestier, and F. Rézaï-Aria, "Characterization and modeling of forged Ti-6Al-4V titanium alloy with microstructural considerations during quenching process," *International Journal of Mechanical Sciences*, vol. 142-143, pp. 456–467, 2018.

[28] Q. Chao, P. D. Hodgson, and H. Beladi, "Thermal stability of an ultrafine grained Ti-6Al-4V alloy during post-deformation annealing," *Materials Science and Engineering: A*, vol. 694, pp. 13–23, 2017.

[29] M. Jia, Y. Alshammari, F. Yang, and L. Bolzoni, "Effect of heat treatment on the microstructure and mechanical properties of blended elemental Ti-6Al-4V produced by powder forging," *Materials Science and Engineering: A*, vol. 791, p. 139724, 2020.

[30] L. Haijun, X. Yong, Z. Zhimin et al., "Effect of multi-pass hot deformation on flow stress and microstructure of Ti-6Al-4V

titanium alloy prepared by hot isostatic pressing," *Procedia Manufacturing*, vol. 50, pp. 652–657, 2020.

[31] A. P. Singh, F. Yang, R. Torrens, and B. Gabbitas, "Solution treatment of Ti-6Al-4V alloy produced by consolidating blended powder mixture using a powder compact extrusion route," *Materials Science and Engineering: A*, vol. 712, pp. 157–165, 2018.

[32] Z. Liu, Z. Zhao, J. Liu et al., "Effects of solution-aging treatments on microstructure features, mechanical properties and damage behaviors of additive manufactured Ti-6Al-4V alloy," *Materials Science and Engineering: A*, vol. 800, p. 140380, 2021.

[33] V. Msomi, N. Mbana, and S. Mabuwa, "Microstructural analysis of the friction stir welded 1050-H14 and 5083-H111 aluminium alloys," *Materials Today: Proceedings*, vol. 26, pp. 189–192, 2020.

[34] S. Mabuwa and V. Msomi, "Comparative analysis between normal and submerged friction stir processed friction stir welded dissimilar aluminium alloy joints," *Journal of Materials Research and Technology*, vol. 9, no. 5, pp. 9632–9644, 2020.

[35] S. Mabuwa and V. Msomi, "The impact of submerged friction stir processing on the friction stir welded dissimilar joints," *Materials Research Express*, vol. 7, p. 096513, 2020.

[36] X. Li, G. Wang, Y. Gu, and J. Yang, "Electrically assisted diffusion bonding of Ti2AlNb alloy sheet using CP-Ti foil interlayer: microstructural characterization and mechanical tests," *Materials Science and Engineering: A*, vol. 744, pp. 733–745, 2019.

[37] G.-D. Pang, Y. C. Lin, Y.-Q. Jiang et al., "Precipitation behaviors and orientation evolution mechanisms of α phases in Ti-55511 titanium alloy during heat treatment and subsequent hot deformation," *Materials Characterization*, vol. 167, p. 110471, 2020.

[38] Y. C. Lin, Y. Tang, X.-Y. Zhang, C. Chen, H. Yang, and K.-C. Zhou, "Effects of solution temperature and cooling rate on microstructure and micro-hardness of a hot compressed Ti-6Al-4V alloy," *Vacuum*, vol. 159, pp. 191–199, 2019.