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EFFECT OF ELECTRIC CURRENT PULSE ON MECHANICAL PROPERTIES OF ULTRA-HIGH STRENGTH STEEL 1180CP

Nguyen Trung Thien[1,*], **Sung-Tae Hong**[2]

[1]*Center of Mechanical Technology Training & Practice, Hung Yen University of Technology and Education, Dan Tien, Khoai Chau, Hung Yen, Viet Nam*

[2]*School of Mechanical Engineering, University of Ulsan, 93 Deahak-ro, Nam-gu,Ulsan, South Korea*

Email: trungthienckc@gmail.com*

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ABSTRACT

Effect of the pulse electric current on mechanical properties of an ultra-high strength steel (UHSS) is experimentally investigated. A single pulse of electric current with a short duration of 0.36 sec is applied to the specimen under tensile plastic loading. The experimental result showed that flow stress of the UHSS nearly instantly drops at moment of electric current, following strain hardening until necking of the specimen. Uniform elongation completely depends on the pulsing strain, while ultimate tensile strength slightly changes after electric current.

Keywords: electric current, ultra-high strength steel, mechanical property.

1. INTRODUCTION

In recent years, ultra-high strength steels (UHSS) with a tensile strength higher than 1 GPa, often up to 1.8 GPa, have been increasingly selected in the automotive industry due to their outstanding advantages including high crashworthiness, high strength to weight ratio, excellent weld ability, and cost effectiveness [1]. The use of UHSS in structural areas such as pillars, bumpers, and front cross-members can make automotive frames much stronger, stiffer, and lighter than those made of conventional steels. However, UHSS generally show low formability and high spring back, which make it difficult for automakers to manufacture UHSS automotive parts in desired shapes with an affordable cost. Therefore, it is natural that a huge demand exists in the automotive industry for a cheap and easy-to-implement technology to improve the formability of UHSS.

Hot working is a typical method to enhance the formability of metal alloys. However, this method has encountered several drawbacks, such as large energy consumption, increased adhesion between the material and the die, reduced effects of lubrication, and decreased die strength [2]. As alternatives to hot forming, various forming methods, such as hydroforming [3, 4] and incremental forming [5] have been considered. Although these relatively new alternatives provide various technical advantages, they also have their own disadvantages including a longer manufacturing cycle and a significant amount of initial capital investment.

It has been argued that the material property of a metal alloy can be temporarily or even permanently modified by simply applying electricity to the metal during deformation. Since the classical work by Troitskii [6], suggesting that the flow stress of certain metals can be lowered by pulsed electricity, Conrad [7, 8] showed that the plasticity and phase transformation of various metals and ceramics are affected by pulsed or continuous electric current. This phenomenon has been referred to the electroplasticity. While a completely satisfactory explanation for the mechanism of electroplasticity has not been provided yet, a recent study by Kim *et al.* [9] has shown that the electroplastic behavior may not be simply understood as a result of resistance heating and suggested the occurrence of electrically induced annealing by a pulsed electric current during deformation.

Even without a complete explanation of its mechanism, the phenomenon of electroplasticity is very attractive to researchers and industries in the field of metal forming. While the formability of metal alloy can be significantly enhanced by a continuous electric current under compression [10 - 12], a continuous electric current during tension generally results in a very poor formability for many metal alloys [13, 14], even though the forming load reduces significantly for both compression and tension with a continuous electric current. To overcome the disadvantage of the reduced maximum elongation under a continuous electric current, researchers chose to apply a pulsed electric current to a specimen under tension [15 - 17]. Under a pulsed electric current, the formability of metals could be significantly enhanced while the flow stress significantly and almost instantly decreases in the duration of each pulse of electric current. The almost instant stress decrease was defined as the stress-drop [17].

In the present study, the effect of a single pulse of electric current on the tensile behavior of an typical automotive ultra-high strength steel (UHSS) is experimentally investigated. The result of the present study will contribute to the development of an electrically assisted (EA) sheet metal forming process of the UHSS.

2. MATERIALS AND METHODS

Complex phase ultra-high strength steel sheets (the tensile strength of 1.2GPa) with a 1.2 mm thickness were used for experiments. Typical tensile specimens with a 12.5 mm gage width and a 50 mm gage length were fabricated by laser cutting along the rolling direction of the sheet. The quasi-static tensile tests were conducted using a universal testing machine with a constant displacement rate of 2 mm/min. The force history during the experiment was measured by a CSDH load cell (Bongshin, South Korea) with a maximum capacity of 2500 kN as a function of time using a PC-based data acquisition system. The displacement history was measured using a LX500 laser extensometer (MTS, USA) by attaching retro-reflective tape (MTS) to the specimen to fix the gage length to 50 mm.

