Study on Influencing Factors of Resistance Spot Welding Performance of Press-Hardened Steel

W. F. Wang(✉), Y. Y. Ji, C. J. Cheng, and P. H. Dai

Technology Center of Ma'anshan Iron and Steel Company, Ma'anshan 243000, China
877795074@qq.com

Abstract. The orthogonal test was performed on 22MnB5 press-hardened Steel. The results show that the order of priority affecting the mechanical properties of spot welded joint is welding current, electrode pressure and welding time. The best mechanical properties of the welded joint and the good welding quality can be gotten with the best welding parameters welding current of 8.5 kA, welding time of 525 ms and electrode pressure of 4 kN. The press-hardened steel welded joint consists of the BM zone, the tempering zone, the softening zone, the critical zone and the nugget zone. There is a serious stress concentration at the weld joint line in the nugget zone, which is a dangerous area for the failure of press-hardened steel welded joints. In addition, it is also founded that welding splash is an important factor to decline mechanical properties of welded joints.

Keywords: Press-hardened steel · Influencing factors · Best welding parameter

1 Introduction

With the development of China's automobile industry and the increase of automobile production and ownership, energy consumption, safety and environmental problems have gradually attracted people's attention. Press-hardened steel has high strength, which improves the crash-worthiness and overall safety of the body, and reduces the weight of the vehicle and saves energy consumption effectively. It is the best balance between lightweight and safety [1, 2]. At present, resistance spot welding is the main welding method for BIW welding assembly. Due to the large amount of alloy elements added in press-hardened steel, welding spatter is prone to occur during welding. It is easy to form a complex micro-structure distribution in the welding area after welding, and the joint quality is difficult to guarantee [3]. Therefore, we carry out the spot welding orthogonal test of hot forming steel, and clarify the influence of welding process parameters on the quality of spot welded joints to provide reference for the welding operation of automobile main engine factory.

2 Tested Material and Method

The test material is 1.2 mm 22MnB5 produced by a steel plant. The chemical composition of the material is shown in Table 1. The properties of the steel plate after press hardening

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Table 1. Chemical compositions of tested material (wt.%).

C	Si	Mn	P	S	Cr	Mo	B	Fe
≤0.30	≤0.50	≤2.00	≤0.025	≤0.008	≤0.30	≤0.35	0.002–0.004	Balance

Table 2. Mechanical properties of tested material.

Thickness/mm	Rp0.2/MPa	Rm/MPa	δA_{50}/%
1.2	1050	1536	5.86

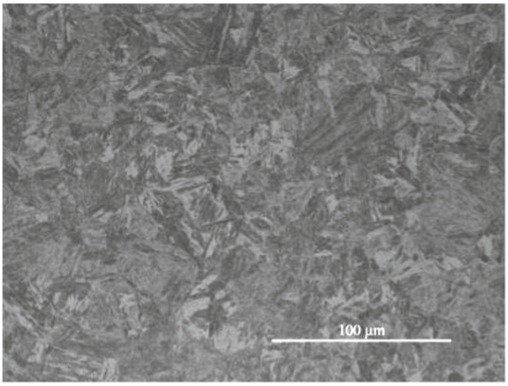


Fig. 1. Microstructure of tested material.

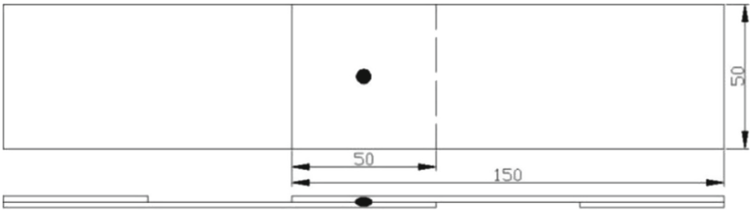


Fig. 2. Tensile test specimen of welded joint.

are shown in Table 2. The micro-structure of the substrate after press hardening is shown in Fig. 1, which is consist of martensite. The sample size is 50 mm × 150 mm, using lap single point welding method, as shown in Fig. 2.

The spot welding equipment is DRG-130 intermediate frequency servo welding machine. The end face size of the electrode is Φ6 mm-R40 mm arc shape, as shown in Fig. 3. The electrode material is chromium zirconium copper alloy.

