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MULTI-OBJECTIVE OPTIMIZATION OF THE RESISTANCE SPOT-WELDING PROCESS PARAMETERS FOR THE WELDING OF DUAL-PHASE STEEL DP500

VEČOBJEKTNA OPTIMIZACIJA PROCESNIH PARAMETROV ZA UPOROVNO TOČKOVNO VARJENJE DVOFAZNEGA JEKLA VRSTE DP500

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Resistance spot welding (RSW) is still the most used form of welding in the automotive industry, primarily for welding steel. One of the advanced steels used in the automotive industry is dual-phase steel, so it is important to properly select the welding parameter for these steels. Therefore, this paper presents multi-objective optimization in the RSW welding process of DP 500 steel. The paper considers three different mechanical characteristics i.e., the failure load (*F*), failure displacement (*l*) and weld nugget diameter (*D*), as all these welding characteristics play significant roles in evaluating the quality of spot welding. The results show that the welding current is the most influential parameter with respect to the mechanical characteristics. The effect of welding time on the weld quality is the least significant. The optimal parameters for welding DP 500 steel obtained in this paper are weld current 8 kA, electrode force 4.91 kN and weld time 400 ms.

Keywords: resistance spot welding, multi-Taguchi method optimization, DP steel

Uporovno točkovno varjenje (RSW; angl.: resistance spot welding) je še vedno najbolj pogost postopek varjenja jeklenih delov v avtomobilski industriji. Ena od najbolj naprednih vrst jekel, ki se uporabljajo v avtomobilski industriji, so dvofazna (DP; dual-phase steels) feritno-martenzitna jekla. Pri tem je zelo pomembno, da zanje izberemo primerne parametre varjenja. V članku avtorji predstavljajo večobjektno optimizacijo RSW-postopka za jeklo tipa DP 500. Kot najpomembnejše mehanske karakteristike kakovosti zvara ocenjujejo napetost (*F*) in odmik (*l*) pri njegovi porušitvi ter premer točkovnega zvara (*D*). Rezultati preiskav so pokazali, da na mehanske karakteristike zvara najbolj vpliva električni tok med varjenjem. Vpliv časa varjenja na kvaliteto zvara ni toliko pomemben. Avtorji ugotavljajo, da so optimalni procesni parametri za izbrani primer uporovnega točkovnega varjenja jekla tipa DP 500 naslednji: električni tok varjenja 8 kA, pritisna sila elektrode 4,91 kN in čas varjena 400 ms.

Ključne besede: uporovno točkovno varjenje, večobjektna Taguchi metoda optimizacije, dvofazno jeklo

1 INTRODUCTION

Resistance spot welding (RSW) is the most commonly used method for joining steel, especially in the automotive industry, so one car has over 5000 RSW points[1] and each car factory has more than 200 welding machines.[2] Traditionally, steels have been the material of choice for the fabrication of automobile structures. However, in order to respond appropriately to economic and environmental requirements for lighter but faster vehicles, many automobile manufacturers are re-directing their research and development efforts towards advanced, high-strength steels (e.g., TRIP steels and dual-phase steels).[3] Dual-phase DP steels are composed of a ferrite matrix with martensite as a second phase. This dual microstructure makes it possible to obtain a balance between strength and ductility, which is very attractive to reduce the weight of automobiles.[4]

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There are some research papers concerning the resistnce spot welding of DP steels. D. Zhao et al.[5] were investigating the weld defects of spot-welded dual-phase steel. Expulsion, shrinkage voids, and cracks are the major defects occurring during the spot-welding process, and they have no ignorable effects on the welding quality. The effects of welding parameters on the cross-tension strength, failure behavior and microstructural evolution of DP1000 steel were investigated in the research of A. Chabok et al.[6]

The parameter settings of each welding machine have been difficult because there are many sensitive factors. Therefore, it is necessary to analyze the parameters affecting the quality and mechanical properties of a RSW joint using optimization method. There is plentiful literature about optimization and lot of papers that deal with parameter optimization for RSW. Most of them have been done on a single objective optimization, which is shown in the review paper of Z. Nasir et al.[7] The following **Table 1** shows a review of the optimization of the

Table 1: A review of the optimization of the RSW process for different steels and parameters

