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Determination of Remanufacturing Parameters of Al7039 Armor Alloy

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Abstract: In this study, the determinability of the remanufacturing parameters of Al7039 alloy, nowadays known as armor material, are emphasized. Commercially obtained Al 7039 alloy plates are melted in a casting furnace and cast into a specially prepared mold. After the mold pressure cap is closed, the samples are squeezed into the mold with a pressure of about 18 MPa. Plates were examined by cooling at different cooling rates in order to determine the proper casting process. After the parameters of homogenization heat treatment, which is usually applied after casting, is determined, hot forging process is started. After waiting at 400 ^{o}C temperature for 15 minutes, the plates decreased from 15 mm thickness to 6 mm thickness and cooled in the air after the process. In the heat treatment process, which is another of the production processes, the samples were made available by specifying the parameters of heat treatment, solution, quenching and artificial aging. The microstructure images taken at each stage of production and the applied mechanical tests were examined and evaluated.

Keywords: Al7039 alloy, casting, heat treatments

Al7039 Zırh Alaşımının Yeniden Üretim Parametrelerinin Belirlenmesi

Öz: Bu çalışmada, günümüzde zırh malzemesi olarak bilinen Al7039 alaşımının, yeniden üretim parametrelerinin belirlenebilirliği üzerinde durulmuştur. Ticari olarak elde edilen Al7039 alaşımlı plakalar, döküm fırınında ergitilerek, özel olarak hazırlanmış kalıp içerisine dökülmüştür. Kalıp basınç kapağı kapatıldıktan sonra, numuneler yaklaşık 18 MPa basınç ile kalıp içerisinde sıkıştırılmıştır. Uygun döküm sürecinin belirlenebilmesi için plakalar farklı soğuma hızlarında soğutularak incelenmiştir. Genellikle döküm sonrasında uygulanan homojenleştirme ısıl işlem parametreleri belirlendikten sonra, sıcak dövme işlemine geçilmiştir. 400 ^{o}C sıcaklıkta 15dk bekletildikten sonra, 15mm kalınlıktan 6mm kalınlığa düşürülen plakalar, işlem sonrası havada soğutulmuştur. Üretim süreçlerinden bir başkası olan ısıl işlem evresinde çözeltiye alma, su verme ve suni yaşlandırma ısıl işlem parametrelerinin belirlenmesi ile numuneler kullanılabilir hale getirilmiştir. Her üretim aşamasında alınan mikro yapı görüntüleri ve uygulanan mekanik testler incelenerek değerlendirilmiştir.

Anahtar Kelimeler: Al7039 alaşımı, döküm, ısıl işlemler

1. Introduction

Aluminum, which is one of the youngest members of the global metal world, is now widely used in many areas of the industry, due to the technological advances of today and the technical features it possesses. In practice, the ratio of the strength to the weight (specific strength) is very large, soft and has a ratio of one third of the weight of the steel. When alloyed by adding alloying elements, its

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mechanical properties can be increased so that it can be compared with steel, making this material very attractive in various branches of industry such as medicine, construction, food, automotive and aerospace industry [1].

7xxx series Al-Zn-Mg-Cu alloys are frequently used in structures with difficult working conditions because they are hardenable by aging and have high strength properties[2]. Precipitation microstructures increase the yield strength of the alloy because it prevents dislocation movement through material. The magnitude of the strengthening effect is naturally related to the microstructural properties and interfacial energies of the precipitates [3]. Further improvement of the mechanical properties of Al-Zn-Mg alloys is possible, especially by using the combination of heavy plastic deformation and by repairing the microstructures after heat treatment [4].

In particular, Al7039 alloys have distinctive features due to their high power and energy absorption capacities and are preferred as armor materials in the defense industry [5]. The search for the reproducibility of an alloy with these properties has an important role nowadays. In this respect, the steps to be followed in the production of the 7xxx series Al alloys are schematically shown in Figure 1.

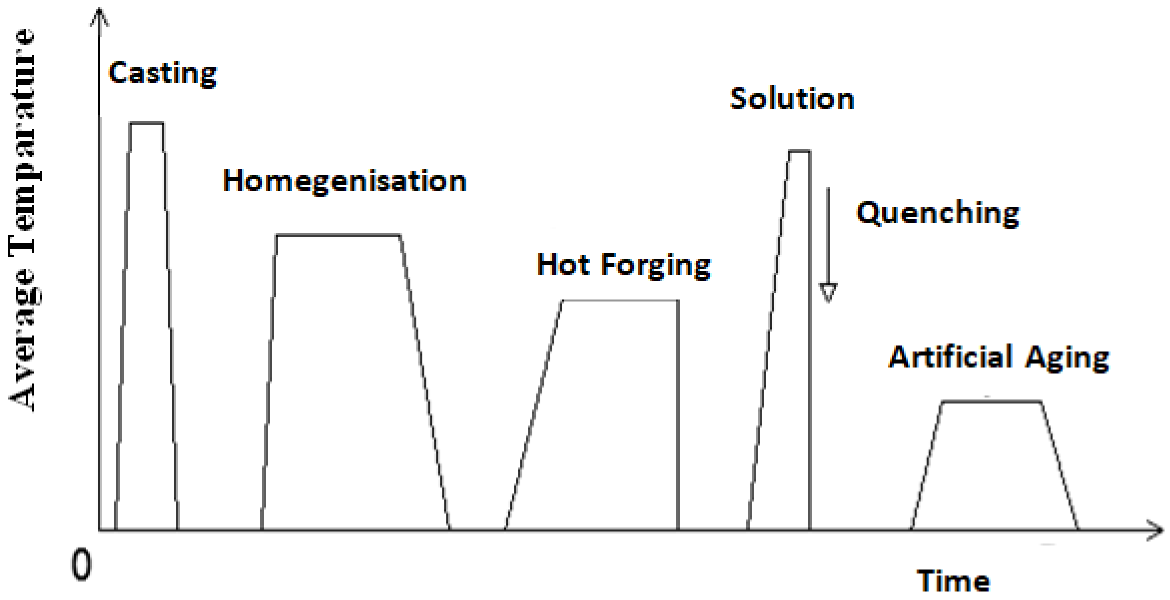

Figure 1. Production stages of 7xxx series aluminum alloys

At the beginning of the production process is the casting process. When the aluminum alloy is cast, the fastest cooling and solidification occurs near the mold surfaces. Aluminum-rich dendrites of α-phase grow in the direction of temperature flow and cause compositional differences at both macro and micro scales [2]. The solidification process also produces semi solid structure phase or equilibrium formed by a liquid-solid eutectic reaction [6]. The resulting unstable structure can be minimized by reducing the solidification rate, but this causes the cast to be longer and the grains to be larger. For this reason, the first thermal process to be performed after casting should be homogenization annealing. The main goal here is to eliminate the consequences of dendritic segregation and to dissolve coarse-grained eutectic intermetallic particles, which lead to a reduction in the mechanical properties of the alloy [7].