According to the standard AWS D8.9M-2012 [4], we kept the electrode pressure 3.8 kN unchanged, under the welding time 350 ms, 438 ms and 525 ms, and adjusted the

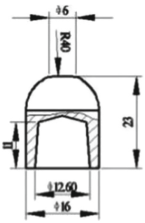
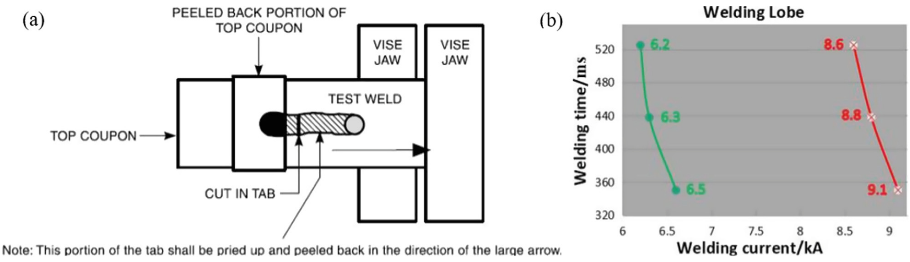


Fig. 3. Sketch of welding process.



Note: This portion of the tab shall be pried up and peeled back in the direction of the large arrow.

Fig. 4. Tearing test and welding lobe: (a) Peel test of welded join; (b) Welding lobe.

Table 3. Factor and level of welding parameters.

Factor	I/kA	T/ms	f/kN
1	6.5	350	3
2	7.5	438	4
3	8.5	525	5

welding current, and conducted peel test, as shown in Fig. 4. Starting from obtaining the required nugget diameter D_{min} to reach 4.38 mm, the nugget diameter gradually increases with the increase of welding current until the welding splash occurs, and the welding lobe under the corresponding welding time is obtained, as shown in Fig. 4.

In the above spot welding lobe, three main influencing factors, namely welding current, welding time and electrode pressure, were selected by orthogonal test method. Each influencing factor was selected at three levels, as shown in Table 3, and the peak load of welded joint was used as the evaluation index. Each group of welding process to produce three samples, using orthogonal table L9 (3^4) process parameters for spot welding test.

3 Analysis of Experimental Results

3.1 Analysis of Extreme Difference and the Variance

With the peak tensile-shear load of welded joint as the evaluation criteria, the orthogonal test results are shown in Table 4. In the table, A, B and C are the influencing factors of welding current, welding time and welding pressure respectively. F_i (i = 1, 2, 3) is the tensile-shear peak load of the specimen under each welding parameter. F is the average value of the tensile-shear peak load under the same welding parameter. K_i (i = 1, 2, 3) represents the sum of the average peak load under the same horizontal welding process in a column. $k_i = K_i/3$ (i = 1, 2, 3) represents the arithmetic average value of the above average load. R represents the range, which is the difference between the maximum and minimum values of the arithmetic average value of the above average load.

Range analysis results can intuitively compare the primary and secondary factors of the test. The influence of welding current (A), welding time (B) and electrode pressure (C) on spot welding performance of 22MnB5 press-hardened steel is sorted in descending order. The optimal welding process combination is $A_3B_3C_2$, namely welding current 8.5 kA, welding time 525 ms and electrode pressure 4 kN.

The principle of range analysis is simple, but this method has certain limitations. Although we can sort all the factors examined in primary and secondary order and obtain the main factors, it is uncertain whether the influence of various factors on the test is obvious and at some level. Through variance analysis, we can find out the decisive factors that affect the data and serve as the basis for quantitative analysis. The results of variance analysis are shown in Table 5, F Table for significant test, FA = 56.0013 > F (2, 2) 0.05 = 19, FC = 4.0845 > F (2, 2) 0.25 = 3, the influence of welding current (A) on the test is at 0.05 significant level, electrode pressure (C) is at 0.25 level, and the influence of welding time (B) on the test is not significant.