Authors	Materials	Optimizations methods	Variable input parameters	Output	Results of optimizations
S. H. M. Anijdan at al.[8] (2018)	DP600 / AISI 304 STEEL	Taguchi	Current density Welding time Electrodes force Holding time after welding	Shear-tensile stress (N/mm^2)	Optimal parameter: 16 kA 16 cycle 5 kgf 35 cycle
H.A. Shende et al.[9] (2017)	AISI 304L / AISI 1020 STEEL	Grey-Taguchi /ANOVA	Current Pressure Weld time Hold time	Tensile strength (N/mm^2) Nugget diameter (mm)	Optimization technique revealed that the best combination of parameters for maximum tensile strength and minimum nugget diameter is current 10 kA, pressure 4 bars, weld time 10 cycles and hold time 25 cycles. The descending order of parameters that have most influence on the response in this research is I 91.6 %, W T 7.16 % , P 1.19 %, 0.017 % H T.
F. Reyes-Calderón et al.[10] (2018)	DP290/DP 290 STEEL	Taguchi	Force, Time and Current Intensity	Force (N)	Optimal conditions are: 0.75 MPa of pressure, 3.5 kA of current and 1,800 ms of welding time. Force (*F*) -33,82%, Time (*T*)- 19,5% and Current Intensity (*I*) -46,67%
A. Arumugam et al[11] (2015)	SPHC / SPRC35 STEEL	Grey-Taguchi /ANOVA	Force, Time and Current Intensity	Tensile shear strength and weld diameter	The optimum welding schedule obtained from this paper is a combination of 3 kN of electrode force, time of 15 cycles and 9 kA welding current. Force (*F*) -21.5 %, Time (*T*)- 11.9 % and Current Intensity (*I*) -58.7 %

RSW process for different materials and parameters over the years.

However, practical applications of the RSW process involve several objectives to be considered simultaneously. Multi-objective optimization is the determination of the values of decision variables that correspond to and provide the optimum of more than one objective.[12] This paper considers three different weld characteristics, i.e., the failure load (*F*), failure displacement (*l*) and weld-nugget diameter (*D*). These weld characteristics play significant roles in evaluating the quality of the spot weld. Finally, a multi-Taguchi Method will be used for the optimization of the weld parameters.

2 EXPERIMENTAL PART

In this research, sheet metals of DP500 steel were used as the parent metal to be lap welded. The dimensions of the specimen, which are defined by the standard ISO 14273:2016, are shown in **Figure 1**. The chemical composition and basic mechanical characteristics of the investigated DP steel are listed in **Table 2**.

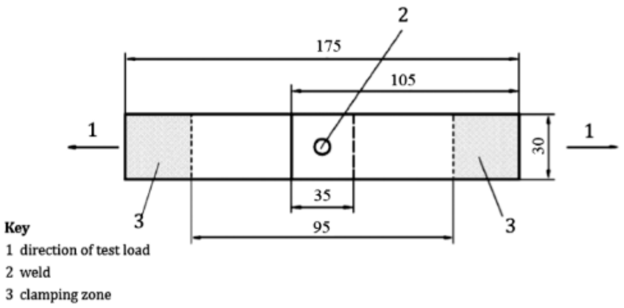

Figure 1: Dimensions of the specimen

Table 2: The chemical composition and basic mechanical characteristic of DP500 steel

Chemical composition (*w*/%)						
C	Si	Mn	P	S	Al	Nb+Ti
0.1	0.5	1	0.025	0.01	0.015	0.1
Mechanical propertis						
Yield strength $R_{p0,2}$ (MPa)		Tensile strength R_m (MPa)		Elongation A_{80} (min %)		
290–370		500–600		20		

Docol 500DP dual-phase steel possesses good formability and weldability and is suitable for car-safety components such as reinforcements. This steel undergoes a special heat treatment, producing mainly a two-phase structure. The ferrite that imparts unique forming properties represents one phase, and the martensite that accounts for the strength represents the other phase. Bainite may be present as a complementary phase.[13]

The experiment involved the joining of two sheet metals using a RSW machine manufactured by Kocevar & sinovi, which is managed using BOSH 6000 software. The welding was carried out using an electrode type F1. The welding machine and the dimensions of the electrode obtained from the standard ISO 5821:2009 are showed in **Figure 2**.

