Comparative Analysis of the Conventional Heat Treatment and Electro-Pulsing Treatment for the Microstructural Analysis

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Abstract. Heat Treatment is the most common application in the metallurgical analysis. For alternating some of the properties of the metal like physical and chemical, heat treatment plays a crucial role. Conventional heat treatment is a very common and traditional treatment in the study of material science. To make a sample as hot and cold, conventional treatment is very common but for the microstructural analysis like recrystallization, change in mechanical properties conventional heat treatment is not sufficient to make the precious analysis. Electro-pulsing treatment (EPT) creates the difference from the conventional heat treatment for the microstructural evaluation. In this work, we have reviewed a few of the samples (Eg. Cu strip, Si steel strip, Titanium alloy, etc.) from the experimental data and made a comparison between conventional heat treatment and EPT by analyzing the experimental data. Mainly we have focused on the Tensile strength, Elongation and Yield strength for both of the mentioned heat treatment. This work will be helpful to get a clear comparative view of the heat treatment of the two different methods.

Keywords: Electro-pulsing treatment, Conventional Heat Treatment, Microstructural analysis

1. Introduction

Physical and Chemical properties of the material is the study of the metallurgical analysis. Heat treatment plays the key role of this material analysis study. Conventional heat treatment is the widely used processes in which a piece of metal has been showered through heat from an external heat chamber[1-5]. It has to go several repetitive heating processes [7] that results the enhancing of its mechanical properties [8] like increasing of tensile strength [2-3], yield strength, elongation [6], increasing of ductility, removing of internal stress etc. It is worth to be noted that, it is a continuous flow of heat unlike the Electropulsing treatment (EPT) [4] in which some discrete electric pulses have been carried out through the metal and causes Joule heating effect [11-13].

2. Conventional Heat Treatment

When the temperature difference is created, the heat flows continuously from higher temperature end to lower end through the metal by conduction until the equilibrium arises. The thermal energy flowing per unit area per unit time has been characterized by:

\[ Q = -K \frac{dT}{dy} \]  \hspace{1cm} (1)

where \( K \) = thermal conductivity and \( \frac{dT}{dy} = \) temperature gradient. Steady- state condition has been satisfied when \( \frac{dQ}{dt}=0 \)[22]
Recrystallization is another property that is to be considered. Heat treatment causes deformation in the internal structure of metals, which leads to concentration gradient in the atoms. This arises the phenomenon of diffusion and is characterized by the coefficient of diffusion which further leads to the recrystallization in the internal structure. The number of atoms crossing the given surface per unit area per unit time is given by:

\[ P = -D \frac{dn}{dy} \]

(2)

where \( D \) = coefficient of diffusion and \( \frac{dn}{dy} \) = concentration gradient[26]

Several heat treatment methods [18] are used for the improvement of the metals. Some methods include:

Annealing is the process in which the metal has to be heated up to a certain temperature (critical point) and then it goes down to a slow cooling rate. By that, a well-refined microstructure reproduces which improves machinability of the metal. In ferrous alloy, annealing results the formation of pearlite. Annealing often soften the metal and through recrystallization it repairs the defects caused by plastic deformation.

In Normalizing technique, the grain size gains uniformity throughout the metals. It also makes the metals harder and stronger but less ductile than annealing. In this technique, the steel is heated above 40 degree above its upper critical temperature.

Stress relieving method is used to reduce the internal stresses of metals, in which the metals are heated below the lower critical temperature and then it is cooled indiscriminately. Tempering is used to improve the ductility of metals and thus to reduce the brittleness. In tempering, the steel is heated under the lower critical temperature (often from 205 to 395 degree centigrade) to impart some toughness, though some yield strength is lost.