During the next process, hot rolling, significant dynamic recovery occurs, and dislocations rearrange themselves with the shaping of the grains. In this structure, which is defined as recrystallization, new grains are formed in the deformed grains and nucleation occurs [2]. The purpose of the post-deformation solution treated is to obtain a complete solution of the majority of the alloy elements. In this case, a suitable temperature is determined in the single-phase stable solid melt range and the material is held at this temperature for the specified time. After this process, it should be cooled rapidly in the room temperature water system [8]. After the dissolution process, aging heat treatment should be applied to ensure that the precipitates are well dispersed. With this method, materials can harden by blocking the movement of crystal defects called dislocations. For this reason, a well dispersed sediment is needed. This formation is called aging hardening [9].

2. Material and Method

In this work, commercially obtained Al7039 plates were cut to the appropriate dimensions and melted in the electric furnace after being placed in the graphite crucible. As shown in Fig. 2, the mold specially prepared for obtaining the casting sample of dimensions 110x110x15 (WxHxL) mm^3 is tightened with bolts at the edges with the aim of ensuring the sealing in the pressure medium. The prepared mold was placed in the annealing furnace and kept at a temperature of about 400 ° C for 30 minutes so that no sudden cooling occurred after casting and a completely homogeneous internal structure was formed. Immediately after the mold was removed from the furnace, molten material in the crucible was cast to mold. While the molten material was in the mold, the mold pressure cap was closed and squeeze process was performed at a pressure of 18 MPa. It is planned to eliminate defects such as gas jams, shrinkage and porosity by the applied pressure [10]. After squeeze process, the material solidified under pressure and the pressure was removed and the material was allowed to stand in the air for complete cooling in the mold. Thus, the production of the pressure casting sample cooled in the mold is completed.

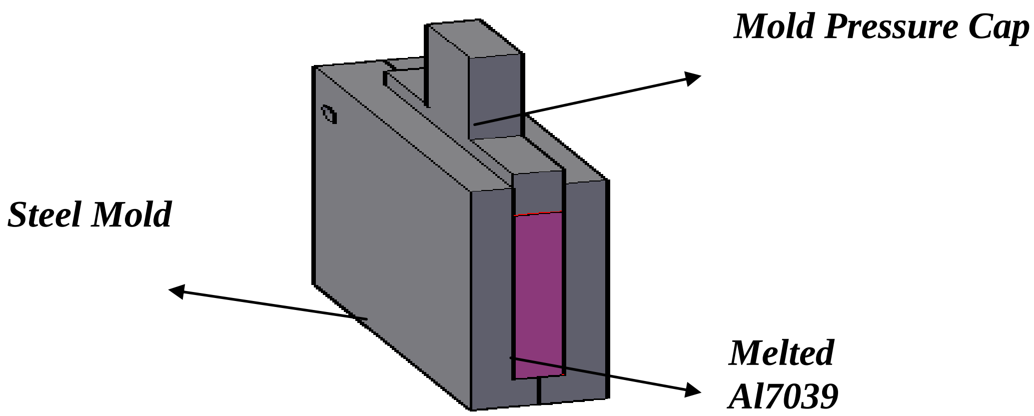

Figure 2. Pressure application after casting.

In addition to the method described above, various applications have been identified for examining other cooling types. In the second application stage, the same production method was continued but for post-pressure cooling, the mold was cooled to 1 ° C per minute in a 500 °C oven and waited until reached room temperature. In the third stage, the mold is opened directly after pressure and the produced material is cooled in the air. As the fourth stage cooling method, a non-pressurized sudden cooling casting process was applied. In this process, cold mold casting process is done by not heating the mold and the material is immersed to the water together with the mold as soon as the casting process is finished, When the molten material is poured into the mold, the solidification process begins and pressure is not applied. In this case, the rapid cooling process has been studied.

Since the four methods have different advantages and disadvantages, the application of pressure - fast cooling method which is a mixture of these methods has been put forward. In this application, the mold was heated as in the first method, the molten metal was poured and the pressure was applied by closing the mold pressure cap. When the mold temperature in the thermocouple measurement shows 500 ^{o}C, the mold is immersed in water and suddenly cooled down.

As a result of the casting applications, the sample required for homogenization annealing was determined and cooled in the furnace by heating at 465 ° C, 470 ° C, 475 ° C, 480 ° C and 485 ° C for 24 hours to determine the heat treatment parameters. As a result of the necessary determinations, the sheet having a thickness of 15 mm was forged to a thickness of 6 mm on the forging machine by heating at 400 ° C for 15 minutes in the furnace. After the forging process, the samples prepared for the solution taking process in dimensions of 15x10x6 mm3 were subjected to quenching at room temperature after being kept in furnace at 400, 420, 440, 460, 480 and 500 ^{o}C for 2 hours. In the light of the obtained results, the correct solution temperature is estimated. However, when we work to save cost and time, the optimal combination of temperature and time of waiting for solution heat treatment has been determined.