For the quasi-static tensile test under a single pulse of electric current, the electric current was generated by a Vadal SP-1000U power supply (Hyosung, South Korea) with a programmable pulse controller and was applied to the specimen during tensile deformation as shown in Fig. 1. Note that the electric current was applied to the specimen over a given duration at the selected engineering strain (defined as a pulsing strain) without stopping the tensile displacement. The testing equipment was insulated from the electric current by inserting a set of bakelite insulators between the specimen and the grip to isolate the electricity from the testing equipment.

Table 1. Experimental parameters.

Pulsing strain [%]	True electric density* (ρ_i) [A/mm^2]	True electric energy density (ρ_j) [J/mm^2]	Duration (t_d) [s]	Displacement rate [mm/min]
1.5	50	0.31	0.36	2
	60	0.45		
	72	0.65		
	86	0.93		
	103	1.33		
3	50	0.31		
	60	0.45		
	72	0.65		
	86	0.93		
	103	1.33		

* Base on the cross-sectional area of the specimen at the pulsing strain

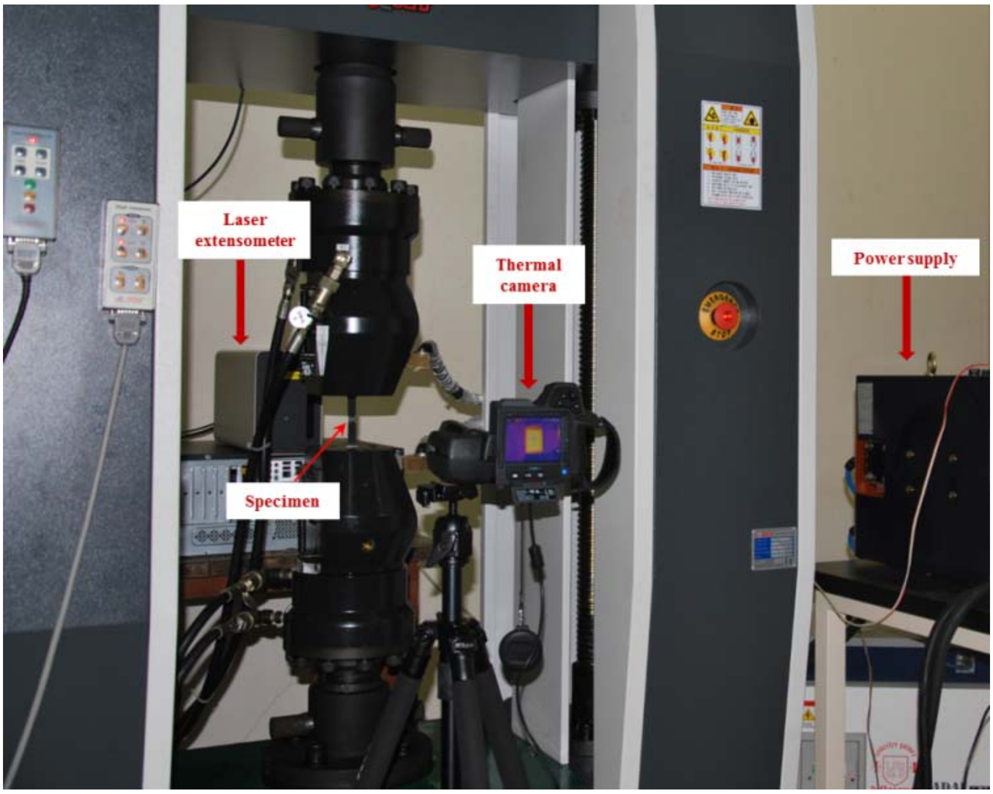


Figure 1. Actual image of experimental set-up.

Also, an infrared thermal imaging camera (FLIR, Sweden) was employed to monitor the temperature change of the specimen throughout the experiment. Note that one side of specimen was painted by a thin layer of heat resistance black paint in order to stabilize emissivity around 0.98 during the experiment. For the parameter study, two different pulsing strains were combined with five different true electric current densities (based on the cross sectional area of the specimen at the given pulsing strain) with a fixed duration of electric current of 0.36 sec, as listed in Table 1. Note that the pulsing strains (1.5 and 3 %) selected in the present study correspond to the 31 % and 62 % of the engineering strain at the ultimate tensile strength, respectively, from the baselines tensile test without electric current. For each parameter set, at least four specimens were tested to verify the repeatability of the results.

