

Article

Research on the Recrystallization Process of the Ti-70 Titanium Alloy Sheet

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Abstract: As Ti-70 is a new type of marine titanium alloy, research on the recrystallization process of its sheet is necessary. This article studies the effects of different temperatures and times of annealing on the recrystallization process of 5.0 mm thick Ti-70 titanium alloy cold-rolled sheets by metallographic analyses and hardness tests. The results show that after 30 min of annealing at 620–700 °C, the recrystallization process was mostly complete, and uniform and equiaxed recrystallized grains could be obtained. The recrystallization process starts after 8 min of annealing at 700 °C, and after holding for 15–30 min, the recrystallization process is almost complete and the grain size is about 8.2 μm. The recrystallization activation energy of a Ti-70 titanium alloy cold-rolled sheet is $Q_r = 11.0645 \times 10^4$ J/mol. The ultimate tensile strength (R_m) can be controlled between 705 and 852 MPa, the yield strength ($R_{p0.2}$) can be controlled between approximately 623 and 793 MPa, and the elongation percentage (A) can be controlled between approximately 10.0 and 25.0% after rolling and heat treatment of Ti-70 alloy sheets.

Keywords: Ti-70 titanium alloy sheet; recrystallization; microstructure; mechanical property



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1. Introduction

Ti-70 is a kind of near- α titanium alloy with medium strength, good corrosion resistance, and favorable weldability. Its nominal composition is Ti-2.5Al-2Zr-1Fe, and the α/β phase transition temperature is between 940 °C and 960 °C. The alloy with the low-valence Fe element has good seawater corrosion resistance [1,2] and high specific strength, and it is an ideal hull structure material. Ti-70 is a new type of marine titanium alloy independently developed in China, and previous research on it has mostly focused on the forging process and performance testing of its finished products [3,4], while research on the Ti-70 alloy sheet is lacking [5]. Ti-70 alloy sheets can be widely used on the hull, nail plate, fairing, and other ship parts [6–8]. Cold rolling is the main manufacturing process for this alloy, and the recrystallization process directly determines the mechanical and forming properties of the Ti-70 alloy sheet.

The recrystallization process has always been a hot spot in the research of metal materials because it can make a big difference to the microstructure, texture, and properties of alloys [9–11]. A. Ghaderi analyzed the microstructure development in the Ti-5Al-5Mo-5V-3Cr alloy during cold rolling and found that large amounts of deformation bands formed during the cold rolling of the all- β phase alloy, and that recrystallization could be slightly accelerated in the samples containing α phase [12]. Mironov, S. clarified the continuous dynamic recrystallization mechanism of heavily cold-rolled commercial-purity titanium and noticed that grain refinement in the heavily rolled Ti was governed by continuous recrystallization [13]. Kikuchi, S. investigated the combined effects of low-temperature nitriding and cold rolling on the microstructure of commercially pure titanium and found that the recrystallization grain size of the pure titanium decreased with increasing

thickness reduction due to the cold rolling pretreatment, which could dramatically affect the fatigue limit [14]. Zhao, S. researched the effect of annealing temperature on the microstructure and mechanical properties of cold-rolled pure titanium sheets and found that the recrystallization nucleation of cold-rolled sheets occurred in the high strain and the high angle grain boundary regions [15]. Choi, S.W. successfully obtained an excellent strength–ductility combination of pure titanium sheet through a novel cryogenic rolling method and found that grain refinement and grain boundary design can be achieved by controlling the recrystallization process [16]. According to the above content, it can be concluded that the recrystallization mechanism and microstructure evolution have been deeply researched. However, the method for optimizing the parameters of recrystallization heat treatment has not been given much attention, and a suitable method industrial manufacturing is still needed. Moreover, Ti-70 alloy sheets have been prepared [17], and the mechanical properties of the Ti-70 alloy sheet can be dramatically affected by its recrystallization process. Furthermore, the recrystallization heat treatment process of the Ti-70 alloy sheet is not clear, which will directly affect the plastic forming process and applications of the sheet [18].

In this article, the HRC hardness and microstructure evolution of Ti-70 cold-rolled sheets were studied at different heat treatment temperatures and times, the hardness evolution curves were drawn, and the recrystallization activation energy of Ti-70 cold-rolled sheets was calculated. The recrystallization process of Ti-70 alloy sheets was characterized by microstructure observation. The relationship between mechanical properties and heat treatment was clarified. The results can provide a comprehensive heat treatment method for the manufacture of Ti-70 alloy sheets and improve the mechanical and forming properties which would be beneficial for engineering applications of the Ti-70 alloy.