In the aging process as the last of the production processes, the samples taken from the solution were kept at 12-24-36-48 hours separately at 100-110-120 ^{o}C temperatures and the appropriate aging parameters were determined. Applied samples taken at each step, after the grinding and polishing process, where appropriate, Keller chemically (1 ml HF, 1,5 ml HCl, 2,5ml HNO_3, 95 ml H_2O) and Weck chemical (100ml H_2O, 4 g $KMnO_4$, 1 g NaOH) were etched. After etching process, microstructure of samples were examined with Nikon optical microscope and their hardness was measured using a Shimadzu GMV-20 hardness tester using 100 gr load. Samples with cut dimensions given in Figure 3 were prepared by cutting on a wire erosion tool and tested on a ZwickZ100 tensile tester to evaluate the results. Finally, the samples prepared as 30x30x6 mm were subjected to Pin-On Disc wear tested by Hitit University Scientific Technical Application and Research Center.

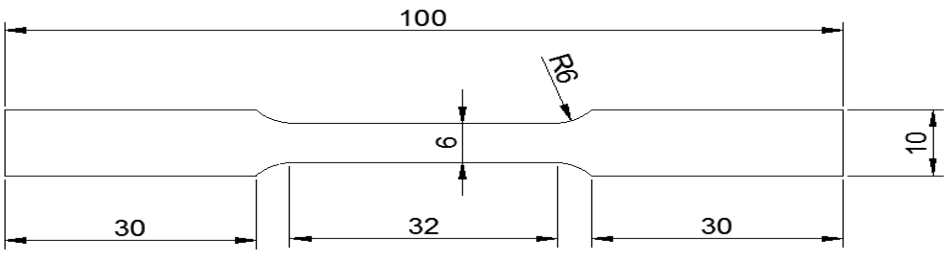

Figure 3. Tensile test sample dimensions (mm)

3. Results and Discussion

3.1.Casting process

Several methods have been applied to determine the casting process parameters which are the initial step in the remanufacturing of Al7039 alloy material. The microstructure images of the samples obtained from different methods applied in Figure 4 are given after etching in Keller and Weck solution.

Figures 4a-b show the microstructure of the sample produced by the non-pressurized casting - sudden cooling method. In Figure 4a, there are eutectic structures which occur at grain boundaries due to sudden cooling, and in Figure 4b the appearance of dendritic segregations is given. Non-equilibrium eutectics and intermetallics are precipitated in grain boundaries and interdendritic spaces during the final stage of solidification [11]. This case is seen in all of the sudden cooling methods.

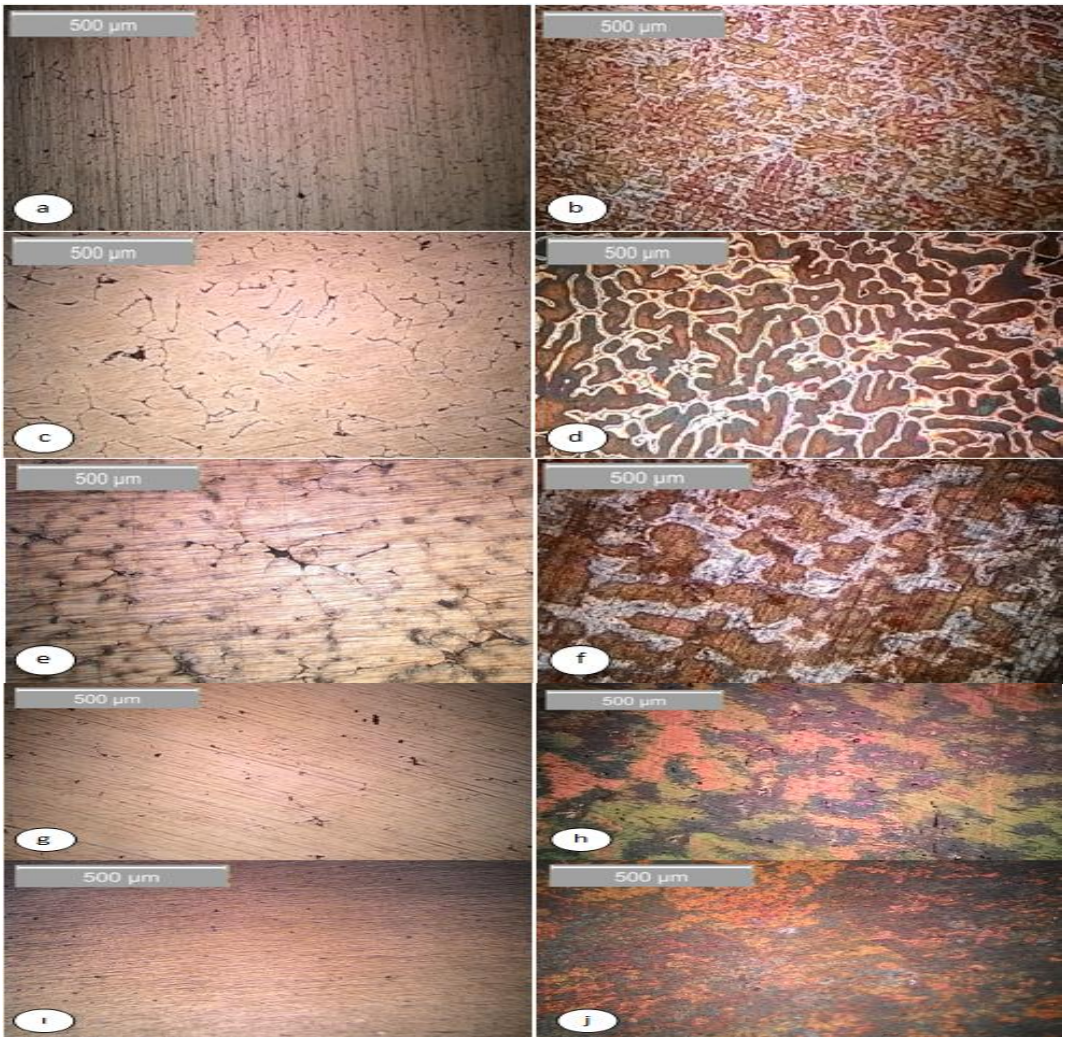

Figure 4. Microstructure images after casting a-b) non-pressurized casting - sudden cooling, c-d) pressure casting - sudden cooling at 500 ^oC, e-f) pressure casting - air cooling after mold opening, g-h) pressure casting - cooling in mold, i-j) pressure casting - cooling in furnace

Figure 4c-d is a microstructure view of the specimen produced by pressure casting - sudden cooling at 500 ^oC. Compared with the non-pressurized casting - sudden cooling method, it has been shown that the grains grow. The existence of the pressure and the excess of the solidification period revealed the correctness of this formation. It has been determined that the eutectic structure is simpler but grows more. Figures 4e-f show the microstructure of the sample produced by pressure casting - air cooling after mold opening method. In Figure 4e it was determined that the eutectic structure formed within in the dentritic cavities came together, but intermetallic structures begin to form. In Figure 4f it is determined that the grain sizes are larger than in the previous method.

