INVESTIGATION OF ADVANCED CURRENT CHARACTERISTICS ON EXPULSION FORMATION AND CHARACTERISTICS OF RESISTANCE SPOT WELDED ADVANCED HIGH STRENGTH STEELS

GELİŞMİŞ YÜKSEK DAYANIMLI ÇELİKLERDEKİ PUNTA KAYNAĞINDA, GELİŞMİŞ AKIM PROFİLİNİN KAYNAK FIŞKIRMASINA VE KAYNAK ÖZELLİKLERİNE ETKİSİNİN İNCELENMESİ

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ABSTRACT

INVESTIGATION OF ADVANCED CURRENT CHARACTERISTICS ON EXPULSION FORMATION AND CHARACTERISTICS OF RESISTANCE SPOT WELDED ADVANCED HIGH STRENGTH STEELS

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In this thesis, the experiments with HSLA600 which is widely used in industry will be investigated. Single, double and triple pulse welding will be applied to the materials to obtain the biggest, homogenous nugget geometry without expulsion by increasing the current value step by step. As a final step, joints will be analyzed by macrostructure analysis, the Vickers hardness test, the lap / shear test, and the tensile fatigue test.

With this thesis, it is aimed to prevent expulsion while improving the nugget's quality by using single, double and triple pulse current formation.

Keywords: Welding, HSLA600, Resistance Spot Welding

ÖZET

GELİŞMİŞ YÜKSEK DAYANIMLI ÇELİKLERDEKİ PUNTA KAYNAĞINDA, GELİŞMİŞ AKIM PROFİLİNİN KAYNAK FIŞKIRMASINA VE KAYNAK ÖZELLİKLERİNE ETKİSİNİN İNCELENMESİ

Oğulcan Göçmen

Yüksek Lisans, Makina Mühendisliği Bölümü
Tez Danışmanı: Dr. Öğr. Üyesi Mehmet Okan GÖRTAN
Ocak 2023, 27 Sayfa

Bu tezde, endüstride oldukça yaygın kullanılan HSLA600 malzemesi ile yapılan deneyler incelenecek. En büyük ve homojen çekirdek geometrisini kaynak fışkırması olmadan elde etmek için tek, iki ve üç fazlı akım formasyonları uygulanacaktır. Son aşamada kaynak bölgeleri makro yapı analizi, sertlik ve dayanım testi ile incelenecektir.
Bu tez ile beraber, bir/iki/üç fazlı akım kaynakları uygulayarak, kaynak fışkırmasının engellenmesi ve aynı azmanda kaynak bölgesi çapını artırmak amaçlanmaktadır.

Anahtar Kelimeler: HSLA600, Kaynak, Punta Kaynağı

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LIST OF ABBREVIATIONS

DP	Dual Phase
DPW	Double Pulse Welding
FZ	Fusion Zone
HAZ	Heat Effected Zone
HSLA	High Strength Low Alloy
IF	Interfacial Failure
ISO	International Organization For Standardization
PF	Pull-out Failure
PI	Partial Interfacial Failure
RSW	Resistance Spot Welding
SCHAZ	Subcritical Heat Affected Zone
SPW	Single Pulse Welding
TSS	Tensile Shear Strength

1. INTRODUCTION

Resistance spot welding (RSW) is a welding method to join dissimilar sheet metals with variable thicknesses from generally 0.5 mm to 3 mm such as alloy steel, high and low carbon steel, aluminium [1]. Even if it is widely used in industry in decades, there are some disadvantages of RSW. One of the important problems is expulsion. There are various strategies such as double pulse RSW, RSW with preheating etc. to keep from those kinds of problems.

The purpose of the thesis is to find optimum solution not to observe expulsion and improve the nugget quality by using advanced welding formation methods for resistance spot welding. HSLA 600 will be used as material in experiments.

2. STATE OF THE ART

Resistance spot welding (RSW) is a joining method which utilizes electrical resistance of metallic materials to heat them and generate coalescence. Since comparatively strong joints can be generated in a rather short time without the need for excessive expertise, RSW is universally used in automotive industry.

Heat is generated inside of the materials during RSW due to the electrical resistance of metallic materials against current flowing inside of them [2]. Generated heat can be represented according to the Joule's first law and has the following form:

$$Q = I^2 R\, t \tag{1}$$

$$\partial Q = I(t)^2\, R(t)\, \partial t \tag{2}$$

where Q is generated heat, I is current, R is total resistance, t is time. All of the parameters of the equation are time dependent. Therefore, Equation 1 can be modified as in Equation 2 [1].

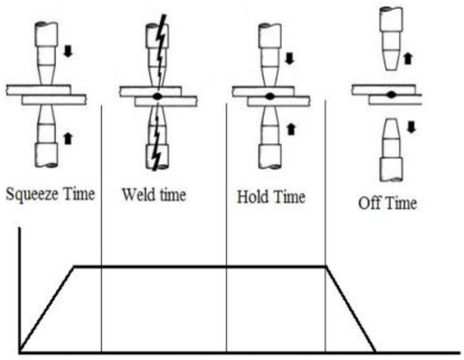

Figure 1. Stages in a typical weld cycle [3]

There are four main steps in every RSW process. First of all, sheet metals to be welded are placed into the welding machine and they are squeezed by copper alloy electrode. Secondly, heat is generated by current flow through the sheet metals in the welding phase. In the following hold phase, current shuts down. However, copper electrodes still apply pressure to the sheet metals and enable fast cooling of those [4]. Finally, electrodes move away from the materials before doing the next welding [1]. A schematically cycle of RSW is shown in Figure 1.

As a result of melting and solidification of metals during RSW, a fusion section is generated around the faying surfaces of metals to be joined. That section is called as nugget. Moreover, a heat affected zone (HAZ) is generated around the nugget section. During solidification, force applied over electrodes cause a thinning in contact regions which is called as indentation. Geometrical parameters of RSW joints are shown in Figure 2 schematically.