3. RESULTS AND DISCUSSION

Throughout the experiments, for the both pulsing strains, the highest temperature measured in the duration of electric current was 270 $^{\circ}$C with ρ_j = 1.33 J/mm^3 (ρ_i = 103 A/mm^2, t_d = 0.36 sec) which is the maximum electric energy density among the electric energy densities selected in the present study. Note that the maximum temperature of 270 $^{\circ}$C is still significantly lower than the usual hot working temperature of UHSS (higher than 900 $^{\circ}$C). Temperature profiles along the gage length of the specimen are shown in Fig. 2, for the pulsing strain of 1.5 %. The temperature profiles in Fig. 2 shows that temperature distributions during the tests were quite uniform along the gage length in comparison with those of titanium [18] tested under a continuous electric current with low electric current density.

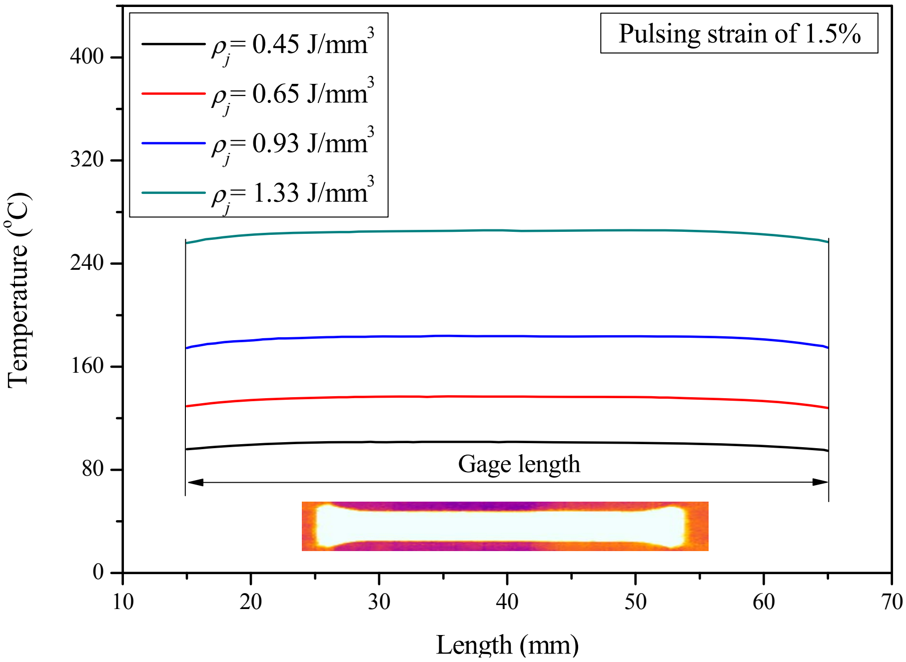


Figure 2. Temperature profiles along the gage length of specimen.

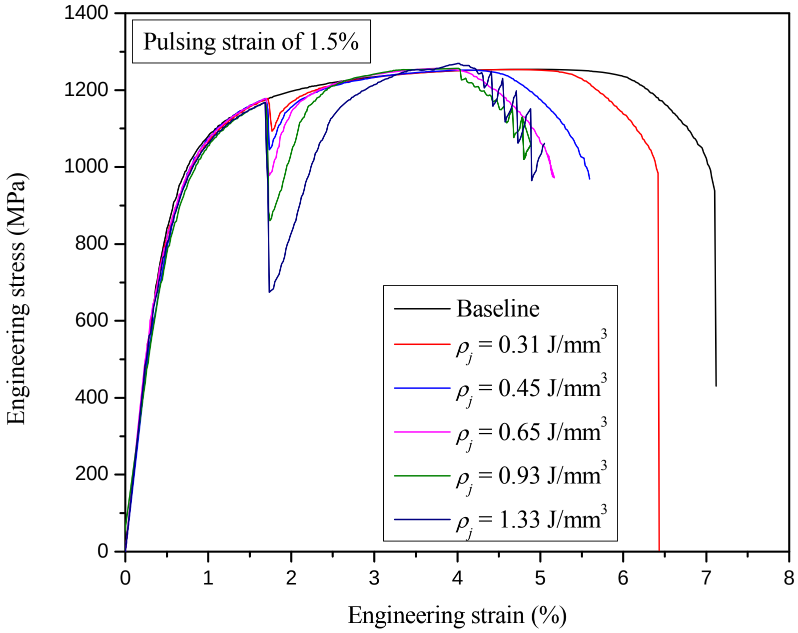


Figure 3. Engineering strain-stress curves under the pulsed electric current.