Figures 4g-h show microstructural images of the sample produced by pressure casting - cooled in the mold method. Figure 4g shows that Mg and Zn, which are the main building blocks of the Al7039 alloy, are uniformly distributed in the structure, and that this regular distribution is confirmed by the absence of any eutectic structure. The slow cooling resulting from the heating of the mold ensured regular intermetallic particles of approximately 10 µm in size. In Figure 4h it was determined that the grain size was almost the same as the previous method.

Finally, in Figure 4ı-j, the microstructure image of the sample, produced by pressure casting - cooled in the furnace is given. In Figure 4ı, it appears that the useful intermetallics are almost complete, and the eutectic structure is completely absent. Moreover, grain growth, one of the detrimental effects of excessive slow cooling in figure 4j, is clearly seen in this method.

The average microhardness values of the obtained samples are given in Figure 5. In the non-pressure casting - sudden cooling method, average hardness value of the structure was determined as 104 HV on the basis of the frequency of the eutectic structure and the small grain size resulting from it. In pressure casting – sudden cooling at 500 ^{o}C method, the hardness value decreased to 80 HV with the eutectic structure and grain size growth. In pressure casting - air cooling after mold opening method, although the eutectic structure has grown even more, the hardness of the structure has increased to 118 HV with the appearance of intermetallic particles. When the cooling rate was reduced to some extent, the eutectic structure completely disappeared and the hardness value increased to 120 HV because it left its place in intermetallic formations. As the cooling rate is reduced further, the hardness value has decreased to 78 HV.

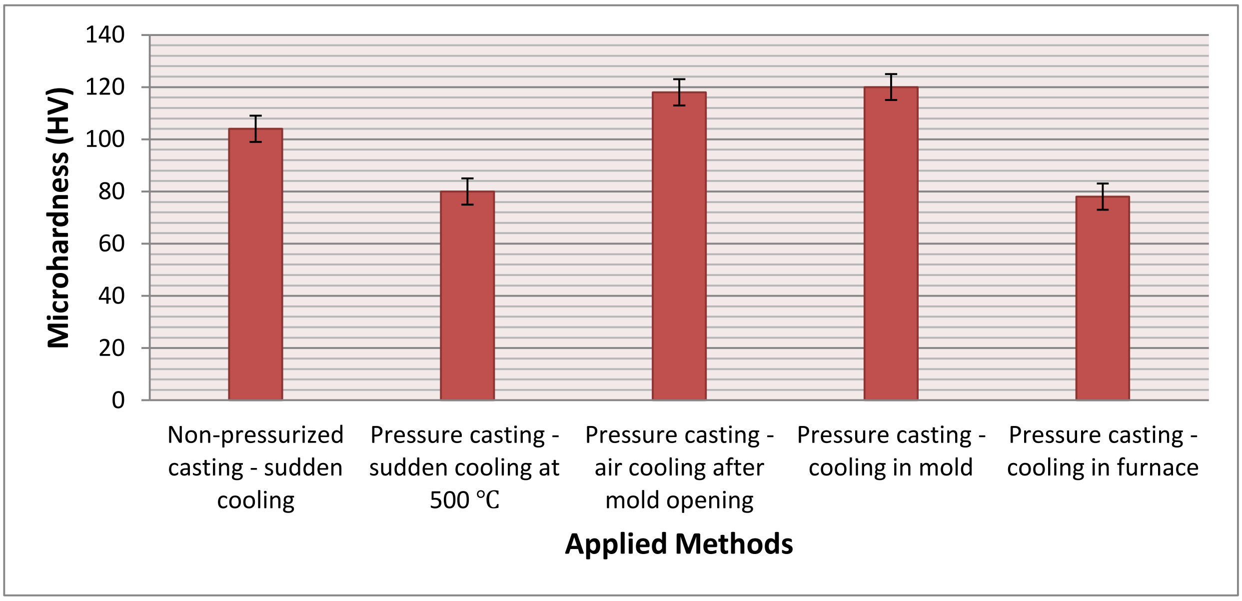

Figure 5. Hardness values of the obtained samples

Because of both the consistency in the microstructure and the priority in the hardness value, pressure casting - cooled in the mold method has been identified as the most suitable production method. It is estimated that the ideal cooling rate is reached in the microstructure examined and homogenization heat treatment is not required for this reason.

3.2. Hot forging process

As a result of the determination of the casting process, the next method, the forging process, has been passed. Firstly, cold rolled method was applied to the finished plate, but it was found that there was excessive cracking on the surface. Therefore, as a result of the pressure casting method, the air cooled sample in the mold is reduced from 15 mm thickness to 6 mm thickness after 15 minutes at 400 °C without being subjected to homogenization. Microstructure images of samples etched in Keller and Weck solution after hot forging are given in Figure 6.

Figure 6. After the hot forging, microstructure images (Respectively Keller and Weck solution)

After the hot forging process, the phases formed after casting have reduced their distance to each other and play a role in preventing the dislocation movement. At the same time, the grain structure became thin and long, and all the existing defects were destroyed. As a result of the microhardness test, it was observed that there was no significant change in the average hardness value after hot forging.