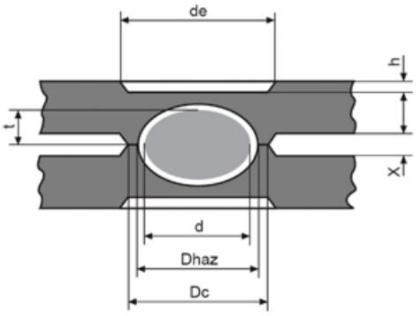

Figure 2. Parameters of the nugget size [1]

The purpose of the RSW is to create biggest, homogenous nugget diameters without any external and internal discontinuities or excessive deformation in the joint [5]. Nugget size directly affects weld strength and durability. Usually as the nugget grows, strength of RSW joints increase. Nevertheless, in order to achieve a large nugget, welding current and time should be increase [6]. Such an increase may yield into defects or ejection of liquid metal form welding region which is named as expulsion [7]. Expulsion causes a significant loss of material in welding region and reduces weld strength [8]. Therefore, parameters which is given in Equation 1 should be chosen properly to prevent any kind defects. Moreover, most of the time, a large welding current or long welding time results in excessive expulsion. As a result, applicable current and time values are limited. Those limits are usually shown in so called lobe diagrams. An exemplary lobe diagram is shown in Figure 3

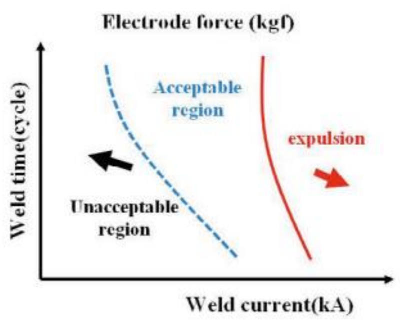

Figure 3. Welding lobe diagram [9]

Since nugget growth is limited by expulsion, advanced cycles are developed to optimize strength of RSW joints. One of the most important advanced cycle types is called as double pulse welding. Its process steps are shown schematically in Figure 4 as an example. It includes applicaton of the welding current in tow different phases with a short pause in between them. There are multiple studie about double pulse RSW in literature.

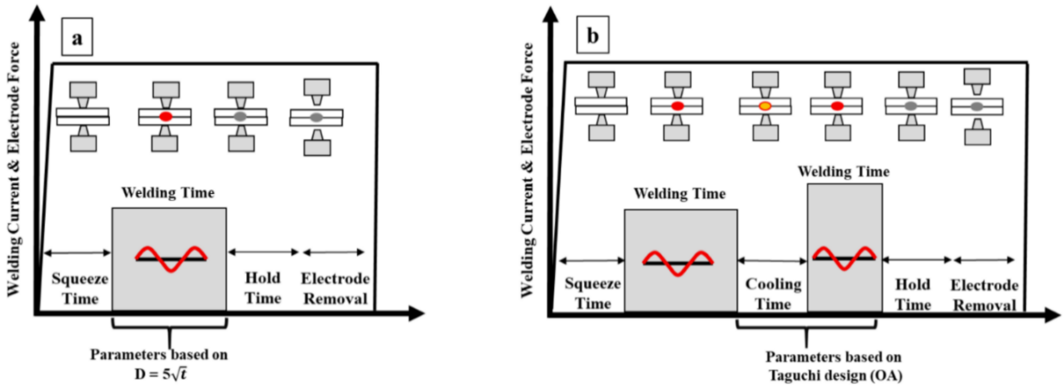

Figure 4. Standard and double pulse spot welding [10]

In first article, 1.8 mm thick Q&P 980 steel and Cu-Cr-Zr alloy with doom-shape tips of diameter 6 mm electrode are used in experiments. Single pulse and double pulse welding with various currents were analyzed. Maximum current was chosen as 7 kA in single pulse welding to prevent expulsion. Experiment parameters are shown in Figure 5.

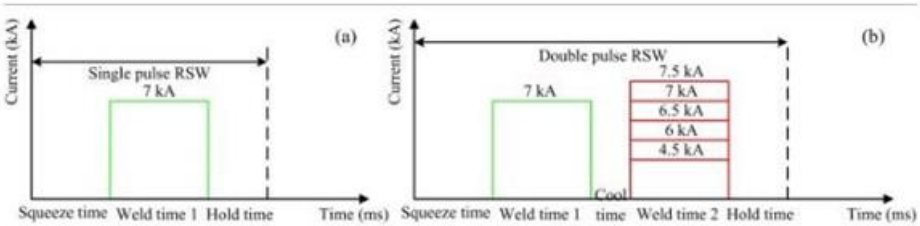

Figure 5. Single and double pulse spot welding [11]

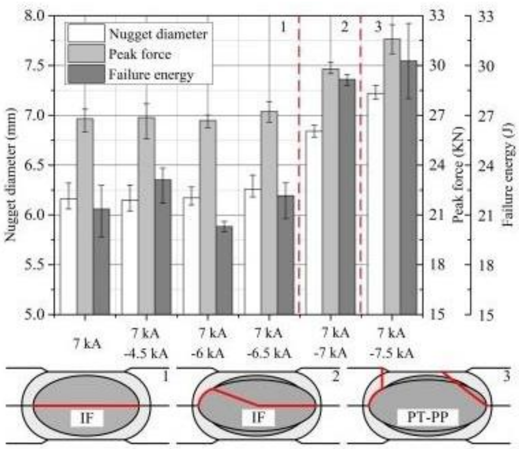

Figure 6. Results of the experiments [11]

According to results, primary and secondary nugget diameters were investigated. Secondary nugget diameters are smaller than primary nugget diameter up to 6.5 kA. It is clear that nugget diameter increases by rising the applied current and it enhanced nugget strength. It can be shown in Figure 6. In the same way, peak force and energy absorption continued steady till 6.5 kA. After, it rises in the same way of the nugget formation.

Peak load and energy absorption have the highest value for highest secondary current. On the other hand, failure mode of the material changed from IF to PT-PP. As a result, double pulse welding improved the welding quality.

Microhardness profiles of the experiments are shown in Figure 7. According to graph, hardness of the HAZ for double pulse welding is slightly higher than single pulse welding. However, hardness of the FZ for each process are nearly same. Thus, FZ was not affected from the different welding types.

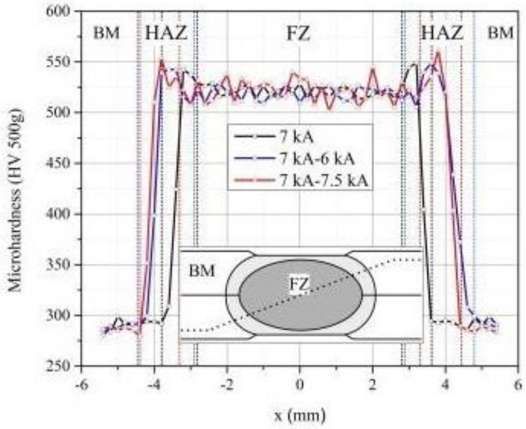

Figure 7. Micro hardness profiles [11]

In the second article, effect of double pulse spot welding for uncoated 15B22 hot stamped boron steel was investigated. Thickness of the material is 1.2 mm. Material was heated up to 930° then cooled down 27°. Expulsion limit of the materials for spot welding is shown in Figure 8. Fixed 400 kgf is applied with Cu-Cr-Zr material truncated cone tips with 6 mm diameter electrodes. Weld time is fixed 250 ms and acceptable range of the welding is from4.6 kA to 6.2 kA.