2. Materials and Methods

The Ti-70 titanium alloy ingot used in the experiment was obtained through melting in a vacuum consumable electric arc furnace three times, and the specific chemical composition is shown in Table 1. The ingot was cogged in the β phase region, and after forging multiple times, the final heated piece was forged into a slab in the $\alpha + \beta$ two-phase region. After surface treatment, the slab was rolled to an 8.0 mm thickness in the $\alpha + \beta$ two-phase zone, and then intermediate annealing and surface treatment were carried out. The hot rolling process was carried out on a four-roll reversible hot rolling mill. After that, the sheet was rolled to a 5.0 mm thickness by the four-roll reversible cold rolling mill, and the mechanical properties and microstructure of the sheet were tested after heat treatment. The recrystallization temperature and time of Ti-70 were calculated by the “hardness method”, and the accuracy of recrystallization temperature and time calculated by the “hardness method” was verified by the “metallographic method”.

The “Hardness method” means that in general, the hardness difference between the original sample and the completely softened sample is defined as 100%, and when the hardness is reduced to 50%, it is defined as the condition of recrystallization (i.e., the recrystallization start temperature or recrystallization start time) [19]. The measured hardness value is related to the test conditions and the corresponding point where the hardness drops to 50% of the total hardness drop can be found, which is the temperature point or time point of recrystallization of Ti-70. The start temperature and end temperature of recrystallization in this experiment are determined by the corresponding annealing temperatures (time) when the hardness reduction reaches 50% and 80% of the total hardness reduction, respectively [20,21]. The specific test method included 3 steps. First, the cold-rolled sheet was heat-treated at 520–800 °C (with 20 °C as the interval) for 30 min, then the cold-rolled sheet was heat-treated at 700 °C for 2–120 min, and three parallel specimens (5 × 20 × 20 mm) were prepared for each heat treatment process. Second, the specimens were surface-treated by etching with a solution of 5% perchloric, 35% butanol, and 60% methanol and then polishing to 0.3 μm Ra. Third, HRC hardness tests were carried out on each specimen according to the National Standard Method GB/T 231.1-2009 [22].

The recrystallization temperature usually refers to the long-term recrystallization temperature. This is the temperature corresponding to the completion of recrystallization of metal materials within a certain time and is generally defined as the temperature corresponding to the completion of 95% recrystallization within 1 h [23]. The “Metallographic method” is used to determine the recrystallization temperature and time by observing the microstructure and calculating the recrystallization fraction of the annealed sheet. The specific test method included 3 steps. First, the cold-rolled sheet was heat-treated at 520~800 °C (with 20 °C as the interval) for 30 min, and then the cold rolled sheet was heat-treated at 700 °C for 2~120 min. Second, metallography specimens were prepared by metallographically polishing the sheet plane and finally chemically etching the plane using an electrolyte solution of 10% perchloric, 10% butanol and 80% methanol. Third, the microstructure of the specimens was characterized by metallography testing and Electron Backscattered Diffraction.

The microstructure of the material was observed using a Axiovert200MAT (Carl Zeiss, Oberkochen, Germany) optical microscope, the tensile property at room temperature was tested with an Instron5885 tensile testing machine, the hardness of the HRC was tested with an OU2200TC, the average grain size was tested with Image Pro Plus software [<https://www.mediacy.com/imageproplus>], the EBSD (Electron Backscattered Diffraction) was tested with a Gemini-SEM-500 scanning electron microscope (Carl Zeiss, Oberkochen, Germany), and the recrystallization distribution was analyzed using Channel 5 software. The EBSD specimens were prepared by metallographically polishing the sheet plane and electro-polishing the plane using the electrolyte. EBSD tests were performed on the sheet plane of the sheets with a step size of 0.1 mm. Tensile tests were carried out on an ETM105D universal testing machine along the transverse direction (TD) and the rolling direction (RD), with a strain rate of $2.5 \times 10^{-4} \text{ s}^{-1}$ at ambient temperature. The tensile specimens with the size of $38 \times 215 \text{ mm}^2$ and the gauge length of 50 mm were machined according to GB/T 228.2-2015 [24]. The tensile strain was measured by an electronic extensometer. Some repeated tests were carried out under each condition to confirm the findings. The impact ductility was measured by the CHARPY notch impact test according to GB/T 229-1994 [25]. The impact specimens were machined to a size of $10 \times 55 \text{ mm}^2$.

Table 1. Chemical compositions of Ti-70 ingots (wt.%).