Engineering stress-strain curves with the pulsing strain of 1.5 % are shown in Fig. 3. The experimental results in Fig. 3 clearly show that the magnitude of stress-drop at the duration of electric current increased as the electric energy density increased. One interesting aspect is that the stress-drops at two different pulsing strains, 1.5 and 3 % have relatively identical values, which linearly increase as the electric energy density increases as shown in Fig. 4. The insignificant effect of the pulsing strain on the stress-drop is probably due to the relatively small magnitudes of the pulsing strains. In contrast to the steady increase of the stress-drop with the increase of the electric energy density, the ultimate tensile strength after the electric current was nearly constant and identical to that of baseline test without electric current for the pulsing strain of 1.5 %, while slightly increase in UTS after the electric current is observed with the pulsing strain of 3 % (Fig. 5).

Regarding the ductility, similar to the result of Kim *et al.* [19], the adverse effects of a pulse of electric current on the elongation at fracture (or simply, the fracture elongation) and the maximum uniform elongation (or simply, the uniform elongation) of the selected UHSS are observed as shown in Figs 6(a) and (b). It is interesting to note that the adverse effect of a pulse of electric current on the ductility decreases for the larger pulsing strain of 3 % in both the facture elongation and the uniform elongation. With the pulsing strain of 3 %, the facture elongation and the uniform elongation increase again as the electric energy density increases from 0.93 to 1.33 J/mm^3, which is the maximum electric energy density selected in the present study. With the pulsing strain of 3 %, at the maximum electric energy density of 1.33 J/mm^3, the fracture elongation becomes close to the result of the baseline test (a tensile test without electric current), while the uniform elongation even becomes higher than the result of the baseline test.

A comparison of the stress-drop due to the thermal expansion in elastic region with the stress-drop in the plastic region (pulsing strain of 1.5 %) in Fig 7 clearly shows that the stress-drop in the plastic region is higher than that in the elastic region for all the electric energy densities selected in the present study. In the present study, the difference between the stress-drop in the elastic region and that in the plastic region is defined as the corrected stress-drop due to the athermal/thermal effects of electric current on the flow stress. Note that for the thermal softening by Joule heating, which contributes to the stress-drop in the plastic region, the result of separate tensile tests at elevated temperatures suggests that the effect of thermal softening on the

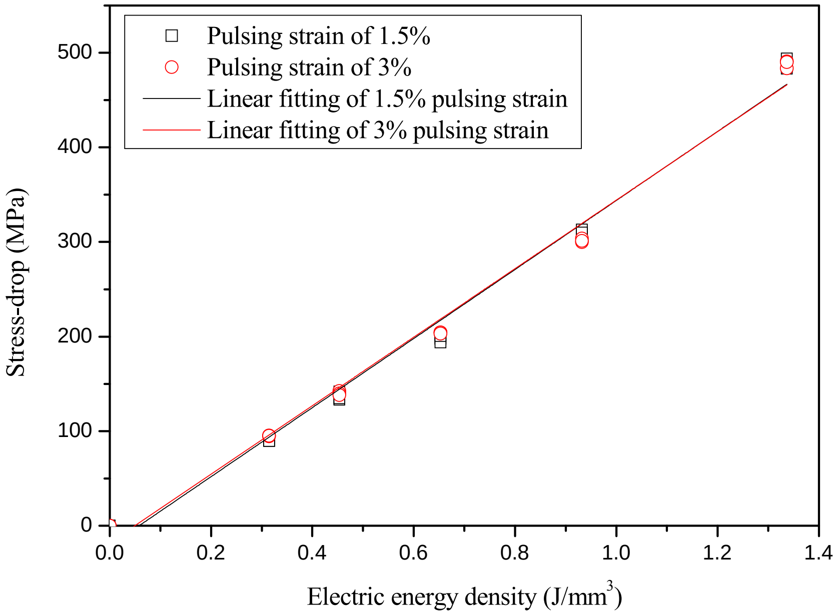


Figure 4. Linear increase of stress-drop with increase of electric energy density.