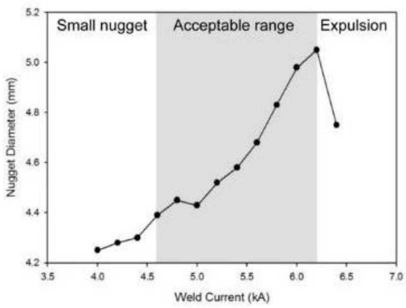

Figure 8. Welding current range of 15B22 [12]

In the next step, double pulse spot welding process was investigated for the same material by applying 1000, 250, and 200 MS, respectively.

In Figure 9, it is clear that nugget diameter increases by applying secondary current. However, when other results are investigated, it shows that hardness changes suddenly in some regions such as PMZ and SCHAZ. They altered the microstructure of the materials and finally, strength of the material decreases.

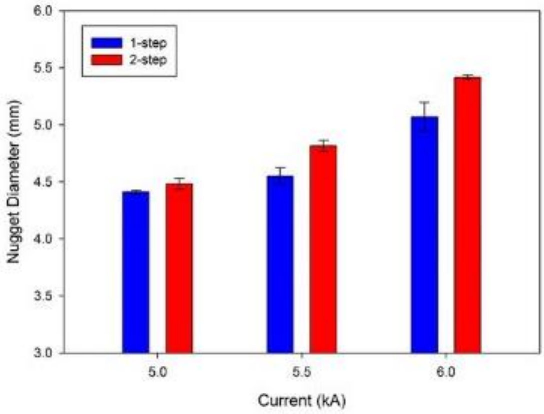

Figure 9. Nugget Diameter [12]

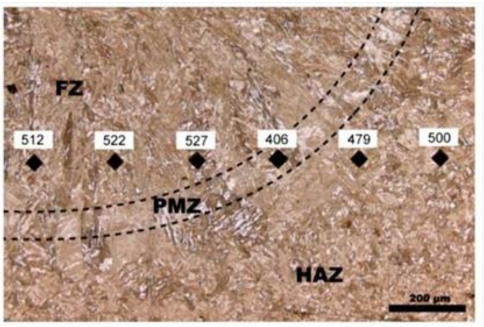

Figure 10. Hardness distribution in nearby partially melted zone (PMZ) at 6.0 kA in the two-step RSW [12]

In Figure 10, two different softening regions are shown in HAZ and PMZ. Especially, PMZ regions really effected from welding conditions. On the other hand, hardness values in the sub-critical heat affected zone for double pulse welding is not more preferable than the one step spot welding. It is shown in Figure 11

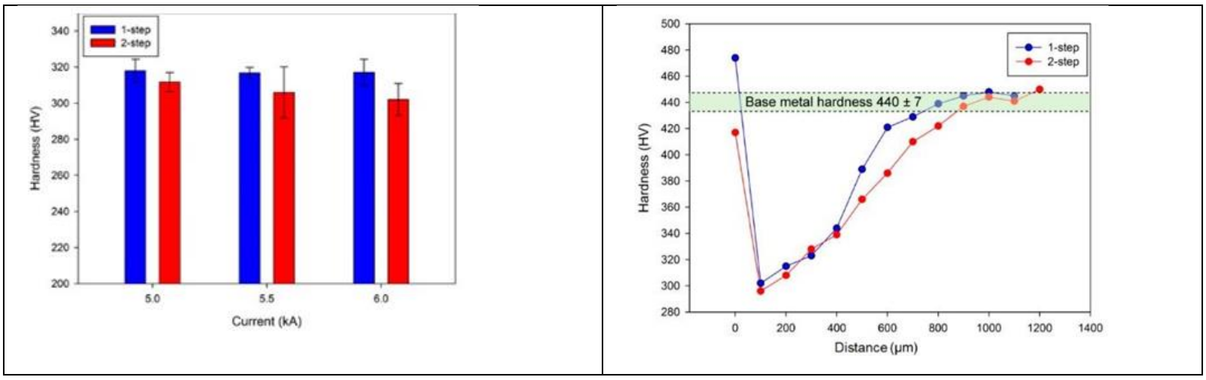

Figure 11. Hardness distribution of the sub-critical heat affected zone (SCHAZ) and in the one-step and the two-step RSW [12]

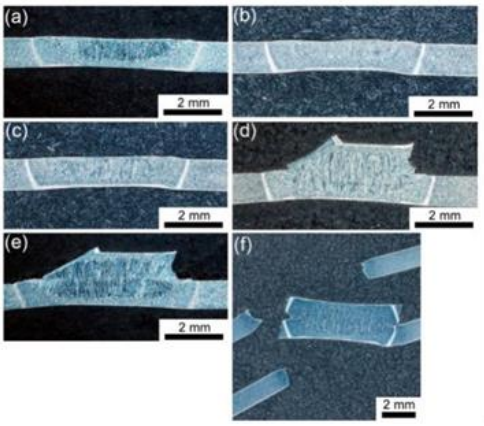

Figure 12. Failure modes for different weld conditions (a) 5.0 kA in one-step (b) 5.0 kA in two-step (c) 5.5 kA in one-step (d) 5.5 kA in two-step € 6.0 kA in one-step (f) 6.0 kA in two-step [12]

Failure modes of the experiments are shown in Figure 12. In summary, IF failure mode is shown for lower current values (5.0 kA). When the current was rised by double pulse spot welding, failure mode transformed from IF to PT-PP. With the highest heat input, SCHAZ regieon was softened.

As a result, according to all graphs, double pulse spot welding for 15B22 hot stamped boron steel increased the nugget diameter. Normally, it is a good sign to improve better nugget quality. However, welding quality gave worse results outside of the nugget. That means it created unexpected earlier fractured regarding the softening of some regions in the material.

In the third article, 3rd generation 1 GPa complex phase AHSS with a thickness of 1.3 mm material was examined. It is cold rolled and galvanized. The experiments are completed in three steps. First of all, single pulse spot welding was applied to the materials and after double pulse spot welding with various currents was investigated. 4 kN pressure was applied by 16x5.5 electrodes. 6.2 kA current was applied as single pulse. After that 6.2 and 5.7 kA currents were applied as second current. Final primary weld nugget diameters are 5.1mm, 5.2 mm and 5.2 mm, respectively.

Hardness of HAZ of the double pulse welding is much more than single pulse spot welding (SPW). Also, hardness of the nugget is slightly higher than SPW because of extra heat input.