Ti	Al	Zr	Fe	Si	C	N	O
bal.	2.8	2.0	0.98	0.02	0.01	0.01	0.11
bal.	2.7	2.1	0.96	0.03	0.01	0.01	0.12

3. Result and Discussion

The recrystallization process of a Ti-70 alloy sheet is affected by the rolling reduction, heat treatment temperature, heat treatment time, and some other factors, and the recrystallization process will reshape the microstructure of the alloy, thus affecting the mechanical properties such as hardness, tensile strength, and impact. In this part, the accurate heat treatment parameters of a Ti-70 plate were obtained through hardness testing, microstructure characterization, and quantitative analysis of the recrystallization temperature and time. In addition, by comprehensively testing the mechanical properties of Ti-70 alloy plates in each stage of recrystallization, the influence of the recrystallization heat treatment process on the microstructure and properties was studied.

3.1. Calculation of the Recrystallization Temperature of Ti-70 Alloy Sheets through the “Hardness Method”

A cold-rolled Ti-70 alloy sheet (5.0 mm thick) is used in the heat treatment experiment, with the steps as follows: ① heat at 520~800 °C, with 20 °C as the interval, maintain the temperature for 30 min, test the HRC hardness of the annealed sheet, and plot the relationship between hardness and temperature, as shown in Figure 1; ② keep the temperature at 700 °C for 2~120 min, test the HRC hardness of the annealed sheet, and draw the relationship curve between hardness and holding time, as shown in Figure 2.

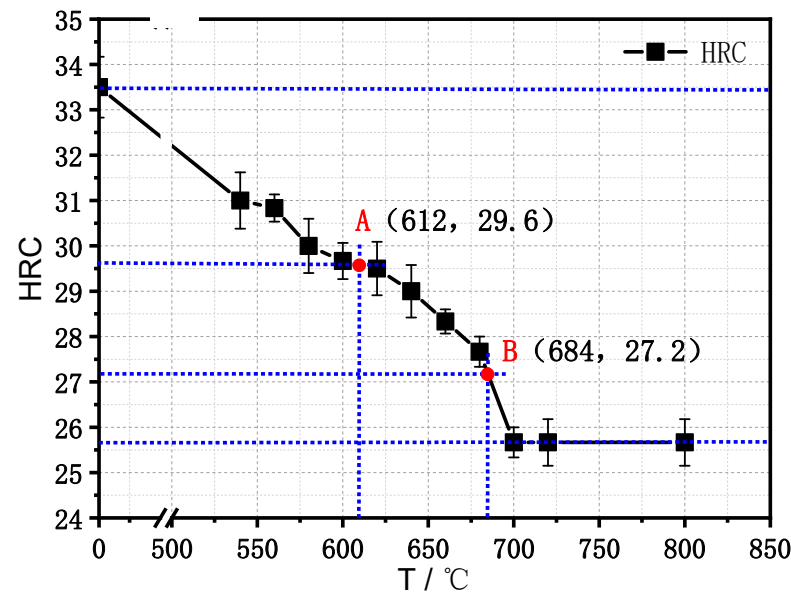


Figure 1. Effect of annealing temperature (30 min) on the HRC hardness of the Ti-70 alloy sheet.

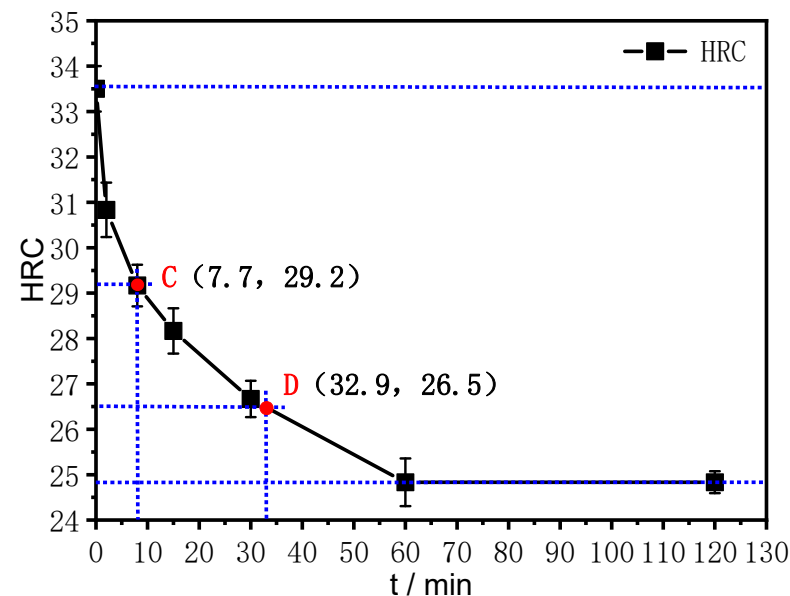


Figure 2. Effect of annealing time (700 °C) on the HRC hardness of the Ti-70 alloy sheet.