Three welding parameters, such as RSW weld current *I*, the electrode force *F* and the weld time *T* were selected for experimentation with three levels of factors. The value of the welding process parameter at different levels is tabulated in **Table 3**. Other welding parameters such as the squeeze time (*SQZ* = 300 ms), the hold time (*HLD* = 300 ms), the pre-heating time (*Pre-Weld* = 0 ms), the Cool Time (*CT* = 0 ms), the Up Slope Time (*UST* = 0 ms) and the Down Slope Time (*DST* = 0 ms)

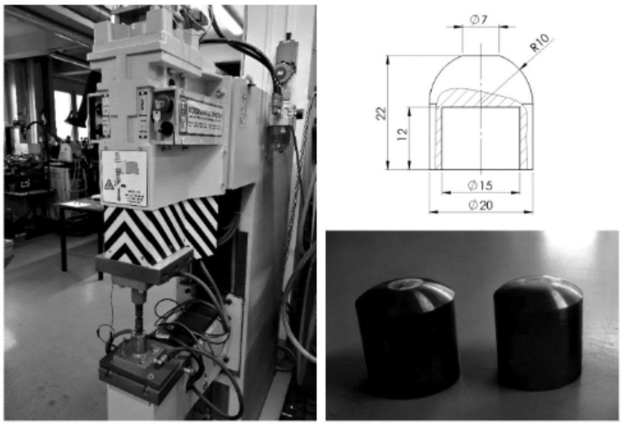

Figure 2: Welding machine and dimensions of the electrode

were constant during the experiment. All the specimens were fully welded.

Table 3: Selected levels for the parameters of the welding

Factor/level	L1	L2	L3
Weld current *I* (kA)	6	8	10
Electrode force *F* (kN)	2.45	3.68	4.91
Welding time *T* (ms)	200	300	400

The tensile-shear tests were performed according to the standard ISO 14273:2016 at a cross-head speed of 2 mm/min with a Beta 50-7 / 6×14 testing machine. As per the L_9 orthogonal array (OA), for each combination of process parameters there were three repetitions of the testing. The results (failure load *F*, failure displacement *l*, weld-nugget diameter *d*) obtained from the tests are given in **Table 4**. The weld-nugget diameter was measured using the weld cross-section on a VHX-6000 microscope.

Table 4: Experimental layout using L_9 OA and the result from the tensile-shear tests

Runs	Weld current *I* (kA)	Electrode force *F* (kN)	Welding time *T* (ms)	Failure load *F* (kN)	Failure displacement *l* (mm)	Weld-nugget diameter *d* (mm)
1	6	2.45	200	13.36	5.41	6.17
2	6	3.68	300	14.005	4.3	6.2
3	6	4.91	400	12.627	5.56	5.67
4	8	2.45	300	19.455	6.7	6.73
5	8	3.68	400	20.340	7.7	6.93
6	8	4.91	200	18.167	9.59	6.47
7	10	2.45	400	22.043	11.46	7.63
8	10	3.68	200	16.227	8.13	6.76
9	10	4.91	300	17.480	8.7	6.3

2.1 Multi-objective Taguchi method

The selection of the OA is based on the total degree of freedom (DoF) of the process. Mathematically, the DoF can be computed as [12]:

DoF = [((number of levels – 1) for each factor) + ((number of levels – 1) × (number of levels – 1) for each interaction + 1)] (1)

The procedure of the multi-objective Taguchi method is explained in the following steps:

1. Calculation of qualty loss values (dB) – MSD

In this research, for the failure load *F* and failure displacement *l*, the larger-the-better was chosen and for the nugget diameter d, the smaller-the-better was chosen, using the following Equations (2) and (3):[12]

$$\text{Larger-the-better} – MSD = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \tag{2}$$

$$\text{Smaller -the-better} – MSD = \frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2} \tag{3}$$

where MSD is the mean square deviation for the output characteristic and commonly known as the quality loss function, *n* is the number of tests, y_i is the value of responses.

2. Calculation of the Total Normalised qualty loss values – TNQL

The total normalised qualty loss values can be calculated as[12]:

$$TNQL = \sum_{i=1}^{k} w_i \frac{L_{ij}}{L_i^*} \tag{4}$$

where w_i is the weighting factor for the *i*-th quality characteristic, *k* is total number of quality characteristics and is the normalised quality loss associated with the *i*-th quality characteristic at the *j*-th trial condition, *Lij* is the MSD for the *i*-th quality at the *j*-th trial, and L_i^* is the maximum quality loss for the *i*-th quality characteristic among all the experimental runs.