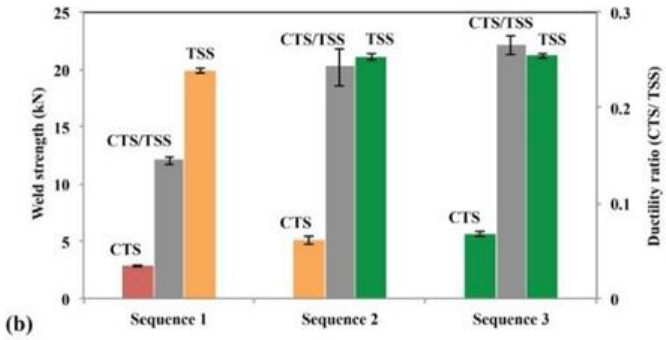

Figure 13. Weld Strength [13]

TSS test results are shown in Figure 13. It is clearly understood TSS of the double pulse method is higher than SPW. Moreover, sequence 3 has highest ductility ratio. On the other hand, failure mode of the welding, partially plug failure for sequence 1 and full plug failure for sequence 2 and 3 are observed. According to all results, double pulse welding is improved the mechanical properties of the material.

In the next article, DP1000 steel was used in the studies. Nominal sheet and zinc coating thickness is 1.5 mm and 50g/mm2, respectively. Load is constant and 4.5 kN F1 16-20-5.5 electrodes are used in the experiments.8 kA current is applied for single and double pulse welding. Current time is 380 Ms for SPW and two times (8 kA) 380 Ms for DPW. Other parameters of the experiments are same for each test.

According to test results, welding quality can be understood from Figure 14. Energy absorption of the double pulse welding has better results till the maximum load. Maximum load is 9.2 kN for SPW and 11.7 kN for DPW and failure energies are 55.3 J for SPW and 75.2J for DPW.

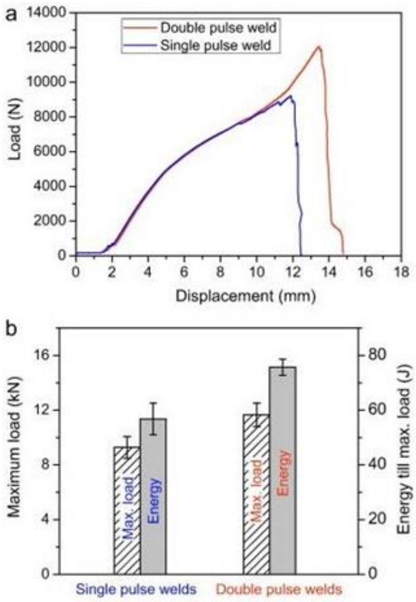

Figure 14. Mechanical properties of the welding [14]

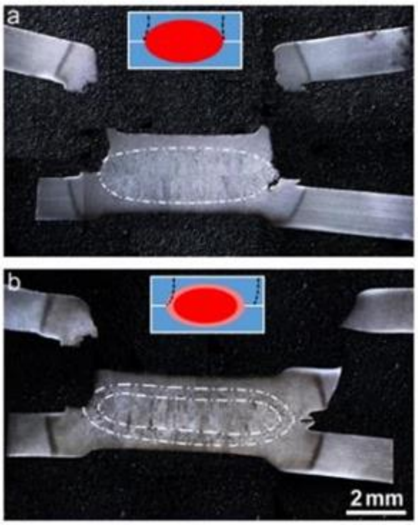

Figure 15. Failure modes of the materials [14]

Failure modes of the single and double pulse welding are pull-out failure mode which is shown in Figure 15 and it is clear that failure area is bigger for double pulse welding. The difference can be seen right side of the specimens. According to experiment results, diameters of the fractured areas are nearly 7 mm and 7.4 mm, respectively.

At the final, nugget diameters are 7 mm for each experiment. Hardness results of the specimens are shown in Figure 16. On the contrary of the other examples, double pulse welding has lower hardness results for each point of the material. Softening of the materials increased the ductility. In this way, the material can absorb much more energy as it seen in Figure 14.

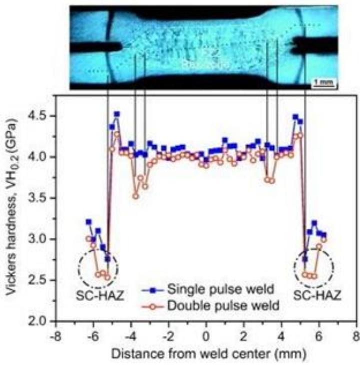

Figure 16. Micro hardness profiles [14]

In conclusion, double pulse welding can improve the strength of RSW joints by increasing the nugget diameter and ductility of HAZ. Nevertheless, there are conflicting suggestions in standards about the usage of single and double pulse welding. For instance, in the reference document of American Welding Society, single pulse welding is suggested for most of the applications [15]. However, internal standards of automotive companies suggest the usage of double or triple welding even for thin sheet metals.

3. MOTIVATION AND METHODOLOGY

3.1. Motivation

Resistance spot welding (RSW) is a joining method which is widely used especially in the automotive industry thanks to its advantages over other welding methods. Nevertheless, expulsion is seen as a major disadvantage for RSW. There are various strategies such as double or triple pulse RSW. to avoid those kinds of problems.

The purpose of the thesis is to find optimum solution not to observe expulsion and improve the nugget quality by using double and triple pulse formation method for resistance spot welding.

3.2. Methodology

Effect of single, double and triple pulse welding on mechanical strength and microstructure is investigated in this study. A conventional high strength steel, HSLA 600 with a thickness of 1.2 mm is used as test material. Its mechanical properties and chemical composition are summarized in Table 1 and Table 2, respectively.

Table 1. Mechanical Properties of HSLA 600

	Yield Strength (Mpa)	Tensile Strength (Mpa)	Strain Failure (%)
HSLA 600	590,5 ± 10,6	722,4,7 ± 1,3	34,13 ± 0,49

Table 2. Chemical Composition of HSLA 600

	C (%)	Si (%)	Mn (%)	Al (%)	Ti (%)	Fe (%)
HSLA 600	0.11	0.42	0.171	0.04	0.073	balance

Tensile-shear strength test specimens were prepared in accordance with ISO 14273 standard. Sample geometry is shown in Figure 17 schematically.

