Effects of Electropulsing on Steels

Achal R. Pathak[1], Avani M. Kala[2], Kamlesh M. Rana[3]

[1]Student, Mechanical Engineering Department, A.T.C. Indore, Madhya Pradesh, India
[2]Student, Computer Science & Engineering Department, A.T.C. Indore, Madhya Pradesh, India
[3] Assistant Manager, Quality Department, Essar steel India ltd, Hazira, Gujarat, India.

***

Abstract - *The invention of new techniques and improving the existing one is the main thought for development. The phase transition in metals is the transformation of a thermodynamic system from one phase to another by the process of heat transfer, and it can also done by various methodologies like heat treatment, particle and wave radiations, hydraulic pressure, electric and magnetic fields etc. Electropulsing or Electric pulse treatment is one of the modern techniques, and it shows tremendous results to improve various properties in metallic materials such as strengthening and grain refinement, crack healing,* nucleation rate and nanostructure formation, diffusion and precipitation enhancement *etc. To study the mechanisms governing electropulsing and its effects on microstructure and mechanical properties various researches are carried out. The main aim of this literature is to summarize the existing studies on the influence of electropulsing or electric pulse treatment on various steels.*

Key Words: Electropulsing, Strengthening of steel, Precipitation, Non-metallic inclusions, Crack healing.

1. INTRODUCTION

In the present era, the main aim of all the steel industries is not only to make a large production but also to obtain a maximum strength of steel. As the strength of materials increases the durability of material increases due to which we can consume a limited amount of material for satisfying our needs. For the improvement of mechanical properties and microstructural development, various pretreatment processes are carried out like heat treatment processes. Electropulsing treatment is a very efficient process as compare to other conventional treatments required for improving mechanical properties and give better results in a very less time and energy. Electropulsing is a process which provides phase transformation and it is capable of inducing low-temperature recrystallization in metallic materials at an accelerated rate compared to more traditional heat treatment methods. In this study, we cover the effects of electropulsing on steel grades such as 2205 duplex steel, Pearlite steel, 316L Stainless Steel, Molten Steel etc. The effects such as Strengthening at high temperature, crack healing, nucleation rate and Nanostructure formation, diffusion and precipitation enhancement, and effect on resistivity are discussed briefly.

2. STRENGTHENING OF STEEL AT HIGH TEMPERATURE (2205 DUPLEX STAINLESS STEEL)

Electropulsing usually reduces the stability of metastable structures and it induces the spheroidisation of cementite under ambient conditions. The mechanisms behind these observations are, the process of electropulsing-reduced kinetic barrier to structural transformation and it enhanced atomic mobility. The temperature rise caused by electrical heating may also accelerate the transformation of metastable phases [6].It is known from experimental measurements that the electrical resistivity of pure iron drops when its crystal structure changes from a body-centered-cubic (δ-phase) to a face-centered-cubic (γ-phase) at 1667 K. Electropulsing should stabilize the γ-phase and destabilize the δ-phase in dual-phase steels. The strength of the γ-phase is higher than that of the δ-phase. The σ-phase appears to be in the form of small particles that provide strengthening to the steel, despite the unfavorable effect of the σ-phase in terms of corrosion resistance.

$$\delta \rightarrow \gamma + \sigma$$

When electropulsing was done at high temperature it promotes the phase transformation according to the above reaction.

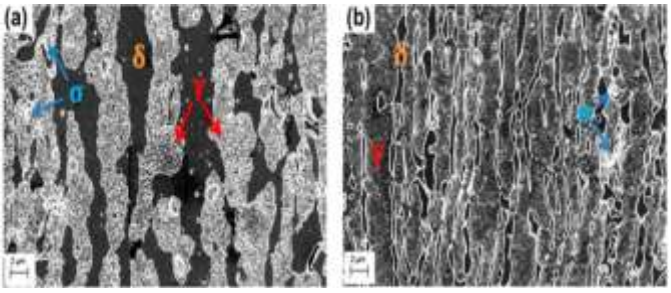

Fig -1: SEM images of the samples annealed (a) without and (b) with electropulsing at 835 °C for 40 min. **Reproduced from W.J. Lu et al. (2014), pp.3 Fig.2.**

After the EPT on the sample the volume fraction of δ-phase was decreased significantly, whereas the volume fraction of γ-phase and σ-phase are increases, which enhances its mechanical property.

3.DIFFUSION AND PRECIPITATION ENHANCEMENT (316L SS)

Precipitates are typically small particles, consist of high solute composition, and are formed in supersaturated alloys. Coarsening of precipitates can give rise to the loss of strength, localization of stress, initiation of crack, creeping and many other detrimental effects.