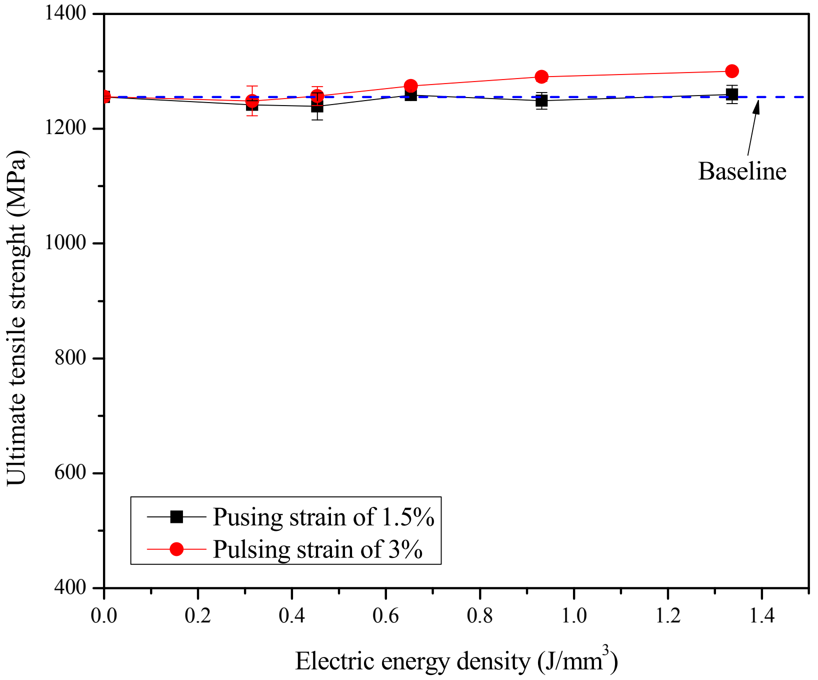
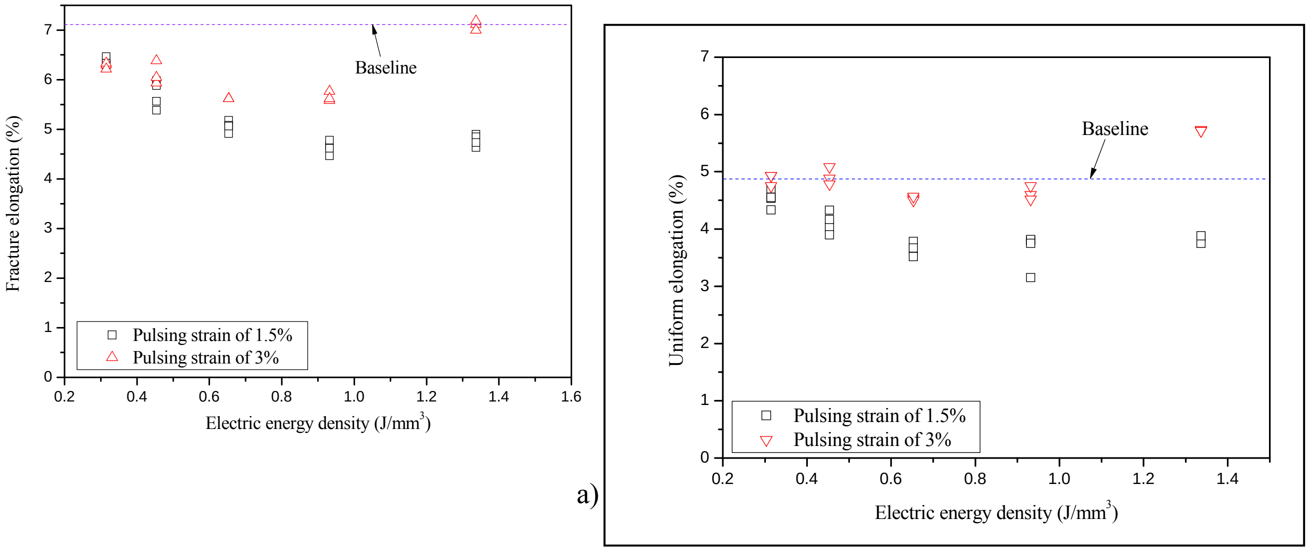


Figure 5. Ultimate tensile strength after electric current.



a)

b)

Figure 6. (a) Fractured elongation and (b) uniform elongation after electric current.