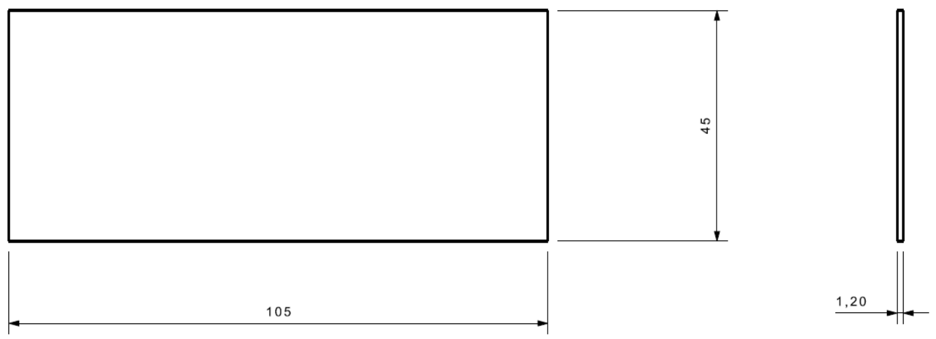

Figure 17. Sample geometry

All welding operations are applied on a pedestal type AC (50 Hz) resistance spot welding machine with a capacity of 70 kVA and equipped with CNC unit. Pointed type copper electrodes with a face diameter of 6 mm are used which are made of copper, chromium and zirconium (Resistance Welding Manufacturers Alliance Class 2).

Samples with single, double and triple pulse welding strategies are generated. Electrode force was kept constant at 2.6 kN. Moreover, welding time was equal to 11 cycles for every pulse. Firstly, single pulse spot welding was investigated from 7.5 kA to 12 kA by increasing 0.5 kA step by step. Secondly, effect of double pulse spot welding was studied from starting 7.2 kA to 9.3 kA by increasing 0.3 kA step by step and finally triple pulse spot welding experiments were completed from 7.2 kA to 9.3 kA by increasing 0.3 kA step by step. Moreover, welding experiments with 10 kA and 11 kA by using double and triple pulses were added to studies.

8 different samples are welded for every parameter. Tensile-shear strength of 7 samples is tested according to ISO 14273 with a constant speed of 10 mm/min. Nugget geometry is investigated on the cross section of welds. Therefore, welds are separated in the middle of the joint and standard microstructural preparation techniques are applied. Precisely, cross sections are sanded with P400, P800, P1200 and P2500 papers and afterwards polished with 6 μm and 1 μm diamond solution. All samples are etched with a 12% Nital solution for 10 seconds. Microstructural studies are completed on those etched surfaces using optical microscope and scanning electron microscope (SEM). Moreover, hardness of the joints is investigated using Vickers hardness test according to ISO 6507-1. All measurements are taken along a line 0.2 mm above the joining section of the metals parallel to sheets.

4. EXPERIMENTAL STUDIES

4.1. Tensile Shear Test

Tensile/shear strength and failure energy data were calculated according to tensile test results. Tensile/shear strength value is the top point of the stress/strain graph. Failure energy is the area under the stress/strain graph. All the calculations were done by using Microsoft Excel Visual Basic Application.

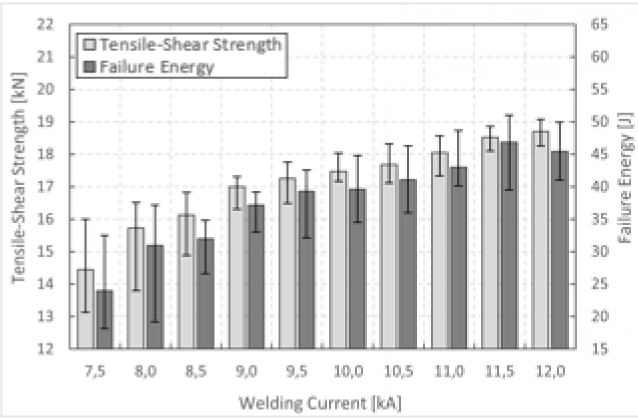

Figure 18. Tensile shear strength/ Current diagram of single pulse welding

Figure 18 shows tensile shear strength-failure energy/welding variation for single pulse formation. For single pulse welding, tensile shear strength and failure energy increased steadily with current. The standard deviation, on the other hand, decreased as current value increased. A significant point is that failure energy diminished after 11.5 kA despite shear strength continued increasing. Therefore, the optimum current value for single pulse welding could be determined as 11.5 kA with 18.8 kN tensile strength and 47 J failure energy.

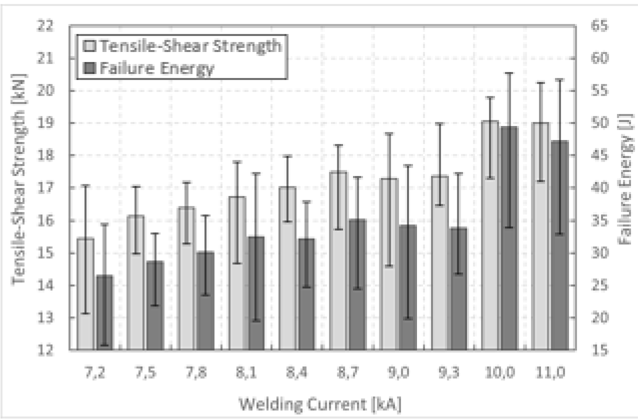

Figure 19. Tensile shear strength/ Current diagram of double pulse welding

Figure 19 demonstrates tensile shear strength-failure energy/welding variation for double pulse formation. In the same way, tensile strength and failure energy increased up to 19 kN and 49J for the double pulse welding. After 10 kA, tensile strength diminished by a fair amount. Standard deviation is generally higher than single pulse welding for each current value.

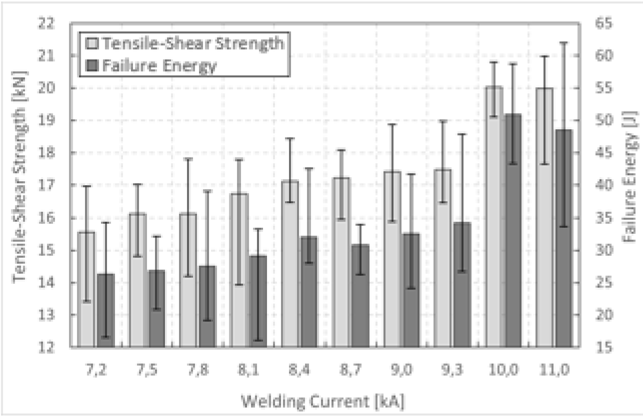

Figure 20. Tensile shear strength/ Current diagram of triple pulse welding

Figure 20 presents tensile shear strength-failure energy/welding variation for triple pulse formation. Results are nearly the same with double pulse welding. The optimal point for double and triple pulse welding is 10 kA due to the decreasing the failure energy at 11 kA.

To sum up, tensile strength increased to 19.2 kN with a double pulse, 20 kN with a triple pulse and failure energy increased to 49 J with a double pulse, 51 J with a triple pulse at 10 kA. According to tensile shear test results, double and triple pulse welding improved nugget strength.

4.2. Fracture Type

Figure 21, Figure 22 and Figure 23 compare fracture types after tensile strength tests.