The alloy used in experiment (316L SS) is in fully austenite crystal structure when the temperature is between 1125.15 and 1495.88 K. Precipitation tends to take place when the temperature is lower than 1125.15 K and when the steel is in service at elevated temperatures.[15]

Precipitation of Mo and Cr increases its risk from corrosive failure, after electropulsing this sample the precipitates was dissolve due to which all the undesirable effects can be avoided. The average size of the precipitates in the electropulsed sample is much smaller than that of without electropulsing treatment. The acceleration effect of pulsed electric current contributes to the faster microstructure evolution of a material. This enhanced mobility may help precipitates to evolve to either direction of coarsening or dissolving more quickly. Different sizes and number densities of precipitates cause different electric current distributions.

The electropulsing accelerated kinetics allows dissolving precipitate that formed in a relatively long duration between pulses.

On the other hand, when electropulsing treatment is done on the spherical graphite iron there is an increase of graphite nucleation sites by the pulse current.

The experimental result indicates that the formation of graphite is accelerated by electropulsing during solid-state graphitization of the spherical graphite iron and a large quantity of spherical graphite appears in the structure. [11]

If the conductivity of new precipitate is higher, then the free energy change due to electric current during the formation of this precipitate is negative, the nucleation rate of precipitate increases.

On the other way, if the precipitate has higher resistivity, to lower the energy of the system, inclusion dissolves and atoms are transferred to defects and grain boundary.

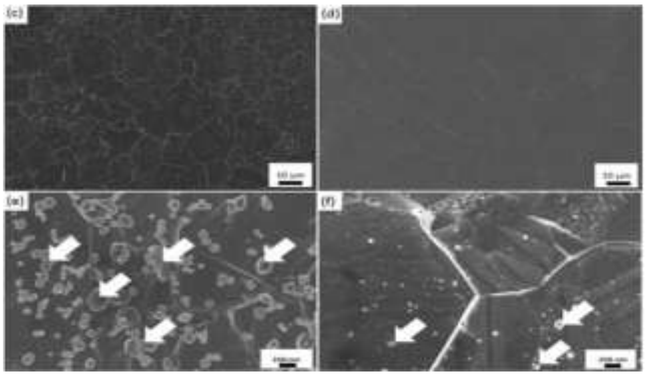

Fig -2: c and e are distribution of precipitates in sample without electric current treatment, d and f are the distribution of precipitates in sample with electric current treatment, **Reproduced from W. J. Lu et al (2014), pp.3 Figure 3.**

4. EFFECT ON NUCLEATION RATE AND NANO-STRUCTURE FORMATION (PERLITE STEEL)

Pearlite steel wires are applied broadly in engineering fields for their high tensile strength, high fatigue resistance, high wear durability and other merit mechanical properties.

Deformation and recrystallization can induce a lamellar to grain nanostructure transformation, where carbon atoms in cementite are transported to the ferrite phase by mechanical alloying and subsequently precipitate to the interface between Nano-scale ferrite sub-grains. The nanostructured lamellar pearlite can be obtained by controlling chemical and thermal processing conditions, where the migration of the ferrite-cementite interface has been controlled by the addition of aluminum and cobalt to steels.

The electropulsed microstructure in the annealed samples is similar to that of the cold-drawn samples.

However, electropulsing the cold-drawn pearlite steel wire generate more thorough grain nanostructure than that of the annealed wire because in this case cementite and ferrite plates are more aligned as compare to annealed pearlite steel wire.[7]

The lamellae perpendicular to the current direction causes more severe mechanical and thermal elevations than that of the parallel ones when electric current passes the pearlite steel wire. This means that the lamellae perpendicular to the electric current direction are easier to transform into grain structure than that of parallel ones. Hence, the orientation of cementation pearlite matters. In the fabrication of nanostructured grain pearlite steel wire, carbon diffusion within cementite during spheroidisation and from cementite to the interface of ferrite grains plays an important role in nanoscale lamellar to grain transformation.

The conductivity of wire increases surprisingly (almost double in these case).

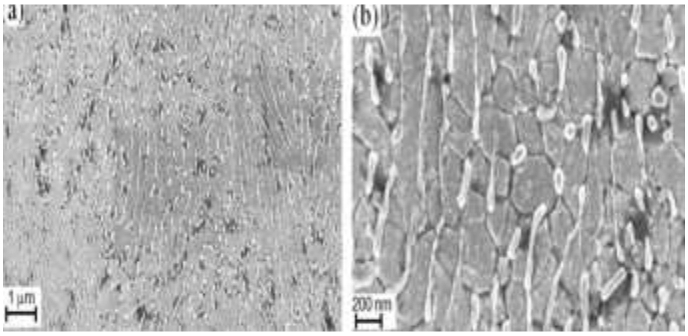

Fig -3: (a) and (b) SEM images for the electropulsed pearlite steel. **Reproduced from Rongshan Qin et al. (2017), pp 4, Figure-5**

5. INCLUSION CONTROL (MOLTEN STEEL)

Non-metallic inclusions are very harmful to the mechanical properties of steel by decreasing the toughness and increasing the risk for mechanical or corrosive failure of the final product. Actually, the conventional clean steel fabrication techniques, such as electromagnetic stirring, bubbling, and filtration are not efficient at eliminating inclusions of sizes smaller than 50 micrometers and involve significant energy consumption thus we use EPT on molten metal for removal of inclusions.