The annealing temperature (time) can correspond to the start temperature and end temperature of recrystallization when hardness reduction reaches 50% and 80% of the total hardness reduction, respectively. As can be seen from the curve in Figure 1, recrystallization of the Ti-70 alloy sheet starts at 612 °C for 30 min, and the HRC hardness decreases by 50% to 29.6, as shown by point A. Recrystallization was completed after holding at 684 °C for 30 min, and the HRC hardness decreased by 80% to 27.2, as shown by point B.

From the curve in Figure 2, it can be seen that recrystallization of the Ti-70 alloy sheet begins at 700 °C for 7.7 min, and the HRC hardness decreases by 50% to 29.2, as shown by point C. Recrystallization was completed after holding at 700 °C for 32.9 min, and the HRC hardness decreased by 80% to 26.5, as shown by point D.

Two groups of isothermal annealing times t_1 (point A) and t_2 (point C) and corresponding recrystallization temperatures T_1 (point A) and T_2 (point C) are measured by the “hardness method”, and the formulae for calculating recrystallization activation energy Q_r and coefficient A can be derived by the Avrami formula $\frac{1}{t} = Ae^{-\frac{Q_r}{8.314T}}$ [26,27].

$$Q_r = \frac{R \ln \frac{t_2}{t_1}}{\frac{1}{T_2} - \frac{1}{T_1}} \quad (1)$$

$$A = \frac{1}{t_1} e^{\frac{Q_r}{RT_1}} \quad (2)$$

When the parameters $T_1 = 612$ °C (885 K), $t_1 = 30$ min (1800 s), $T_2 = 700$ °C (973 K), $t_2 = 7.7$ min (462 s), and $R = 8.314$ J·(mol·K)^{−1} are substituted into Equation (1), the recrystallization activation energy $Q_r = 11.0645 \times 10^4$ J/mol is obtained.

When the parameters $T_1 = 612$ °C (885 K) and $t_1 = 30$ min (1800 s) are substituted into Equation (2), the coefficient $A = 1920$ s^{−1} is obtained.

To sum up, the Avrami relation formula between the recrystallization temperature T and the annealing time t of a Ti-70 alloy sheet can be obtained as follows.

$$\frac{1}{t} = 1920e^{-\frac{110645}{8.314T}} \quad (3)$$

3.2. Microstructure of the Ti-70 Alloy Sheet after Different Heat Treatment Processes

Using a 5.0 mm cold-rolled Ti-70 alloy sheet for the heat treatment experiment, the specific scheme is as follows. First, some cold-rolled specimens are prepared for the heat treatment experiment, and the annealing temperature is set between 580 °C and 800 °C at intervals of 20 °C and held for 30 min. The microstructure of the alloy is then observed after heat treatment, as shown in Figure 3. Second, another scheme of heat treatment is used, keeping the annealing temperature at 700 °C for 2–120 min and observing the microstructure evolution, as shown in Figure 4.

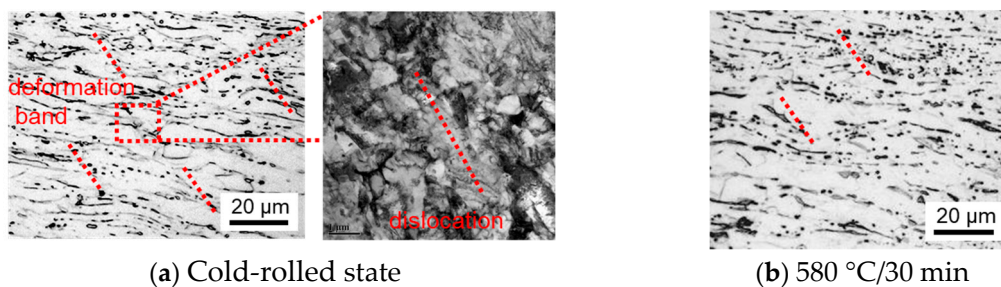


Figure 3. Cont.