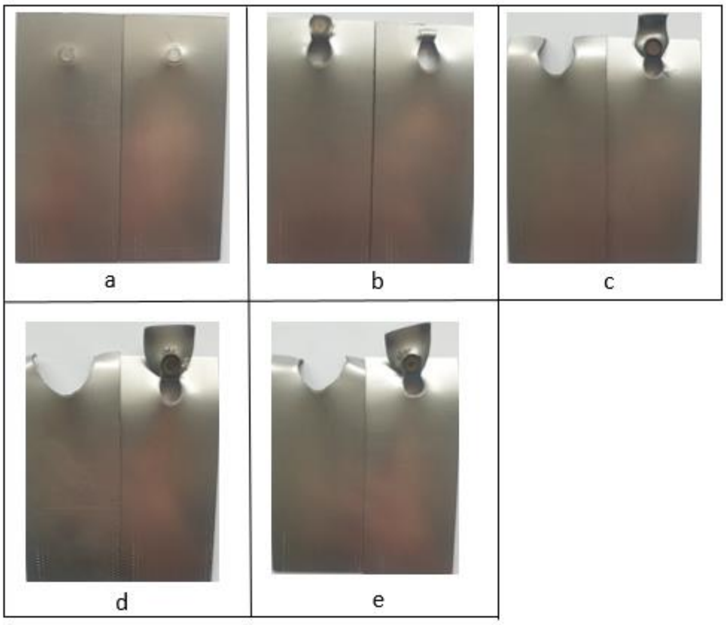

Figure 21. Fracture type of single pulse welding, a)8 kA b)9.5 ka c)10 kA d)11 kA e) 12 kA

Figure 21 shows that for single pulse welding, nugget strength improved with current. Interfacial failure was observed at 8 kA. However, pull-out failure type was observed for all other current values. Especially, complete tear out after pull-out failure was shown at 11-12 kA and expulsion started after 9 kA.

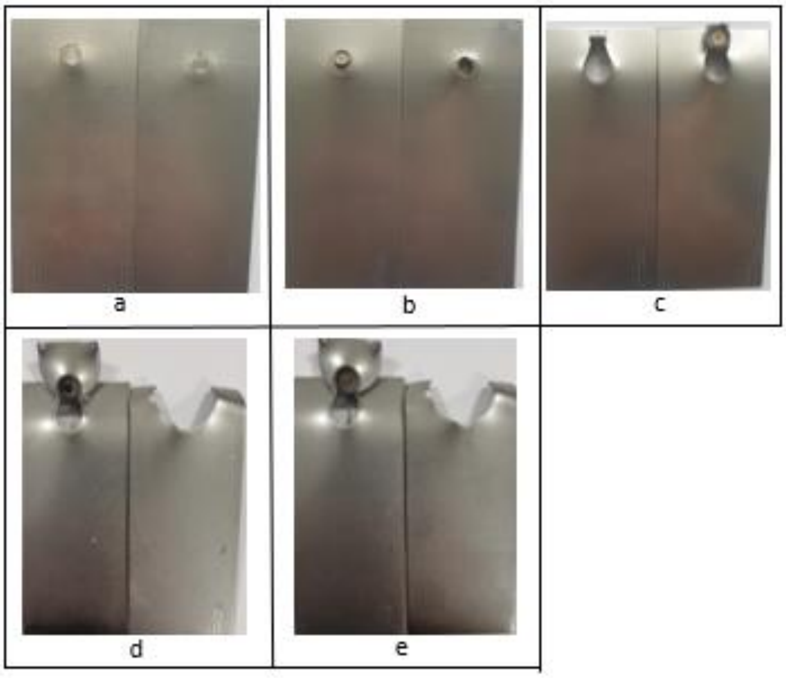

Figure 22. Fracture type of double pulse welding, a)7.2 kA b)8.4 kA c)9 kA d)10 kA e)11kA

As shown in Figure 22, IF at 7.2 kA, PP at 8.4 kA and PF at other currents were observed for double pulse welding. In the same way with single pulse welding, increasing current value enhanced nugget strength. Expulsion started at 10 kA.

Figure 23. Fracture type of triple pulse welding a)7.2 kA b)8.4 kA c)9 kA d)10 kA e)11kA

According to Figure 23, interfacial fracture was observed at 7.2 kA and partial interfacial fracture was detected for all other current values. Expulsion started at 10 kA.

In summary of fracture types, the nugget quality of single and double pulse welding is better than triple pulse welding. The reason is that the strength of the heat affected zone in triple pulse welding is lower than others. So, the third welding pulse tempered the nugget, and it lowered its strength.

4.3. Geometrical Properties

The most important parameter which effects the nugget diameter is current according to Joule's law as mentioned in earlier chapters.

Figure 24 and Figure 25 show the variation in nugget diameter corresponding to current for single and double/triple pulse welding formations, respectively.

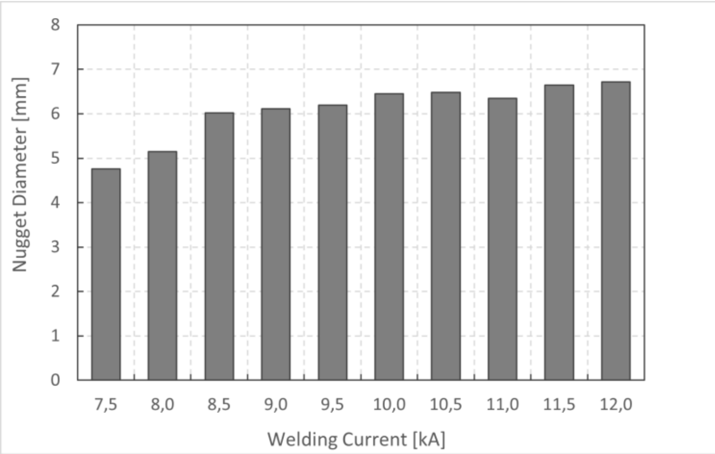

Figure 24. Nugget diameter/ Current diagram of single pulse welding

According to Figure 24, nugget diameter expanded with higher current values. However, rate of increase started decreasing after 10 kA because of the expulsion. Expulsion caused a significant loss of material in welding region and reduced weld strength. Therefore, nugget diameter could not expand overmuch. Highest nugget diameter reached 6.8 mm at 12 kA.