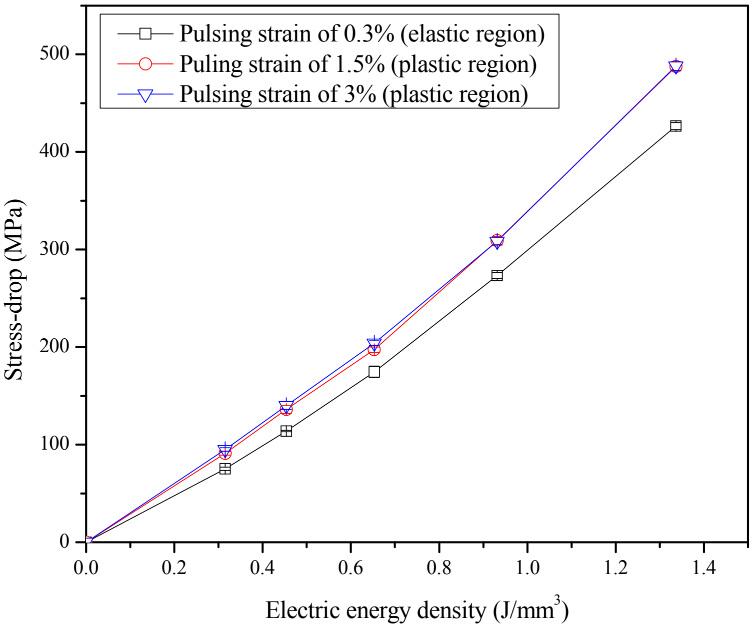


Figure 7. Stress-drop at different pulsing strains.

mechanical behavior of the selected UHSS is insignificant at the temperatures up to 290 °C. Also, it should be noted that in the present study, the effect of electric current on the elastic properties of the selected UHSS is assumed to be negligible and consequently, the stress-drop in the elastic region is assumed to be purely induced by the thermal expansion of the specimen under tension. Since the athermal effect of electric current on metal alloys in elastic region still needs further investigation, the corrected stress-drop in the present study needs to be considered as the lower bound of the actual decrease of the flow stress (actual stress-drop) of the specimen in the duration of electric current.

4. CONCLUSIONS

The effect of a single pulse of electric current with short duration on the quasi-static tensile behavior of the ultra-high strength steel 1180CP was experimentally investigated. A nearly instant stress-drop has occurred in the duration of the electric current and the flow stress showed strain hardening until the failure of the specimen. Thermal expansion effect partially contributed to stress-drop at the plastic region, while it purely induced stress-drop at the elastic region.

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TÓM TẮT

ẢNH HƯỞNG CỦA DÒNG XUNG ĐIỆN ĐẾN TÍNH CHẤT CƠ HỌC CỦA THÉP CÓ ĐỘ BỀN KÉO CAO 1180CP

Nguyen Trung Thiên[1, *], Sung-Tae Hong[2]

[1]*Trung tâm Đào tạo và Thực hành Công nghệ Cơ khí, Trường ĐHSPKT Hưng Yên,*
Dân Tiến, Khoái Châu, Hưng Yên

[2]*Khoa Cơ khí, Trường Đại học Ulsan, 93 Deahak-ro, Nam-gu,Ulsan, Hàn Quốc*

[*]Email*: trungthienckc@gmail.com*

Nội dung tóm tắt bài báo**:** Ảnh hưởng của dòng xung điện đến cơ tính của thép có độ bền cơ học cao 1180CP được khảo sát bằng thực nghiệm. Một xung điện được tác dụng tới mẫu thí nghiệm trong khoảng thời gian rất ngắn (0,36 giây) tại vùng biến dạng dẻo của vật liệu trong khi vật liệu đang chịu tải trọng kéo. Kết quả thí nghiệm cho thấy: ứng suất biến dạng dẻo của vật liệu được khảo sát giảm đột ngột khi được tác dụng xung điện, sau đó sự biến cứng tăng cho tới khi phá hủy. Sự biến dạng đồng nhất hoàn toàn phụ thuộc vào vị trí tác dụng xung điện, trong khi đó độ bền kéo thay đổi không đáng kể. Ngoài ra, nhiệt độ lớn nhất sinh ra bởi dòng xung điện khoảng 270 °C, nhiệt độ này rất thấp so với nhiệt độ kết tinh lại của vật liệu được lựa chọn, do đó ko làm ảnh hưởng đến cấu trúc tế vi của vật liệu.

Từ khóa: dòng điện, thép độ bền cao, cơ tính.