3. Electropulsing Treatment

Electropulsing treatment (EPT) [9][10], is also known as high density electric current pulse [12] (ECP), is a process of heating of different material. Like conventional heating, Electropulsing not only heats of the material but also it improve the microstructural property [1][19] of the material like, recrystallization[15] grain size of the material, different strain, stress, and elongation[14][16]. Since the pioneering work of Trotsky in 1960’s this technique used in different material like copper, steel, and aluminium alloys [20]. The term electro pulse means the pulse of high density current with different time periods, which control by charging and discharging of the capacitor[17] using the circuit of electro-pulse system. The temperature of the material is increase due to increasing heat, produced by the electropulsing treatment of the material. Using the given equation, we can measure the temperature of the material,

\[ \Delta T = \rho j^2 t (C_P D)^{-1} \]

(3)

\( p \) = Resistivity of the material
\( j \) = Current density
\( t \) = Time
\( C_P \) = Specific heat of the material
\( D \) = Density of the material
\( T \) = Temperature

4. Comparative Analysis

4.1. For Deformed ZrTiAlV Alloy

We have also studied about another alloy to investigate its electropulsing effect on mechanical property [4]. The chemical formula of that alloy is Zr40Ti5Al4V. The electropulsing heat treatment is first-heating method. After this treatment on the material we can see the improvement of both microstructure of the material and also mechanical property. In case of conventional heat treatment of deformed ZrTiAlV alloy, the phase transition and recrystallization occur. But the improvement of microstructure like grain size is better in case of electropulsing treatment than the conventional heat treatment.

The sample was prepared with 40.2 wt. % Ti, 4.5 wt. %Al, 4.2 wt. % V and remain Zr was melting in a vacuum consumable electrode arc furnace and forged in to around bar with a size of 50 mm. The length of the specimen is 63 mm, height is 15 mm, and width is 2.86 mm. The applying current density of the electro-pulse on the sample with charging volt of 2kV, 4 kV, 6 kV and 8 kV [1].

The time interval between two pulses of the electropulsing effect is 400 µs. The electropulsing treatment is applied one time on each sample with current density 0.8, 0.93, 1.44, and 1.92 kA/mm² respectively.
Figure 1: Here, specimen (a) is treated with 2kV, specimen (b) is 4kV, and specimen (C) is 4kV and specimen (d) is 8kV charging. From the above picture, we can see that with increasing the charging voltage to 8k the material is fully recrystallized the average grain size is 26±5 µm, shown in figure (d).

It is again proved here that the grain size of the specimen during the conventional heat treatment is greater than the EP treatment, which is about 61 µm [23]. We also say that the microstructural change is negligible when the charging voltage is not above 4kV. The temperature increment due to electro pulsing treatment is calculated by the equation,

\[ \Delta T = \rho (C_p dS^2)^{-1} \int_0^t I^2 dt \]  

(4)

- \( C_p = 478 \text{ J/kg } ^\circ \text{C} \) is the specific heat
- \( D = 5.20 \times 10^3 \text{ kg/m}^3 \) the density of sample
- \( P = 1.78 \times 10^{-6} \text{ V } \Omega \text{m} \) the resistivity
- \( \tau_p = 400 \mu s \)
- \( I = J_0 \), \( J = \text{current density} \), \( s = \text{surface area} \).

The calculated temperature of the specimen is 86 °C, 284 °C, 614 °C, 1076 °C at 2kV, 4kV, 6kV and 8 kV respectively.

| Specimens        | \( \sigma_{0.2} \) (Yield strength) (MPa) | \( \sigma_{UTS} \) (Tensile strength) (MPa) | \( \varepsilon \) (%) | \( \phi \) (%) |
|------------------|------------------------------------------|------------------------------------------|----------------------|----------------|
| ST               | 739                                      | 922                                      | 21.0                 | 22.1           |
| Cold-rolle       | 1110                                     | 1280                                     | 7.2                  | 10.7           |
| Charging volt 2kV| 989                                      | 1231                                     | 7.9                  | 12.5           |
| Charging volt 4kV| 1050                                     | 1263                                     | 5.3                  | 9.6            |
| Charging volt 6kV| 1164                                     | 1337                                     | 2.0                  | 1.9            |
| Charging volt 8kV| 817                                      | 959                                      | 22.0                 | 35.2           |