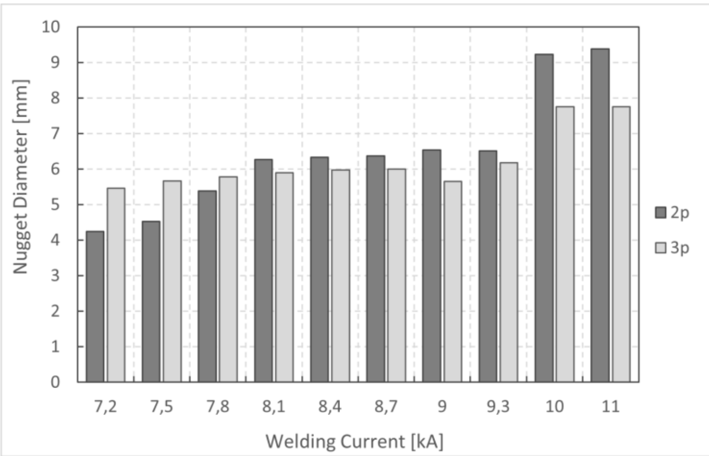

Figure 25. Nugget diameter/ Current diagram of double/triple pulse welding

Figure 25 compares the nugget diameter of double and triple pulse welding formations. As in single pulse welding, nugget diameter enlarged as current level rose in both double and triple pulse welding. The rate of increase started decreasing after 8.1 kA.

Furthermore, the highest nugget diameter of single pulse welding could be obtained with 9 kA with using double or triple pulse welding. Nugget diameter expanded visibly at 10-11 kA for both (2P, 3P) welding formations. And it reached 9.3 mm (2P) and 7.8 mm (3P).

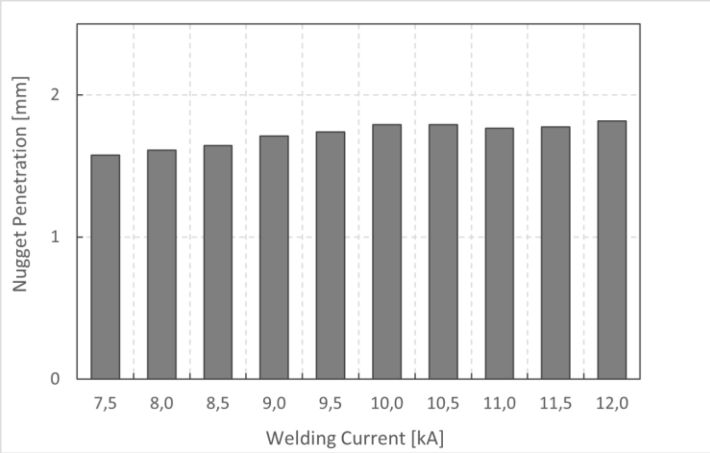

Figure 26. Nugget penetration/ Current diagram of single pulse welding

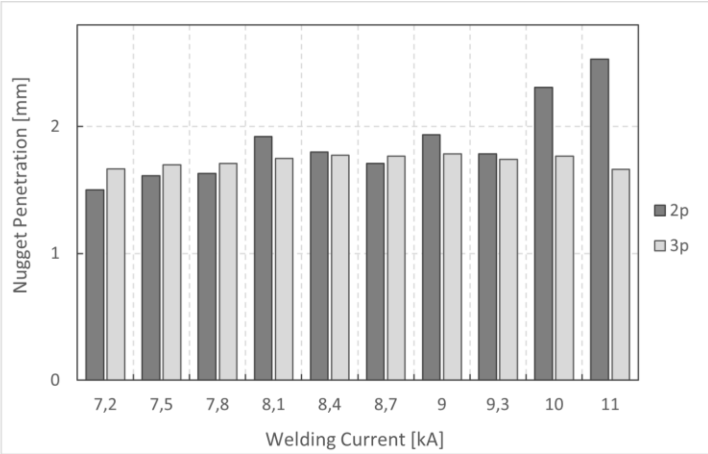

Figure 27. Nugget penetration/ Current diagram of double/triple pulse welding

Figure 26 and Figure 27 represent the nugget penetration of various current values for single, double and triple pulse weldings, respectively. Nugget thickness expanded with the increase in current for single and double pulse welding. Nugget thickness started to decrease after 9 kA for triple pulse welding. However, it continued rising with double pulse welding. Moreover, nugget penetration nearly reached the total thickness (2.4 mm) of the materials at 11 ka in double pulse welding.

As a results, all the figures related the nugget dimensions demonsrate that current is the most important parameter to increase nugget diameter and thickness.

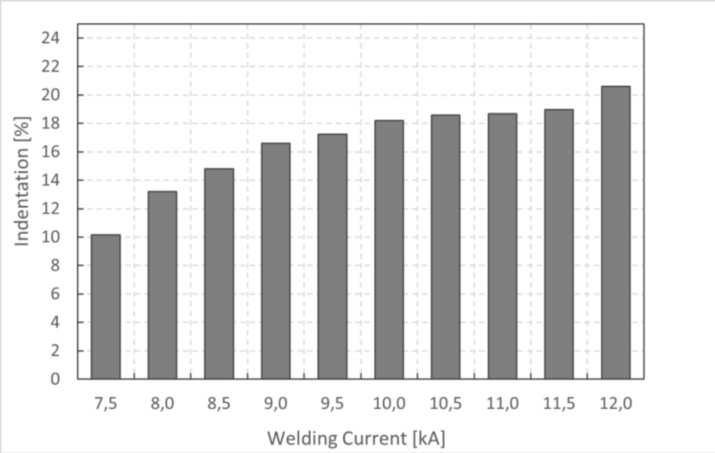

Figure 28. Nugget indentation/ Current diagram of single pulse welding

The changing of indentation/welding current variation for single pulse welding is shown in Figure 28. Indentation increased with current up to 12 kA. According to standards, the results are less than the acceptable indentation limits.

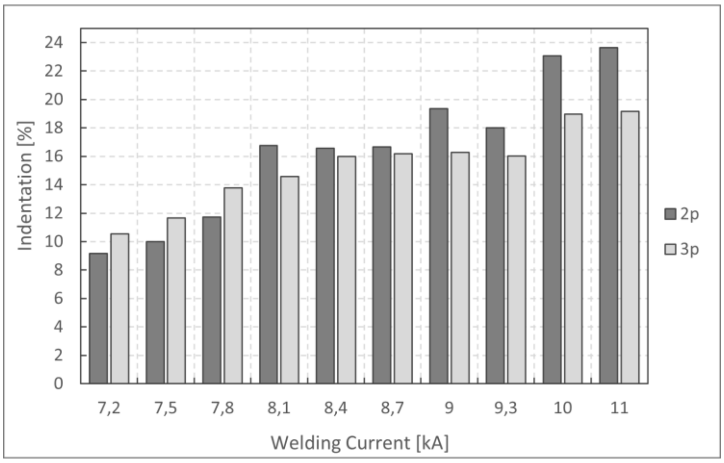

Figure 29. Nugget indentation/ Current diagram of double/triple pulse welding

Figure 29 compares the indentation of double and triple pulse welding formations. It is clear that indentation reached its maximum value at 11 kA due to expulsion.