3.3. Solution Heat Treatment Process

The samples taken after the hot forging process were prepared to determine the temperature of solution heat treatment. The microstructure images resulting from the quenching process at room temperature after 2 hours waiting time at 400, 420, 440, 460, 480 and 500 °C are given in Figure 7. As a result of the investigations, it was observed that secondary phase particles come together at 400 °C temperature. These secondary phases, which are formed by the phases dissolved in the structure, accumulate at the beginning of the solution process, this phenomenon is generally called as precipitation formation [12]. This process was clearly completed at 440 °C and turned into fine particle distribution at 460 °C. At 480 °C, it showed growth again and partially disappeared at 500 °C, showing signs of excessive temperature or time. At larger temperatures, clustering was more irregular.

It was determined that the secondary phases completing the formation are derived from intermetallicities. This phenomenon can be considered as proof of the dissolution process.In order to form the supersaturated solid solution in the α (Al) matrix, the dissolution process must be completed. The dissolution process consists of the separation of phases in the structure. In Figure 7e, it is clear that secondary phases partially destroy the previous intermetallic structure as a result of the treatment at 480 °C. Although this destruction is not acceptable, the considerable proportion of intermetallic particles should not be ignored when the microstructure of commercial Al7039 material is recalled. In this case, the criterion we are looking for in the microstructure is the disintegration of intermetallic particles with regular aggregation during the dissolution process. Zou et al. In their study on Al7075 alloy, they obtained similar results after the solution and quenching process [13]. In order to determine the effect of the structures on the hardness, the results of microhardness measurements are given in Figure 8. In view of the results, the hardness before particle recovery started reached the highest value. This showed that 2 hours of waiting at 460 °C followed by sudden cooling could be considered as the post-casting solution of Al7039 material.

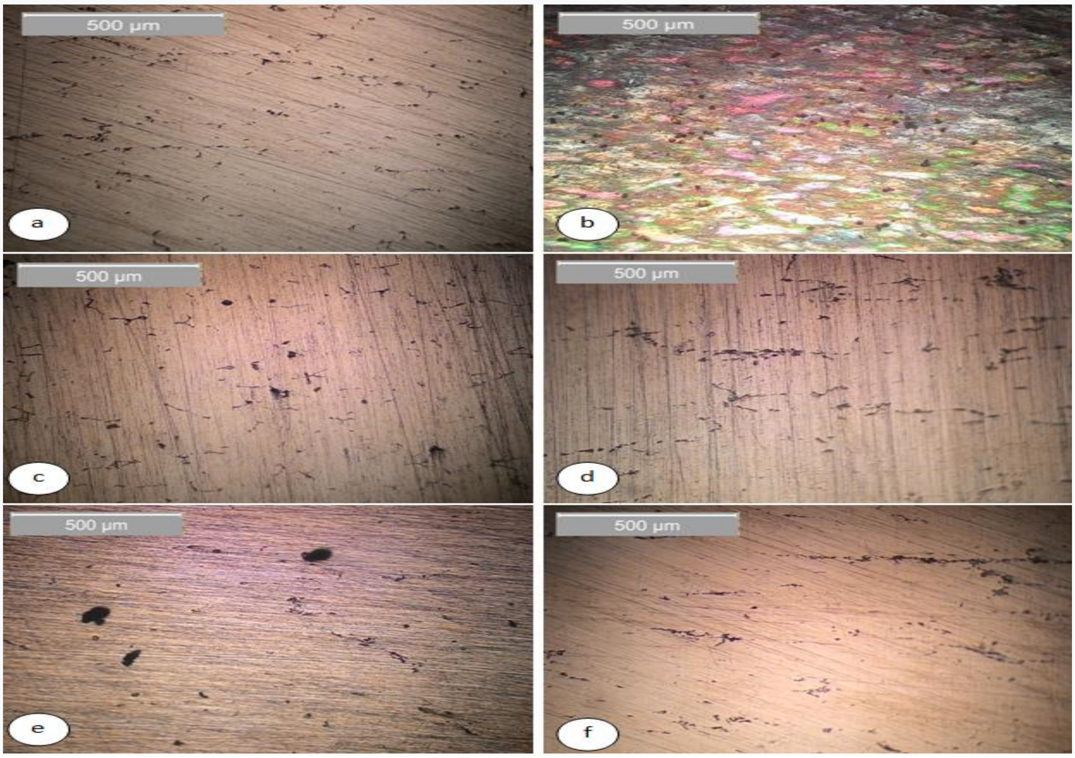

Figure 7. Microstructure images of the solution process with a waiting time of 2 hours at different temperatures a) 400 °C , b) 420 °C, c) 440 °C, d) 460 °C, e) 480 °C, f) 500 °C

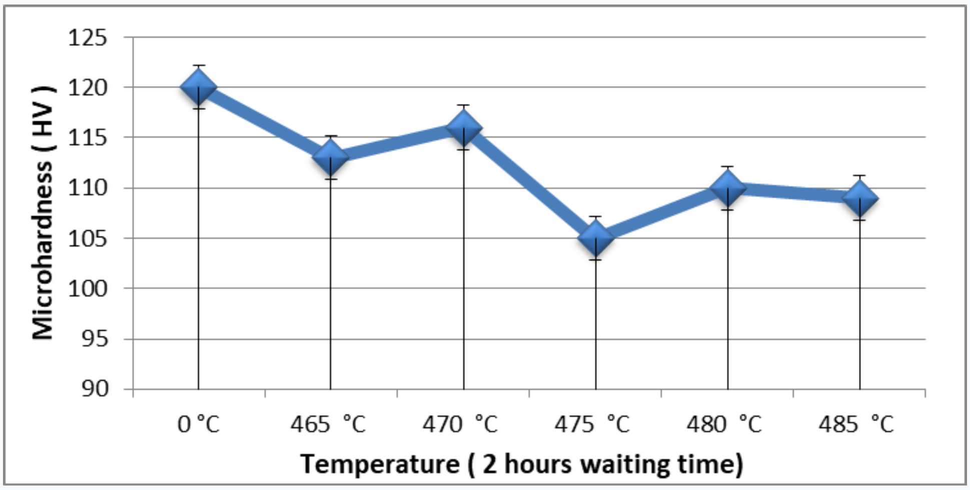

Figure 8. Hardness values of samples subjected to quenching after 2 hours of waiting at the specified temperatures.