4.2. For TC4 titanium alloy sheet

There is another useful material Titanium alloy which also annualized here. Titanium alloy (TC4) is mainly used in aeronautics and astronautics application for its good mechanical properties [21]. It has also few limitations like lower thermal conductivity, causing higher- internal stress and forming cracks [4]. To improve the mechanical property and its microstructure we use high density electro pulsing treatment. The sample was prepared along the rolling direction from the TC4 sheet. The length of the sample was 17 mm, width 4 mm and thickness were 1.4 mm [4]. The samples were divided in three parts sample A, sample B and sample C. Sample A was untreated by electro pulsing and it use to compare the influence of
electro pulsing. Sample A and B were treated by electro pulsing. The schematic diagram of sample is shown in Figure 2.

![Figure 2: Specimen and Waveform](image)

The wave form of the electro pulsing treatment is shown right side. The value of the period of the pulse is same (110 µs) for both the samples but the value of the current density is different. The value of current density for sample B was \( J = 5.26 \text{ KA/mm}^2 \) and for sample C \( J = 5.09 \text{ KA/mm}^2 \). The experimental result is shown blow Table 2 [4]. Figure 3 represents the stress-strain curves.

| Specimen | State          | Tensile strength, \( \sigma_b \) / MPa | Yield strength, \( \sigma_{0.2} \) /MPa | Total elongation % | Uniform elongation % | Yield to tensile ratio | \( \sigma_{0.2}/E \) |
|----------|----------------|----------------------------------------|----------------------------------------|--------------------|----------------------|------------------------|--------------------|
| A        | Annealed       | 1033                                   | 936                                    | 15.6               | 10.0                 | 0.91                   | 0.0086             |
| B        | Pre-EPT        | 1026                                   | 769                                    | 17.90              | 13.0                 | 0.75                   | 0.0071             |
| C        | Inter-EPT      | 947                                    | 750                                    | 23.18              | 18.01                | 0.79                   | 0.0069             |

![Figure 3: The distribution curve between true-stress vs Strain](image)

![Figure 4: (a) (b) and (c) are correspond to sample A B and C. From the picture we see that after Electropulsing treatment the microstructure of the sample have change significantly. The recrystallization occurs in the sheet. And the grain growth was not found.](image)

The possible reasons of electro pulsing effect are the effect of electron wind, joule heating effect and the mosaic thermal action, and the thermal compressive stress [4]. The temperature raising formula of the sample due to joule heating effect is given by

\[
\Delta T = (C_p\rho S^2)^{-1} \int_0^T \gamma I^2 dt
\]

where:
- \( I \) = Amplitude of currant
- \( T \) = Time duration of pulsing
- \( S \) = Cross-sectional area of the sample
- \( \gamma \) = Electrical resistivity of the material (1.8 x 10^-6 Ωm)
- \( \rho \) = Density of the material (4.44 x 10^3 Kg/m^3)
- \( C_p \) = Specific heat capacity of the material (750 J/kg. C)
From the above equation the temperature raise of the sample A and C are -728 and 629 °c respectively.

4.3. **Cu Strip**
The specimen is a cold drawn Copper (99.9%) wire whose thickness is 0.60 mm and the width is 3.12 mm has been kept in room temperature [2]. Following table represents the tensile strength, elongation and the electrical resistance of the cu strip for the conventional and after the EPT processing (Table 3). In tradition case, the tensile strength is 395 MPa and the elongation is only 3.4% [2].

| Sample No. | Electropulsing frequency(Hz) | Tensile strength(MPa) | Elongation (%) | Electrical resistance (× 10^-8 ohm) |
|------------|------------------------------|-----------------------|----------------|-----------------------------------|
| 0          | (conventional treatment)     | 395                   | 3.4            | 1.73                              |
| 1          | 200                          | 321                   | 5.1            | 1.69                              |
| 2          | 300                          | 261                   | 25.0           | 1.68                              |
| 3          | 400                          | 254                   | 32.0           | 1.67                              |
| 4          | 500                          | 238                   | 42.6           | 1.65                              |

The optical microstructure of Cu strips before and after EPT is presented in the following figure. It shows the evident of recrystallization microstructure in which grains grew to 20 µm (Figure 4).