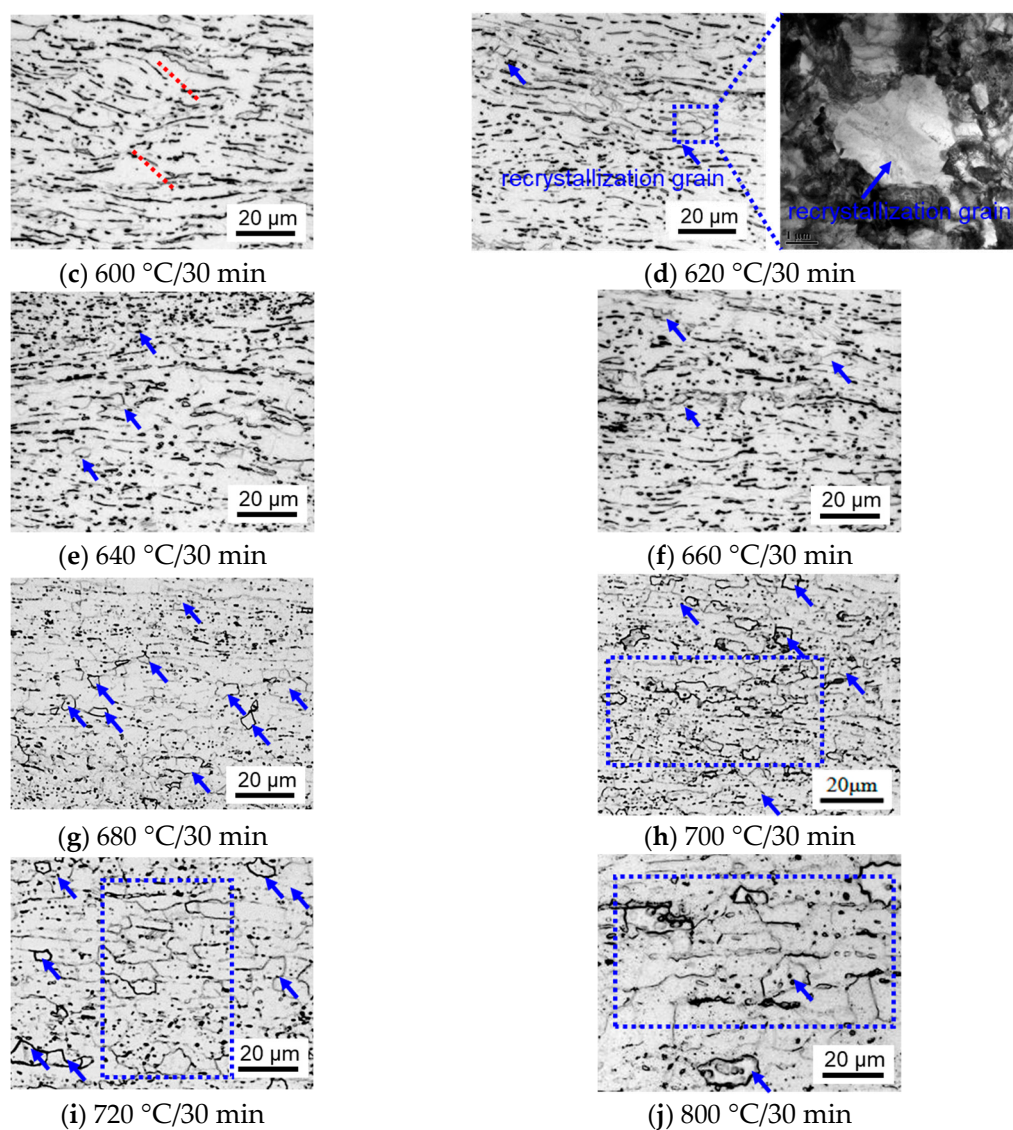


Figure 3. Microstructure of the Ti-70 alloy sheet after annealing at different temperatures for 30 min.

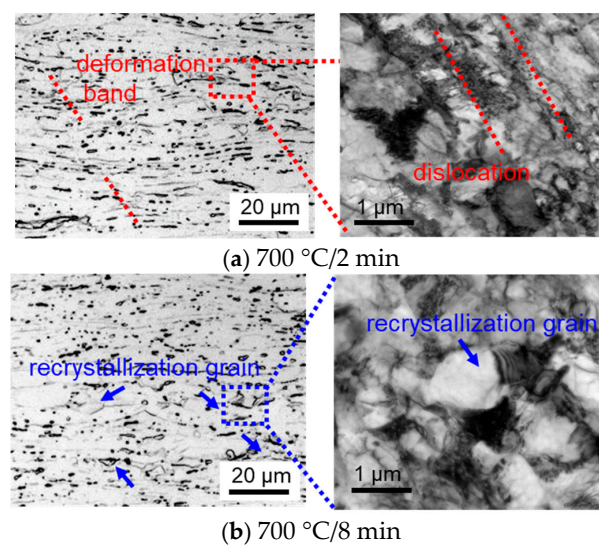


Figure 4. Cont.

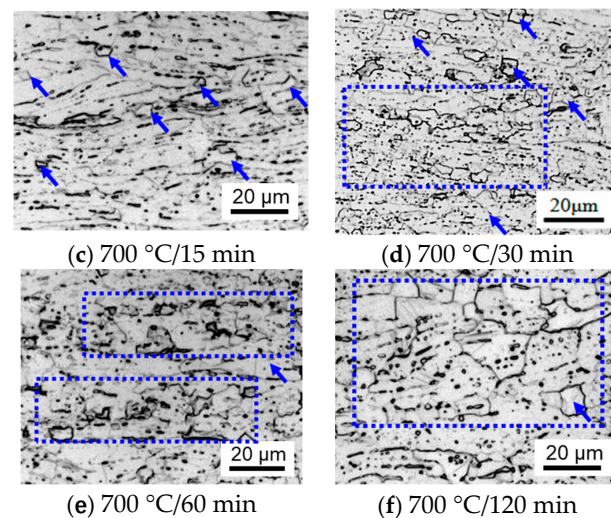


Figure 4. Microstructure of the Ti-70 alloy sheet after annealing at 700 °C for different amounts of time.