In order to control the level of sulphur, manganese is added, which reacts with sulphur to form MnS which is a common type of inclusion encountered in steel. MnS inclusion causes failure of steel through tearing hence clean steel is required
There are three types of morphology of MnS in molten steel

Type 1- Globular sulphides with a wide range of sizes.
Type 2- Dendritic structure (low ductility).
Type 3- angular sulphides on the grain boundary as a mono phase.

Normally the inclusion present in the steel matrix has high resistivity. It is suggested that electric current may expel a high resistivity object from a low resistivity matrix. Non-metallic inclusions have a higher resistivity than that of liquid steels and are expected to be expelled by electropulsing. Experimental results show that MnS inclusions can be expelled to the surface of the steel by using electropulsing treatment.

Hence, all the inclusions are gone from internal and shift to the surface. The morphology of the inclusions was altered greatly after electropulsing that is from angular to chain-like.

After EPT all the MnS inclusions from the bulk is removed and settle on the surfaces thus we can remove them easily with slag.

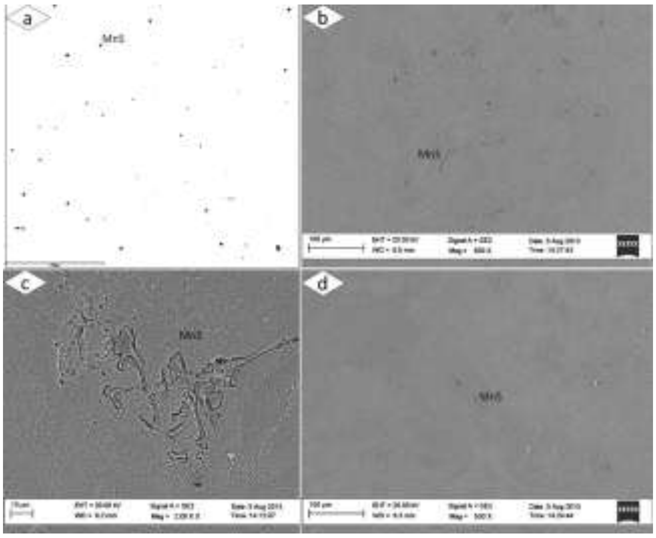

Fig -4: a MnS randomly distributed in untreated as solidified steel; b MnS dispersed on surface in electropulsed steel, c morphology of MnS; d MnS disappeared in inner part of matrix by electropulsing. **Reproduced from X.F. Zang et al. (2014), pp-247, Figure-3**

To physically explain why such a dispersion and morphology of MnS inclusions will be caused by electropulse based processing, the system free energy change ΔG_{elec} of molten steel must be considered. The ΔG_{elec} is obtainable from the expression of where μ is the magnetic permeability; j(r) is the current density at position r.[14]

$$\Delta G_{\mathrm{elec}} = \frac{\mu}{8\pi}\iint \frac{\vec{j}_{\mathrm{b}}(r)\vec{j}_{\mathrm{b}}(r') - \vec{j}_{\mathrm{a}}(r)\vec{j}_{\mathrm{a}}(r')}{|r-r'|} \mathrm{d}r\mathrm{d}r'$$

It means that the free energy is higher in the molten steel with the inclusions than that without it once a pulsed electric current passing through them. In order to minimize the system free energy, an Inclusion will be expelled by electropulsing.

6. CRACK HEALING (MEDIUM CARBON STEEL)

Some recent research has shown that crack in the metallic material can be filled by high-temperature environment but it alters the original microstructure which is undesirable, hence when we can use Electropulsing for crack healing.

With the help of electropulsing, the crack is partly healed and the healing process occurs with a very short duration pulse and the original microstructure in the area without a crack was maintained during the' 'healing" treatment.