**Figure 5:** The microstructure of the Cu strip (a) cold rolling (b) Treated by EP with the frequency of 500 Hz [2]

EBSD orientation map of Cu strips after EPT is shown in the following figure (a)-(d). It seems the average grain sizes increases from 5 to 18 µm as frequency increases [2] (Figure 5).
Figure 6: EBSD orientation map of Cu strip annealed by electropulsing: a) 200 Hz, b) 300 Hz, c) 400 Hz, d) 500 Hz

4.4. Silicon Steel Strips
The material composes with Al(0.024 wt.%), N(0.026 wt.%), Cu(0.10 wt.%), Si(3.0 wt.%), Fe in balance. The width of the alloy strip is 5 mm and the thickness is 0.3 mm which has been produced after a final reduction of 23% of cold rolling [3] (Table 4).

Table 4: Variation in the tensile stress & elongation with the temperature of both EPT & THT

| Temperature (°C) | UTS by THT/MPa | UTS by EPT/MPa | Elongation by THT (%) | Elongation by EPT (%) |
|-----------------|----------------|----------------|-----------------------|-----------------------|
| 420             | 672            | 668            | 7                     | 6.5                   |
| 480             | 613            | 618            | 13                    | 16                    |
| 520             | 548            | 562            | 17                    | 20                    |
| 560             | 519.5          | 532            | 22                    | 26                    |
| 630             | 512            | 520            | 24                    | 32.5                  |
| 720             | 508            | 512            | 27.5                  | 26                    |
| 800             | 498            | 487            | 23                    | 22                    |

Following figure revealed the relation between temperature and mechanical properties of both the THT and EPT specimens. After EPT, the dislocation accumulation developed, especially at the low angle grain boundaries, so dislocation density has increased which causes further development in the elongation and tensile strength [3].
Figure 7: Relationship of elongation and tensile strength of both THT and EPT with temperature

5. Conclusion
After this comparative study of the various samples from the various paper, we have mainly focused to the heat treat process and tried to find out the physical parameters. The collective physical parameters from the different experimental works we listed out few of the parameters to make a constructive analysis to study the defect mechanism of the materials. In this review work we are mainly focused on the ZrTiAlV Alloy, TC4 titanium alloy, Cu Strip and Silicon Steel Strip. From the above review it may concluded that, for the Electro pulsing treatment the tensile strain for the Cu strip & Si strip has decreased and the elongation increased. In terms of grain size, for the first two samples the grain size has decreased. Grain mainly signify the defect mechanism of the material for the micro structural analysis.