However, this value can also be obtained by increasing the temperature and reducing the time of solution. Nowadays, considering the production time and the costs in return, it is inevitable to investigate this process. For this reason, 15, 30, 45, 60, 75, 90, 105 and 120 min waiting times at 480 °C, which is an upper temperature value, were examined and micro hardness graph of these structures is given in Figure 9. As can be seen from the graph, no linear increase in hardness was observed as a result of the change in waiting time.

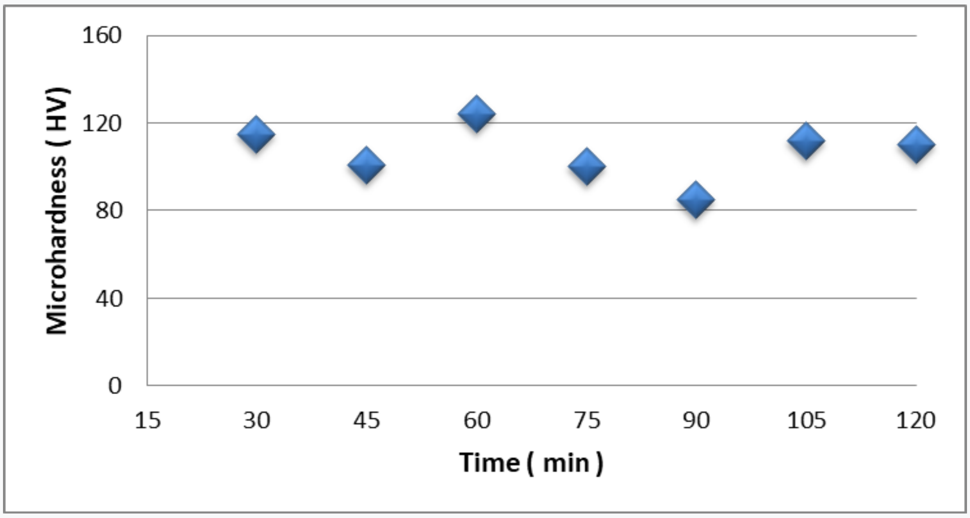

Figure 9. Micro hardness values of the samples which were taken into solution at 480 °C for different periods and subjected to quenching.

As a result of the necessary investigations, it was concluded that after 60 minutes waiting period and subsequent quenching, the formed phase particles were dispersed regularly. In this direction, the quenching process after the 60 min waiting time at 480 °C which has better hardness value but containing lower waiting time was determined as the ideal solution heat treatment parameter.

3.4. Artificial Aging Process

After determining the ideal solution parameter, artificial aging process, which is the last of the production stage, was started. In order to determine the artificial aging temperature and time, temperatures of 90, 100, 110 and 120 °C were selected and samples were kept at these temperatures separately for 24 and 48 hours. Figure 10 shows the microstructure images of the samples obtained.

In the micro structure studies, the formation of the structures as precipitates after dissolution process is observed. It should be noted that the formation of useful intermetallics does not disappear, as well as the formation of precipitates. It was observed that the intermetallic particles were decomposed in the sample which was kept at 90 °C for 24 hours and partly precipitates were formed with the waiting time reaching 48 hours. It is seen that the intermetallics decompose in a waiting time of 24 hours at 100 °C and precipitation is accompanied by this decomposition during 48 hours. The effects of high temperature were observed at the same waiting times at 110 and 120 °C and intermetallic disappearance, but precipitates were not formed sufficiently.

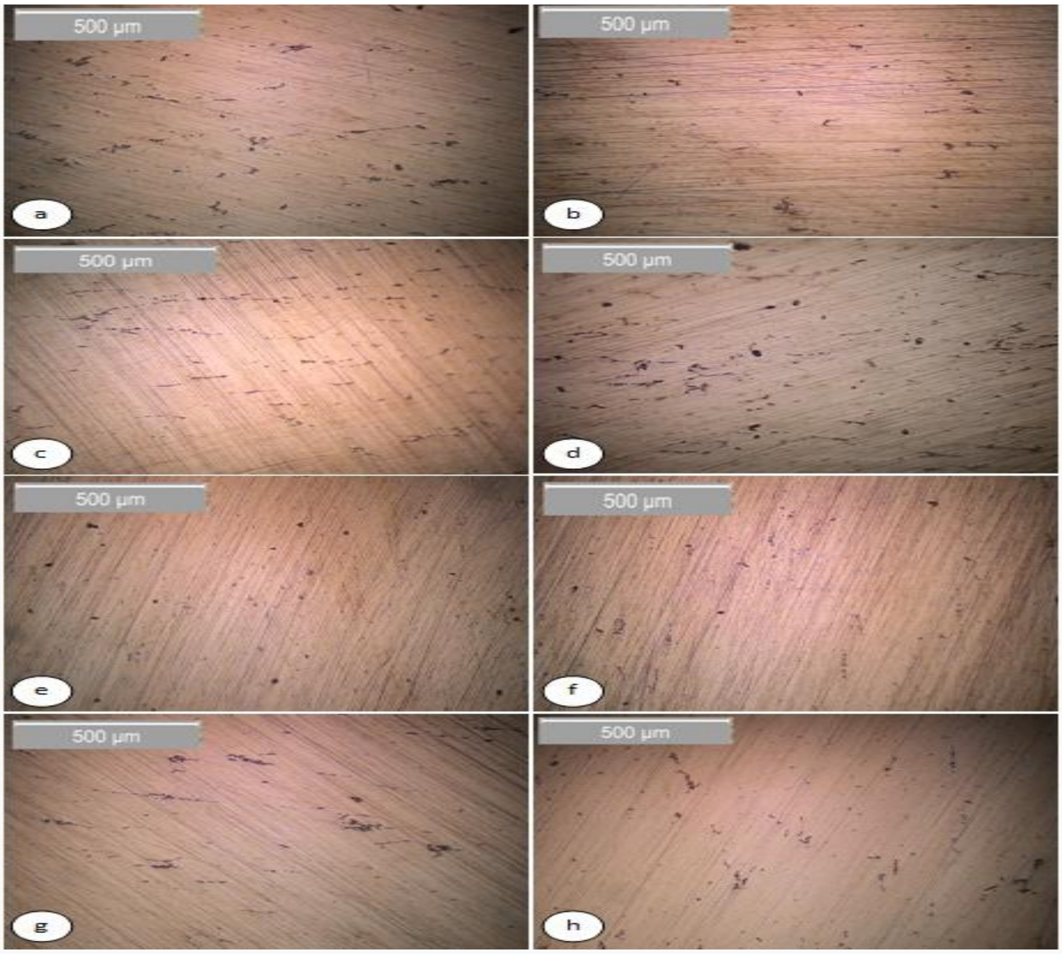

Figure 10. Microstructure images of samples aged at 24 and 48 hours respectively for artificial aging at different temperatures.