3. Calculation of multiple *S/N* ratio – MSNR

In multi-objective optimization, a single overall *S/N* ratio for all quality characteristics is computed in place of separate *S/N* ratios. This overall *S/N* ratio is known as multiple *S/N* ratio (*MSNR*) and mathematically can be computed as[12]:

$$MSNR = -10 \log_{10} (TNQL) \tag{5}$$

3 RESULTS AND DISCUSSION

3.1 Multi-objective Taguchi method

The normalized MSN, TNQL and MSNR for multiple quality characteristics failure load *F*, failure displacement *l*, weld-nugget diameter *d* have been calculated using Equations (1–5). These results are shown in **Table 5**. In calculating the total normalized quality loss, three weights, i.e., $w_1 = 0.34$ for *F*, $w_2 = 0.3$ for *l*, and $w_2 = 0.2$ for *d* have been assumed.

The effect of different control factors on the MSNR is shown in **Table 6**. The optimum levels of different control factors are the weld current at level 8 (8 kA), the

Table 5: Normalized *MSN*, *TNQL* and *MSNR*

Runs	Normalized *MSN*			*TNQL*	*MSNR*
	F	*l*	*d*		
1	0.89328	0.630114	0.652766	0.727065	1.384265
2	0.812894	1	0.65977	0.824108	0.840157
3	1	0.597474	0.551208	0.719065	1.432318
4	0.421248	0.414366	0.777391	0.536504	2.704269
5	0.385388	0.306027	0.824996	0.50427	2.973372
6	0.483097	0.200922	0.717819	0.467438	3.302764
7	0.32814	0.140789	1	0.488028	3.115554
8	0.605514	0.279534	0.785963	0.557489	2.53764
9	0.521816	0.245809	0.681225	0.483339	3.157484

Table 6: Multiple *S/N* ratios response

Factors	Mean of multiple *S/N* ratios			Δ	Rank
	Level 1	Level 2	Level 3		
A (I)	1.218913168	2.993468419*	2.936892609	1.77455251	1
B (F)	2.401363	2.117056	2.630855*	0.513798649	2
C (T)	2.408223	2.23397	2.507081*	0.2731116	3
**Optimal level, Δ = maximum-minimum at level*					

Table 7: Analysis of variance (ANOVA) for multiple *S/N* ratios

Source	Sum of squares	DF	Mean square	*F* value	*P* value	Contribution (%)
A (I)	6.103700523	2	3.05185	49.29779	0.0198	90.56
B (F)	0.39748587	2	0.198743	3.210376	0.2375	5.89
C (T)	0.114727127	2	0.057364	0.926617	0.519	1.71
Error	0.123812861	2	0.061906			1.84
Total	6.73972638	8				100

electrode force at level 3 (4.91 kN) and the weld time at level 3 (400 ms).

Analysis of variance (ANOVA) for the multi Taguchi optimisation is given in **Table 7**. The percentage contributions of the welding current, electrode force and welding time are (90.56, 5.89 and 1.71) %, respectively. The percentage contribution generally indicates the welding parameter effect on the MSNR. The welding current is thus suggested as the most influential parameter on the quality characteristics. The effect of the welding time on weld quality is the least significant.

The failure of resistance spot welds during the tensile–shear test can be described as a competition between the shear plastic deformation of the fusion zone (i.e., IF mode) and the necking in the base metal (i.e., PF mode).[14] All the samples welded with a current of 6 kA (Runs: 1, 2, 3 – **Table 4**) were a failure in the IF mode (**Figure 3a**). Also, the specimen that was welded with the parameters defined under run 9 in Table 4 failure in IF mode, while all the other specimens failed in the PF mode (**Figures 3b** and **3c**). From the foregoing, it can be concluded that the welding current and welding time have a greater influence on the failure type mode than the welding force.