4.4. Hardness

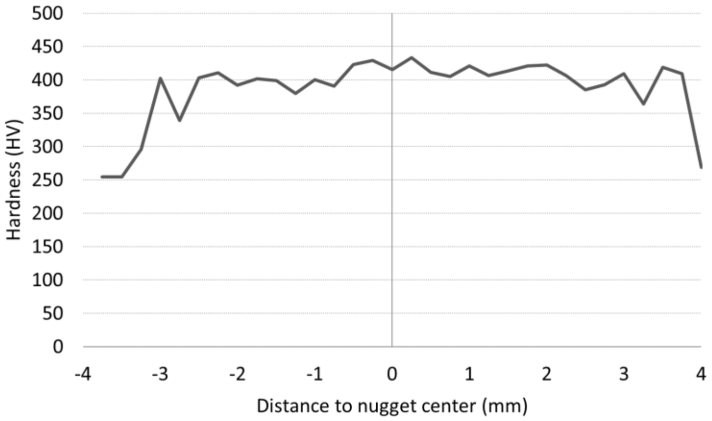

Figure 30. Hardness distribution of single pulse welding at 11 kA

Figure 30 shows the hardness distribution of single pulse welding. Hardness reached its maximum value in the middle of the nugget's geometry. In the HAZ, firstly, hardness decreased from 400 HV to 350 Hv. It then reached approximately to 440 HV at the center of the nugget.

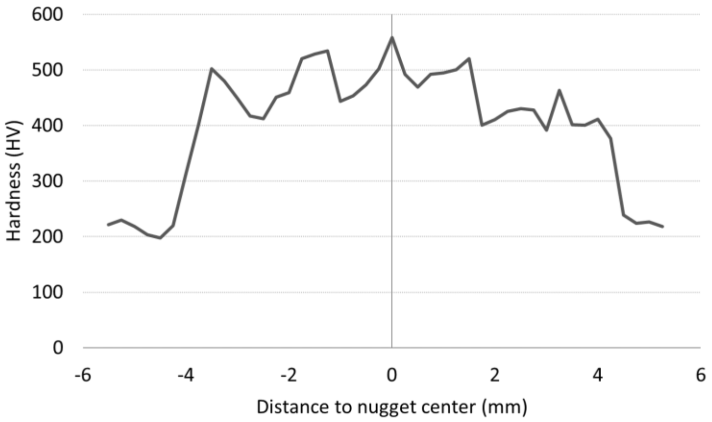

Figure 31.Hardness distribution of double pulse welding at 10 kA

Figure 31 displays the hardness distribution of double pulse welding. As in single pulse welding, it reached its maximum hardness value (530 HV) at the center of the nugget. Moreover, hardness value is higher than single pulse welding in nugget and HAZ.

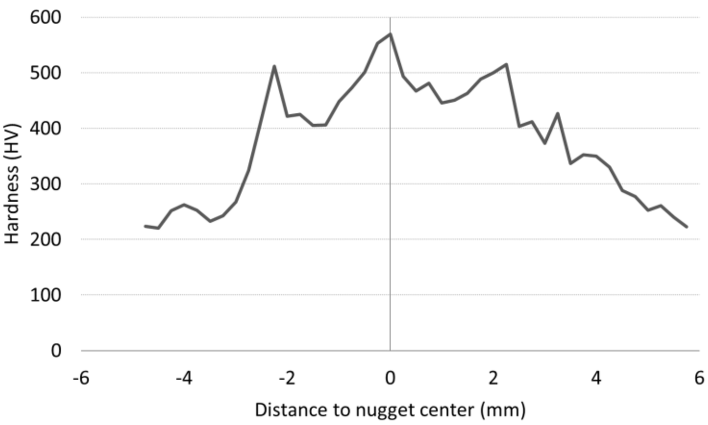

Figure 32. Hardness distribution of triple pulse welding at 10 kA

Figure 32 shows the hardness distribution of triple pulse welding. In the same way, it reached its highest point (560HV) at the center. However, triple pulse distribution is more irregular than single and double pulse welding. It is shown in the graph there is a gradually decrease in hardness out of the center.

5. DISCUSSION

Single, double and triple pulse welding formations were investigated in this thesis with HSLA 600 as the material. Tensile strength, failure energy, geometrical properties and hardness results were given in Chapter 4. According to all experimental results, comments are given below:

- Tensile strength increased with current. However, failure energy started to decrease after a certain point. The optimal current is 11 kA for single pulse welding and 10 kA for both double and triple pulse welding to reach the highest strength and failure energy in the nugget. The use of second and third phase current increased nugget strength.
- IF, PP and PF failure types were observed in single and double pulse welding. The pull-out failure type was shown at higher current values as strength increased. As opposed to single or double pulse welding, IF and PP failure types were only observed in triple pulse welding. The reason is that the strength of the HAZ began to deteriorate with the third pulse welding
- For all welding phases, the diameter of the nuggets enlarged as the current value increased. Yet, the rate of increase diminished after a certain point due to expulsion. The maximum nugget diameter of single pulse welding at 12 kA could be obtained with lower currents in double and triple pulse welding and nugget diameter of double pulse welding is wider than triple pulse welding at each current level except 7.2, 7.5 and 7.8 kA.
- As in nugget diameter, nugget thickness of single and double pulse welding nearly enlarged all welding current and it almost extended up to the material thickness in double pulse welding with 10 and 11 kA. However, after a certain welding point, rate of increase decreased. On the other hand, nugget penetration diminished from 9 kA to 11 kA in triple pulse welding.
- For all single, double and triple pulse welding, indentation increased with current. It also reached its peak at the highest current level.
- The hardness of nugget center increased with the use of double and triple pulse welding. It reached its highest point with triple pulse welding. Nonetheless, hardness distributions of triple pulse welding are asymmetrical, and irregular compared to those of single and double pulse welding.

6. SUMMARY AND OUTLOOK

As a summary, single, double, and triple pulse welding were investigated in this master's thesis. For each one, increasing current values improved nugget quality until a certain point due to expulsion which started at one point for all 1P, 2P and 3P welding.

The results of double pulse welding were generally better than single pulse welding. Tensile strength increased, nugget diameter and penetration enlarged, and hardness of the nugget improved with current. Nevertheless, nugget diameter and penetration started to diminish with triple pulse welding compared to double pulse welding. Even as the nugget's hardness increased, hardness distribution remained irregular. Furthermore, according to fracture type's results, the strength of HAZ was lower than that double pulse welding.

As a result, double pulse welding, rather than single or triple pulse welding, is the finest method for joining HSLA 600.

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