Micro hardness measurements of the obtained samples are given in Figure 11. In parallel with the microstructure properties, hardness values are determined in this direction. As a result of the operations performed, it is seen that the best value is realized at a temperature of 100 °C for 48 hours. Figure 12 shows the microstructure images of the artificially aged sample and the commercially obtained Al7039 sample etched with Keller and Weck at the temperature and time determined.

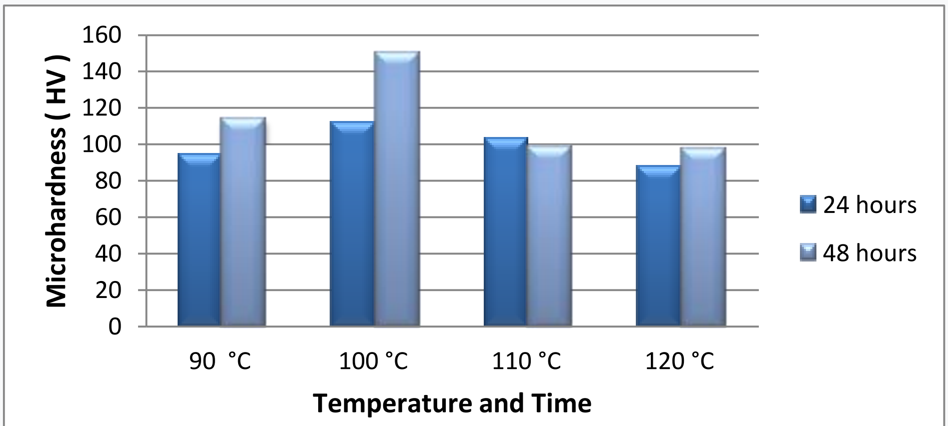

Figure 11. Micro hardness values of samples subjected to artificial aging at different temperatures and waiting times

When the microstructure images are examined, it is seen that there is a great similarity in particle structures and dimensions and grain structure and dimensions. According to the microhardness results of the sample, the average hardness in the α region was 142 HV, the average hardness of the phase particles was 158 HV and the average hardness of the interphase region was 151 HV. Microhardness values of commercially available Al7039 samples from the same regions were determined as 143 HV, 153 HV and 149 HV, respectively. In this case, it can be said that the microhardness similarities as well as the micro hardness values overlap with each other.

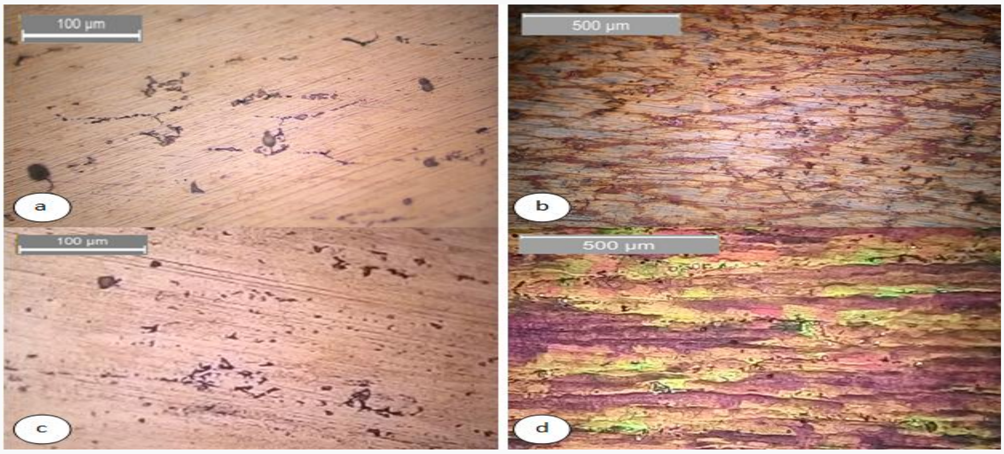

Figure 12. a-b) Microstructure image after artificial aging process, c-d) Microstructure image of commercial Al 7039 sample

Elemental analysis (XRF) results were obtained to determine whether the close results in the microstructure and hardness values were reflected in the chemical contents. Table 1 shows the chemical content of the commercially available material Al7039. When the values prepared according to percentage content are examined, it is seen that the general structure provides Al, Zn, Mg content. After this, Fe, Cr, Mn and Si contents are expected to play a decisive role in intermetallic formations.

Table 1. Chemical content of commercially available material Al 7039

Mg	Zn	Mn	Cr	Si	Fe	Cu	Ti	Diğer	Al
2.28	3.81	0.22	0.80	0.33	1.43	0.09	0.04	0.8	90.20

In Table 2, the chemical content of the material that is remanufacturing is given. It is seen that the chemical values of the elements that make up the material decrease, only Si content increases a little. After re-casting, the decrease in element values is expected. The increase in Si content is seen as an indicator of intermetallic formation.

Table 2. Chemical content of Al 7039 material which has been remanufacturing

Mg	Zn	Mn	Cr	Si	Fe	Cu	Ti	Diğer	Al
1.87	3.05	0.20	0.76	0.39	1.34	0.03	0.04	0.52	91.80

3.5. Mechanical tests

The remanufactured sample was subjected to tensile and wear tests and compared with the commercially obtained sample. The obtained tensile test graph is given in Figure 13. When the graph was examined, it was found that the materials showed the same properties up to 340 MPa but after that the tensile value of commercial Al 7039 sample increased slightly. After the examinations, while the properties of the two samples in the elastic region were the same, the superiority of commercial Al 7039 material in the plastic region was observed.