The crack healing can be explained by a possible low temperature plasma state which may be created in the healed area because of electrical breakdown and due to generation of plasma local temperature at the area can be high. The thermal expansion of the material due to high local temperature since it is restricted by the cool matrix the direction of the matrix is inside the crack. The thermal expansion of matrix due to joule heating also can cause the effective atoms to move into the crack. When the crack face separation distance is small enough due to the thermal expansion, the crack can be healed in combination with the effect of plasma. Electropulsing is a promising method for further development of crack healing technique.[5]

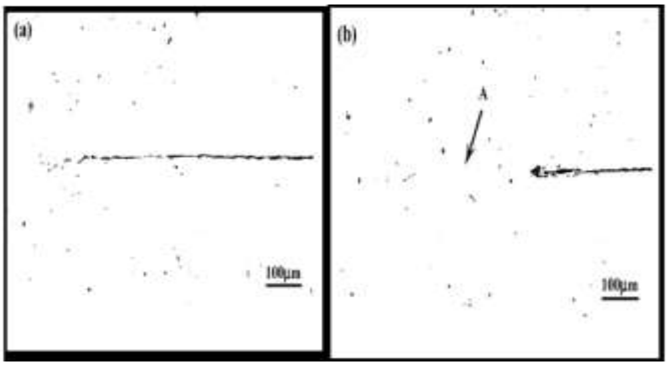

Fig.5 Optical micrograph of the left portion of a crack before (a) and after(b) Electropulsing. **Reproduced from Yizhou Zhoua, et al.d, (2003)**

7. CONCLUSION

In summary, the effects of electropulsing on various steels are studied and it is also clear that EPT provides better results in strengthening of steels, inclusion control in molten steels and also diffusion of precipitates in steel alloys. Different researches must be carried out to clarify the varying mechanical property changes observed across the literature, as the process cannot be feasibly applied in industry without such data.

REFERENCES

[1] H. Wang, L. Chen, D. Liu, G. Song & G. Tang , Study on electropulsing assisted turning process for AISI 304 stainless steel, Materials Science and Technology 2015 VOL 31

[2] Z. Xu, H. Wang, Z. Sun, Y. Ye & G. Tang, Effect of electropulsing-assisted turning process on AISI 5120 cementation steel, 2017 Institute of Materials, Minerals and Mining

[3] S. X. Lin, X. R. Chu, W. K. Bao, J. Gao and L. Q. Ruan, Experimental investigation of pulse current on mechanical behavior of AZ31 alloy, Materials Science and Technology 2014 VOL 0

[4] B. Elliott-Bowman1 and R. S. Qin, The effects of electropulsing on metallic materials,

[5] Yizhou Zhoua, Jingdong Guob, Ming Gao, Guanhu Heb, Crack healing in a steel by using electropulsing technique, 2003

[6] W.J. Lu, X.F. Zhang and R.S. Qin, Electropulsing-induced strengthening of steel at high temperature,2014

[7] Rongshan Qin, Yongkun Luo, Bernadette Elliott-Bowman & Osamudiamen Omoigiade, Fabrication of nanostructured pearlite steel wires using electropulsing, 2017

[8] Atsushi Hosoi, Tomoya Kishi and Yang Ju, Healing of Fatigue Crack by High-Density Electropulsing in Austenitic Stainless Steel Treated with the Surface-Activated Pre-Coating, 2013

[9] Guoliang Hu, Yaohua Zhu, Guoyi Tang, Chanhung Shek and Jianan Liu, Effect of Electropulsing on Recrystallization and Mechanical Properties of Silicon Steel Strips,2011

[10] Yanbin Jiang , Guoyi Tang , Chanhung Shek , Jianxin Xie , Zhuohui Xu , Zhihao Zhang, Mechanism of electropulsing induced recrystallization in a cold-rolled Mg–9Al–1Zn alloy,2012

[11] QingChun Li a, RenXing Li b, XuDong Yuea, GuoWei Changa, QiJie Zhaib, Effect of electropulsing on the formation of graphite during solid-state graphitization of spherical graphite iron,2008

[12] Tao Liu, Haibo Wang, Guoyi Tang & Guolin Song, Surface modification of D36 steel by ultrasonic impact with electropulsing,2017

[13] W.J.Lu , R.S.Qin, Stability of martensite with pulse delectric current in dual-phase steels,2016

[14] X. F. Zhang, W. J. Lu & R. S. Qin, Morphology and distribution control of MnS inclusions in molten steel by electropulsing, Materials Research Innovations 2014 VOL 18

[15] W. J. Lu, X. F. Zhang and R. S. Qin, Stability of precipitates under electropulsing in 316L stainless steel, Materials Science and Technology 2014 VOL 00

[16] Alireza Rahnama1 & Rongshan Qin, Room temperature texturing of austenite/ferrite steel by electropulsing,2017
[17] Effect of Electropulsing on the Microstructure evolution of pearlitic steel by Bhowmik, Arghya (Computational Metallurgy)Graduate Institute of Ferrous Technology ,Pohang University of Science and Technology 2009

AUTHORS

Mr. Achal R. Pathak
Student of ME, ATC, Indore, Madhya pradesh

Mis. Avani M. Kala
Student of CSE, ATC, Indore, Madhya pradesh

Mr. Kamlesh M. Rana
Assistant Manager, Quality Department, Essar steel India ltd, Hazira, Gujarat, India