References
[1] Yang ZN Jiang F Wang XB 2019 Effect of Electropulsing Treatment on Microstructure and Mechanical Properties of a Deformed ZrTiAlV Alloy Materials (Basel) DOI:10.3390/ma12213560
[2] RF Zhu JN Liu GW Tang SQ Shi MW Fu 2012 Properties, microstructure and texture evolution of cold rolled Cu strips under Electropulsing treatment Journal of Alloys and Compounds
[3] Guoliang Hu Yaohua Zhu Guoyi Tang Chanhung Shek Jianan Liu 2011 Effect of Electropulsing on Recrystallization and Mechanical Properties of Silicon Steel Strips Journal of Material Science & Technology
[4] SONG Hui WANG Zhong-jin GAO Tie-jun 2004 Effect of high-density Electropulsing treatment on formability of TC4 titanium alloy sheet
[5] Yizhou Zhou Suhong Xiaojingdong Guo 2004 Recrystallized microstructure in cold working brass produced by electropulsing treatment Materials Letter
[6] M Gao G H He F Yang J D Guo Z X Yuan B L Zhou 2002 Effect of electric current pulse on tensile strength and elongation of casting ZA27 alloy Material Science & Engineering: A
[7] M H Park, A Shibata, N Tsuji “Grain refinement of 2Mn-0.1C steel by repetitive heat treatment and recrystallization”. August 2015. IOP Conference series Materials Science and Engineering 89(1). DOI: 10.1088/1757-899X/89/1/012041
[8] Yanbin Jiang, Lei Guan, Guoyi Tang, Zhihao Zhang “Improved mechanical properties of Mg-9Al-1Zn alloy by the combination of aging, cold-rolling and electropulsing treatment”. Journal of Alloys and Compounds. 25 March 2015
[9] Lei Guan, Guoyi Tang, Yanbin Jiang, Paul K Chu “Texture evolution in cold-rolled AZ31 magnesium alloy during electropulsing treatment”. Journal of Alloys and Compounds. 13 November 2009
[10] Yanbin Jiang, Guoyi Tang, Lei Guan, Shaonan Wang, et al “Effect of electropulsing treatment on solid solution behavior of an aged Mg alloy AZ61 strip”. October 2008. Journal of Materials Research 23(10):2685-2691. DOI:10.1557/jmr.2008.0328
[11] Reiyu Chein, Yeong Chin Yang, Yushan Lin “Estimation of Joule heating effect on temperature and pressure distribution in electrokinetic-driven microchannel flows”. February 2006. Electrophoresis 27(3):640-9. DOI:10.1002/elps.200500314
[12] W J Lu, R S Qin “Stability of martensite with pulsed electric current in dual phase steels”. Material Science and Engineering: A. 20 November 2016
[13] Xin ZHANG, Hongwei LI, Mei ZHAN “Mechanism for the macro and micro behaviors of the Ni-
based superalloy during electrically-assisted tension: local Joule heating effect”. Journal of Alloys and Compounds. 25 April 2018.

[14] Yinying Sheng, Youlu Hua, Xiaojian Wang, Xueyang Zhao, et al “Application of High-Density Electropulsing to improve the performance of Metallic Materials: Mechanisms, Microstructure and Properties”. January 2018. Materials 11(2):185. DOI: 10.3390/ma11020185

[15] Yang Liu, Jianfeng Fan, Hua Zhang, Wei Jin, Hongbiao Dong, Bingshe Xu “Recrystallization and microstructure evolution of the rolled Mg-3Al-1Zn alloy strips under electropulsing treatment”. Journal of Alloys and Compounds. 15 February 2015

[16] Zhu R F Tang G Y Shi S Q 2013 Effect of electropulsing treatment on the microstructure and super elasticity of TiNi alloy Applied Physics A 111(4). DOI: 10.1007/s00339-012-7342-3

[17] Jianyi ZHENG Wen HE Runjie SHEN 2010 Development of Electropulsing Treatment Device Based on Capacitor Energy Storage and Discharge Advanced Materials Research 139-149:163-166. DOI: 10.4028/www.scientific.net/AMR.139-141.163

[18] Hasan MF 2016 Analysis of Mechanical Behavior and Microstructural Characteristics Change of ASTM A-36 Steel Applying Various Heat Treatment Journal of Material Science & Engineering 05(02). DOI: 10.4172/2169-0022.1000227

[19] W Zhang M L, Sui Y Z Zhou D X Li 2003 Evolution of microstructures in materials induced by electropulsing Micron

[20] Phillip J Noell Jeffrey M Rodelas Zahra N Ghanbari Chris M Laursen 2020 Microstructural modification of additively manufactured metals by electropulsing Additive Manufacturing

[21] Yizhou Zhou Jingdong Guo Wei Zhang G H He 2002 Influence of electropulsing on nucleation during phase transformation December Journal of Material Research pp3012-3014. DOI: 10.1557/JMR.2002.0438

[22] Garg S C Bansal R M Ghosh C K (2012). Thermal Physics: Kinetic Theory, Thermodynamics and Statistical Mechanics (2nd edition) McGraw Hill Education (India) Private Limited pp 2.23, 2.26