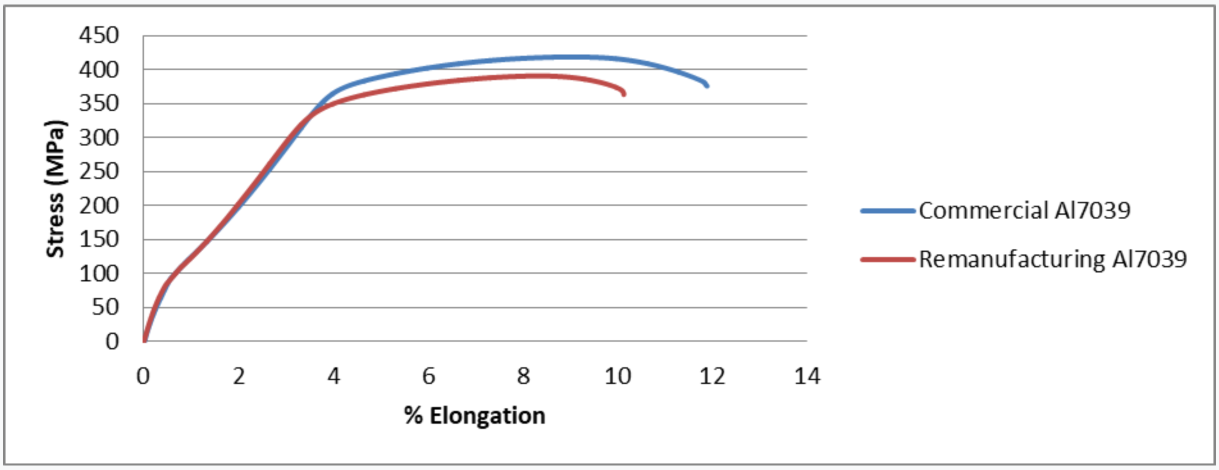

Figure 13. Tensile test graph of commercial and remanufactured Al7039 samples

In the abrasion test, 30x6 mm cross-section of the samples was used as a disc at 200 rpm, while the abrasive pin was contacted by applying 10 N force to leave a trace of 3 mm diameter on the material surface. 200 - 400 - 600 - 800 - 1000 m sliding distance and speed of 1.88 m / min after the completion of the experiment calculated the rate of wear is given in Figure 14.

When the graph is examined, it is determined that both samples have the same wear rate when the shear distance is 200 m and 800 m, while the wear rate of the reproduced sample is lower than the commercial sample at the other shear distances.

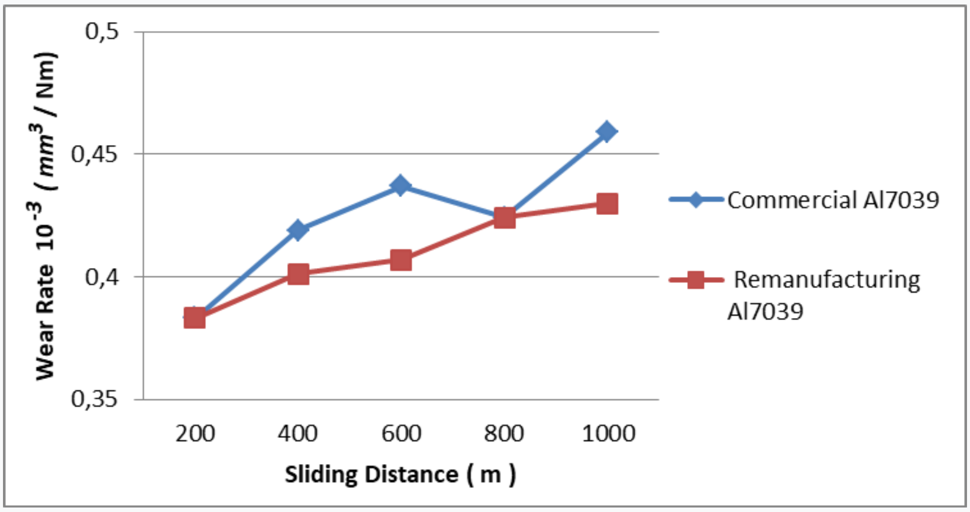

Figure 14. Wear rate graph of commercial and remanufactured Al7039 samples

4. Conclusions

1. In the study carried out on the casting process which is the first production stage of Al7039 material, the samples were molded after melting and subjected to various cooling and compression processes. These processes are called as non-pressurized casting - sudden cooling, pressure casting - sudden cooling at 500 ^{o}C, pressure casting - air cooling after mold opening, pressure casting - cooling in mold, pressure casting - cooling in furnace. When these methods are examined, pressure casting – cooling in mold is determined as the most suitable casting method because of its regularity in micro structure and its priority in hardness value (120 HV).

2. After determination of casting method, homogenization process parameters were investigated. The studies showed that the samples produced by the determined casting method can be used without homogenization process. Thus, the next process, hot forging method was started.

3. It was observed that the grain structure of the material became thin and long after the forging process at 400 ^{o}C and the existing gap defects disappeared. It was found that no significant change occurred in micro hardness value.

4. In the studies we carried out in solution and quenching process, it was determined that the best clustering in the structure was realized by quenching process after 1 hour waiting at 480 ^{o}C. In the case of artificial aging, the best decomposition and precipitations were observed during the 48 hour residence time at 100 ^{o}C and this observation was confirmed by micro hardness measurements.

5. In the micro structure comparisons, it was found that there is a great similarity in particle structure and dimensions of the two samples and grain structure and dimensions. The micro hardness measurement results were around 148 HV and confirmed this similarity.

6. When the tensile test results of these two samples were examined, the determined properties of Al7039 material, which was reproduced, were found to be about 6% lower than commercial Al7039 material. When the abrasion test results were examined, the superiority of the remanufacturing sample was determined.

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