3.2.1. Annealing Microstructure at Different Temperatures for 30 min

Figure 3 describes the microstructure evolution and recrystallization process of Ti-70 cold-rolled sheets at different temperatures. It can be seen from Figure 3 that with the increase in annealing temperature, the recrystallization process of the Ti-70 alloy sheet will be more complete, and the microstructure will gradually evolve from obvious cold-rolled fiber (as shown in Figure 3a–d) to more recrystallization grains (as shown in Figure 3e–g). The recrystallization process will be gradually completed at higher temperatures and grain growth [28] will occur (as shown in Figure 3h–j). The α grains are dramatically elongated and some deformation bands marked by the red dotted lines can be seen in the grain interior in the cold-rolled sample as shown in Figure 3a. The deformation bands consist of a high density of dislocations. After heat treatment at 580–600 °C, the quantity of deformation bands decreases, and the degree of the distortional microstructure becomes weakened. In addition, it can be seen from Figure 3 that when the cold-rolled Ti-70 alloy sheet is annealed at 620 °C for 30 min, recrystallization grains begin to form in the severely deformed regions, as shown in the area marked by a blue arrow and enlarged in Figure 3d. The recrystallization process of the cold-rolled Ti-70 alloy sheet is basically completed after annealing at 680–700 °C for 30 min [29], and the recrystallization grains are equiaxed with a grain size of 8.2 μm , as shown in Figure 3h. With further increases in the annealing temperature, recrystallization grains gradually grow up to 12–17.5 μm as shown in Figure 3i,j. The starting temperature and ending temperature of recrystallization observed by the “metallographic method” are basically consistent with the results of the “hardness method” in Figure 1.

3.2.2. Annealing Microstructure at 700 °C for Different Amounts of Time

Figure 4 describes the microstructure evolution and recrystallization process of the Ti-70 cold-rolled sheets at 700 °C for different amounts of time. It can be seen from Figure 4 that the recrystallization process of cold-rolled Ti-70 alloy sheets becomes more and more complete with the increase in annealing time at 700 °C, and the recrystallization process of the material can be divided into three stages [30–33]. First is the recovery stage, as shown in Figure 4a. Micro-defects are reduced and micro-stress is released. There are still a number of dislocations in the deformed grains. The quantity of deformation bands decreases compared to the cold rolled-sheet as shown in Figure 3a. Second is the recrystallization stage, as shown in (Figure 4b–d). The recrystallized grains nucleate at the grain boundary and deformation bands and gradually replace the deformed matrix. There is almost no dislocation in the recrystallization grain as shown in the TEM image in Figure 3a. Third is the grain growth stage, as shown in Figure 4e,f. The recrystallization grain size gradually

grows larger, and the average grain size of the sheet annealed at 700 °C for 120 min increases to 22 μm .

In addition, it can be seen from Figure 4 that when the cold-rolled Ti-70 alloy sheet is kept at 700 °C for about 8 min, fine recrystallization grains begin to appear along the grain boundary and deformation bands on the cold-rolled matrix [34], as shown in the marked area of the dashed frame in Figure 4b and the enlarged TEM image. The recrystallization process of the cold-rolled Ti-70 alloy sheet is basically completed after holding at 700 °C for 30~60 min, and uniform and equiaxed grains form as shown in Figure 4d,e.

The starting temperature and ending temperature of recrystallization observed by the “metallographic method” are basically consistent with those observed by the “hardness method” in Figure 2, and the sheet can be completely recrystallized at 700 °C for 30 min. Furthermore, it can be confirmed by EBSD that the recrystallization of the sheet after holding at 700 °C for 30 min is as shown in Figure 5. The EBSD recrystallization fraction statistical method is an effective method to study the recrystallization process of materials. In the study of the recrystallization of materials, EBSD technology can be used to measure the change in the crystal orientation of materials. By measuring the change in the crystal orientation, the degree and distribution of recrystallization of the material can be determined. The EBSD recrystallization fraction statistical method is a method to measure the recrystallization fraction of materials using EBSD technology [35,36].