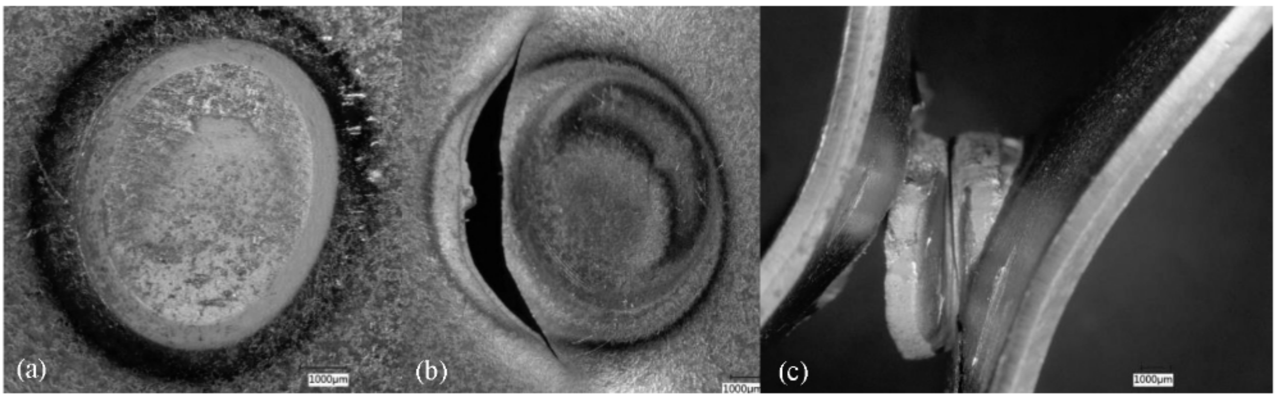

Figure 3: Failure mode: a) IF mode, b) PF mode, c) PF mode

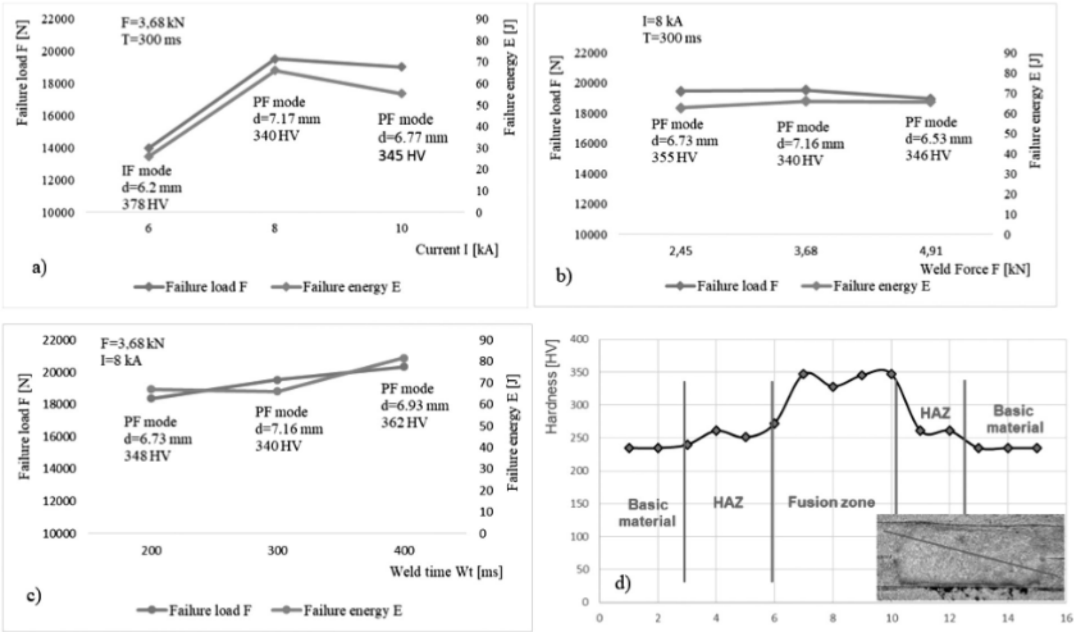

Figure 4: Influence of welding parameters on mechanical characteristics: a) welding current, b) welding force, c) welding time, d) hardness profile of E2 specimen

Table 8: Welding parameters and results of mechanical testing

Runs	Mark	Weld current *I* (kA)	Electrode force *F* (kN)	Welding time *T* (ms)	Failure load *F* (N)	Failure energy *E* (J)	Failure displacement *l* (mm)	Weld-nugget diameter *d* (mm)	Hardness in FZ (HV)	Failure mode
1	E 1	6	3,68	300	14005	26.075	4.3	6.2	378	IF
2	E 2	8	3,68	300	19530	66.017	6.7	7.167	340	PF
3	E 3	10	3,68	300	19036.67	55.297	5.697	6.767	345	PF
4	E 4	8	2,45	300	19455	62.73	6.68	6.733	355	PF
5	E 5	8	4,91	300	18960	65.563	6.847	6.533	346	PF
6	E 6	8	3,68	200	18370	67.133	7.423	6.733	348	PF
7	E 7	8	3,68	400	20340	81.703	7.773	6.933	352	PF

3.2 Welding parameters' effect on the mechanical properties – confirmation test

In order to confirm the Mmulti-objective Taguchi method analysis, a detailed analysis of the influence of welding parameters on the mechanical characteristics of the welded joint was made. This confirmation test was performed under the same conditions as the previous experiment, only the welding parameters were varied. **Table 8** shows the welding parameters and results of mechanical testing. The amount of energy was digitally calculated by measuring the area under the load–displacement curve to failure. Metallographic samples were cut from the center of the joints. The samples were ground and polished based on standard metallography procedures. The DP500 steel was etched using 4 % nital solution (7 s). Microstructures of joints were observed with an VHX-6000 microscope. A Vickers micro-hardness tester Zwick/Roell ZHU 2.5 was used to measure the hardness variations across the joint under a load of 5 N for 12 s.

The results presented in the previous table show that all the specimen were failure in PF mode except for the DP 1 specimen, which was welded with a 6-kA welding current. This confirms the fact that the type of failure mode depends the most on the welding current.

The result of the influence of the welding current on the mechanical characteristics of the joint is shown in **Figure 4a**. It can be easily concluded that the welding current has a great influence on the mechanical characteristics, mainly on the failure load, failure energy and failure mode. However, an increase in the welding current does not necessarily mean better mechanical characteristics, from the figures it is obvious that the failure load and energy are greater for a welding current of 8 kA than a welding current of 10 kA. This confirms that the welding current of 8 kA is optimal for welding DP steel, as evidenced by the previous Multi-objective Taguchi method. **Figures 4b** and **4c** show that the welding force and welding time have very little influence on the mechanical characteristics of the spot-weld joint. Such results were expected as this was also demonstrated by applying an analysis of variance (ANOVA) for multi

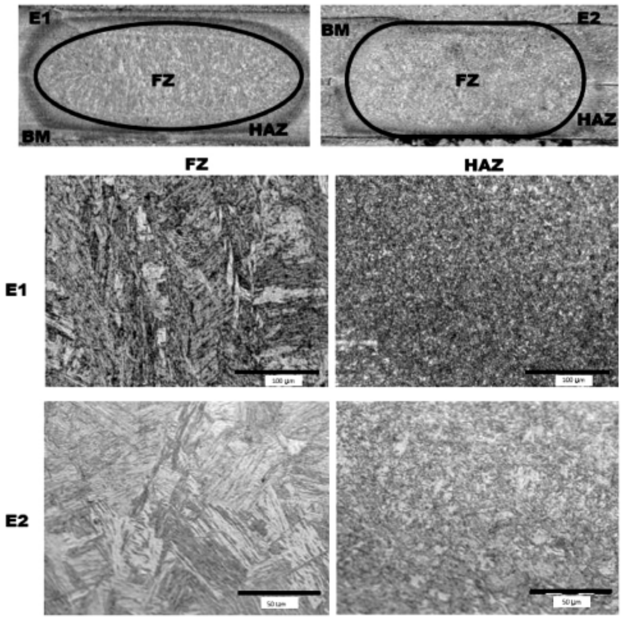

Figure 5: Macro- and microstructure of specimen E1 and E2

Taguchi optimization. The hardness of all specimen in fusion zone is approximately 350 HV. The increase in hardness of the fusion zone was generated by the martensite formation during cooling. The weld thermal cycles induced a soft zone formation (approximately 260 HV) in the heat affected zone. Tha hardness profile of specimen E2 is shown on **Figure 4d**.

The welding current has a great influence on the mechanical characteristics, because it changes the micro- and macrostructure of the joint. **Figure 5** shows the macro- and microstructure of specimens E1 and E2. Generally, in the FZ we can see columnar grains. Within this zone, dendrites disappeared due to solid–solid transformation after solidification. These columnar grains consist of martensite.

4 CONCLUSIONS

The optimal parameters for welding DP 500 steel obtained in this paper are a weld current 8 kA, an electrode force 4.91 kN and a weld time 400 ms.

Percent contributions of welding current, electrode force and welding time are (90.56, 5.89 and 1.71) %, respectively. Welding current is thus suggested as the most influential parameter on quality characteristics. The effect of welding time and force on the weld quality is the very small. Welding current has a great influence on the mechanical characteristics, mainly on the failure load, failure energy and failure mode. However, an increase in the welding current does not necessarily mean better mechanical characteristics.

Welding current and welding time have a greater influence on the failure type mode than the welding force. All samples welded with a current of 6 kA were a failure in IF mode.

The welding current has an effect on the micro- and macrostructure of the RSW joint of DP500 steel but it can be generally concluded that the microstructure FZ consists of lath martensite. The hardness of the FZ zone is approximately and the hardness of the HAZ zone is approximately 260 HV.

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