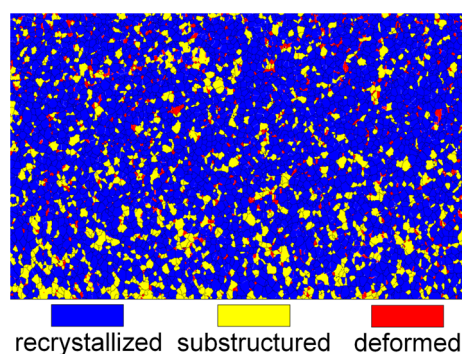


Figure 5. The recrystallization map of the Ti-70 alloy sheet after annealing at 700 °C for 30 min.

The volume fraction of the recrystallization structure marked by the blue color is 82%, the volume fraction of deformed structures marked by the red color is 6%, and the substructure (subgrain and recovery structures) marked by the yellow color accounts for 12%. This confirms that the recrystallization process of the Ti-70 alloy sheet has been fully completed and the Ti-70 alloy sheet will have an optimized microstructure and mechanical properties for further plastic processing after annealing at 700 °C for 30 min.

3.3. Tensile Properties of the Ti-70 Alloy Sheet after Different Heat Treatment Processes

The tensile properties of the Ti-70 alloy sheet in the RD and TD are exhibited in Table 2. It illustrates that the ultimate tensile strength (R_m) of the Ti-70 alloy sheet can be controlled between approximately 705 and 852 MPa, the yield strength ($R_{p0.2}$) of the Ti-70 alloy sheet can be controlled between approximately 623 and 793 MPa, and the elongation percentage (A) of the Ti-70 alloy sheet can be controlled between approximately 10.0 and 25.0% after rolling and heat treatment. The rolling process will break the original microstructure and promote the formation of the elongated structure and deformation bands, as shown in Figure 3a, so the values of R_m and $R_{p0.2}$ go up to a relatively high level. After heat treatment, the strain can be released and recrystallization grains would replace the deformed grains, so the values of R_m and $R_{p0.2}$ go down and the value of A rises. In addition, the tensile properties of cold-rolled sheets can be transformed greatly after heat treatment. It shows that the value of R_m has been lowered by 53~147 MPa, the value of $R_{p0.2}$ has been lowered by 97~170 MPa, and the value of A has been improved by 2.5~15%. Moreover, with the increase in heat treatment temperature from 580 °C to

720 °C, the value of R_m can be reduced from 797 MPa to 705 MPa, the value of $R_{p0.2}$ can be reduced from 696 MPa to 623 MPa, and the value of A can be improved from 15.5 to 25.0%. Below the heat treatment temperature 640 °C, the corresponding ultimate tensile strength and the yield strength of the Ti-70 alloy sheet decreases rapidly, by about 20 MPa for every 20 °C increase in temperature. Between the heat treatment temperatures of 640 °C and 720 °C, the corresponding ultimate tensile strength and the yield strength decreases slowly, about 5~10 MPa for every 20 °C increase in temperature. This is because the fraction of recrystallization grains increases with increasing temperature, as shown in Figure 3. More recrystallization grains can soften the material and optimize the deformed matrix microstructure of the Ti-70 alloy sheet. After heat treatment in the range of 580~640 °C, the deformed matrix is gradually replaced by recrystallized grains, and the dislocations and deformation bands are reduced. The drastic microstructure transformation brings great changes in tensile properties. Therefore, with the increase in temperature, the R_m and $R_{p0.2}$ decrease greatly. After heat treatment in the range of 640~720 °C, the recrystallization process is fully completed, the deformed microstructure has been basically replaced by recrystallized grains, and the main evolution is the increase in grain size. However, the overall grain size grows larger slowly. Therefore, with the increase in temperature, the strength decreases slightly.

Table 2. The tensile properties of Ti-70 alloy sheets after annealing at 700 °C for 30 min.

Heat Treatment Process	Direction	R_m , MPa	$R_{p0.2}$, MPa	A , %
Cold-rolled	RD1	850	790	13.0
	RD2	852	793	12.0
	RD3	848	788	10.0
580 °C/30 min	RD1	797	691	16.5
	RD2	797	696	17.5
	RD3	791	691	15.5
600 °C/30 min	RD1	774	670	18.5
	RD2	777	672	18.0
	RD3	777	679	17.0
620 °C/30 min	RD1	750	663	18.0
	RD2	750	660	19.0
	RD3	755	666	19.0
640 °C/30 min	RD1	739	659	19.9
	RD2	740	653	19.8
	RD3	745	651	20.0
660 °C/30 min	RD1	736	642	20.5
	RD2	730	645	20.0
	RD3	737	641	20.5
680 °C/30 min	RD1	725	632	21.0
	RD2	726	639	22.5
	RD3	728	635	19.5
700 °C/30 min	RD1	712	634	21.0
	RD2	715	626	22.5
	RD3	717	633	22.0
720 °C/30 min	RD1	710	623	25.0
	RD2	710	628	23.0
	RD3	705	629	22.0

Note: the tensile specimens are all along the rolling direction (RD) of the sheet.

Table 3 shows the tensile and impact properties of the Ti-70 alloy sheets after annealing at 700 °C for 30 min. The ultimate tensile strength (R_m) and yield strength ($R_{p0.2}$) of the Ti-70 alloy sheet after annealing at 700 °C for 30 min both decrease because of the formation of recrystallization grains and the decrease in the deformed structure. In addition, the

elongation percentage (A) and impact ductility (KV2) are both improved compared to the cold-rolled sheet. This is because the softer alloy sheet can be obtained through recrystallization heat treatment as shown in Figures 1 and 2. Furthermore, both the tensile and impact properties of the Ti-70 alloy sheet have obvious anisotropic characteristics between the TD and RD. As reported, the mill rolling sheet always obtains a T texture, so the value of R_m and R_{p0.2} in the TD is higher than that in the RD, at about 33.7 MPa and 75.7 MPa. It can be implied that the rolling texture would make more of a difference to the yield strength. Inevitably, the mill rolling sheet always has one or more severe textures, so its effect on mechanical properties is a noteworthy issue.

The specimens along the TD and RD of the Ti-70 alloy sheet were prepared for the impact toughness test shown in Table 3. It illustrates that the values of TD1~TD3 (where the notch direction of the impact test is parallel to the TD) are higher than the values of RD1~RD3 (where the notch direction of the impact test is parallel to the RD). The difference between the TD and RD is 10.3 J on average. Generally speaking, the impact toughness value of a titanium alloy sheet along the TD is higher than the impact toughness value of a titanium alloy sheet along the RD. After a cumulative deformation of more than 90% reduction in the rolling direction, the microstructure of the cold-rolled Ti-70 alloy sheet is continuously elongated along the rolling direction, and finally, a deformed fibrous structure is dominant in the Ti-70 alloy sheet, as shown in Figure 3a. After heat treatment as shown in Figure 3h–j, the recrystallization grains replaced the deformed fibrous structure. However, the microstructure after recrystallization treatment is influenced by heredity, and some deformed structure is residual. This makes the microstructure have a directional characteristic. Specifically, the microstructure of a Ti-70 alloy sheet with full recrystallization heat treatment is still elongated in the RD in some degree, so the impact toughness value of the TD is higher than the value of the RD.

Table 3. The properties of the Ti-70 alloy sheets after annealing at 700 °C for 30 min.

Heat Treatment Process	Direction	R _m , MPa	R _{p0.2} , MPa	A, %	KV2, J
cold rolled	RD1	850	790	13.0	13
	RD2	852	793	12.0	10
	RD3	848	788	10.0	11
700 °C/30 min	TD1	753	716	21.5	38
	TD2	745	696	18.0	40
	TD3	747	708	19.0	40
	RD1	712	634	21.0	28
	RD2	715	626	19.5	32
	RD3	717	633	22.0	26

Note: the tensile and impact specimens are along the rolling direction (RD) and transverse direction (TD) of the sheet.

4. Conclusions

In this paper, the recrystallization behavior and microstructure evolution of Ti-70 cold-rolled sheets were studied after annealing at different heat treatment temperatures and times. The recrystallization process of cold-rolled Ti-70 alloy sheets (5.0 mm thick) was characterized and analyzed by the “hardness method” and “metallographic method”, and the recrystallization law of cold-rolled Ti-70 alloy sheets was researched. The following conclusions are drawn:

- (1) Cold-rolled Ti-70 alloy sheets have a recrystallization activation energy $Q_r = 11.0645 \times 10^4$ J/mol and coefficient $A = 1920$ s^{−1}. Hence, the Avrami relation formula between the annealing temperature and time is:

$$\frac{1}{t} = 1920e^{-\frac{110645}{8.314T}}$$

- (2) The recrystallization process is completed in the temperature range of 680~700 °C for 30 min. The uniform and equiaxed recrystallization structure can be obtained, and the recrystallization volume fraction can reach up to 82%.
- (3) When the cold-rolled Ti-70 alloy sheet is annealed at 700 °C, recrystallization grains begin to appear within 8 min. The recrystallization process is completed at the holding time of 30~60 min and the average grain size is about 8.2 µm.
- (4) The ultimate tensile strength can be controlled between approximately 705 and 852 MPa, the yield strength can be controlled between approximately 623 and 793 MPa, and the elongation percentage (A) can be controlled between approximately 10.0 and 25.0% after rolling and heat treatment of the Ti-70 alloy sheet.

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