3.2 Analysis of Nugget Diameter and Fracture Mode

There are three main fracture modes of spot welded joints, interface fracture IF, button fracture PF and mixed fracture mode I & PF [5]. In this test, there are IF and PF two fracture modes of tensile shear specimens. The nugget diameter of the solder joint and the fracture mode of the joint are related to the strength of the spot welded joint, and can also reflect whether the welding process is suitable. The nugget diameter and fracture mode of solder joints are shown in Table 6. It can be seen that with the increase of welding current, the diameter of nugget increases. When the welding current is small, interface fracture occurs frequently. When the welding current is large, the failure mode of spot welded joint tensile shear test is button fracture.

The cross-section morphology of the fractured joint was observed, as shown in Fig. 5. When the welding current is 6.5 kA, the welding time is 350 ms and the electrode pressure is 3 kN, the failure mode of the samples is interface fracture. The reason of interface fracture is mainly due to the small diameter of the welded joint. When the shear force is applied, the shear force of the central joint in the nugget zone is less than that in other regions. The crack initiates at the tip of the welded joint line and extends to fracture along the weld point center.

When the welding current is 8.5 kA, the welding time is 525 ms and the electrode pressure is 4 kN, the failure mode of the samples is pull-out fracture. At this time, the nugget diameter of the solder joint is large, and the shear force of the central bonding surface of the nugget zone is large. Under the condition of continuous loading, the resistance to positive tension from the tip of the bonding line to the thickness of the solder joint is less than that of other regions. Therefore, the crack initiates at the tip of

Table 4. Result of orthogonal experimental and range analysis.

	Factor			Peak Load/kN			
	A	B	C	F_1	F_2	F_3	$\overline{F}$
	I/kA	T/ms	f/kN				
1	6.5(1)	350(1)	3(1)	10.73	10.35	10.46	10.51
2	6.5(1)	438(2)	4(2)	11.78	11.69	11.53	11.67
3	6.5(1)	525(3)	5(3)	11.38	11.12	11.31	11.27
4	7.5(2)	350(1)	4(2)	12.26	12.89	13.36	12.84
5	7.5(2)	438(2)	5(3)	12.22	11.97	11.67	11.95
6	7.5(2)	525(3)	3(1)	12.89	12.96	13.15	13.00
7	8.5(3)	350(1)	5(3)	14.52	14.25	14.17	14.31
8	8.5(3)	438(2)	3(1)	13.82	14.01	13.68	13.84
9	8.5(3)	525(3)	4(2)	15.35	14.85	15.64	15.28
K1	33.45	37.66	37.35				
K2	37.79	37.46	39.78				
K3	43.43	39.55	37.54				
k1	11.15	12.55	12.45				
k2	12.60	12.49	13.26				
k3	14.48	13.18	12.51				
R	3.33	0.69	0.81				
Priority order	A > C > B						
Priority level	A_3	B_3	C_2				
Priority level combination	$A_3B_3C_2$						

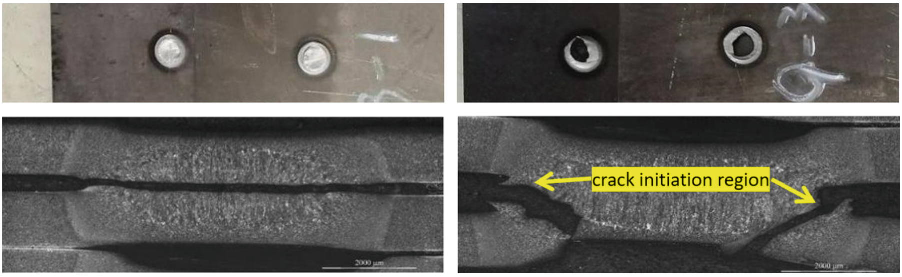
Table 5. Result of variance analysis.

	f	S	F	Significance
Factor A	2	16.6940	56.0013	High
Factor B	2	0.8867	2.9745	Low
Factor C	2	1.2176	4.0845	Low
Error	2	0.2981	–	$F_{(2,2)0.05} = 19$; $F_{(2,2)0.10} = 9$; $F_{(2,\ 2)0.25} = 3$

the bonding line and extends to the thickness of the nugget zone until the fracture failure of the joint. When the welding current is 8.5 kA, the welding time is 525 ms and the electrode pressure is 3 kN, the failure mode of the samples is interface fracture due to the large welding heat input and the splash of the welded joint.

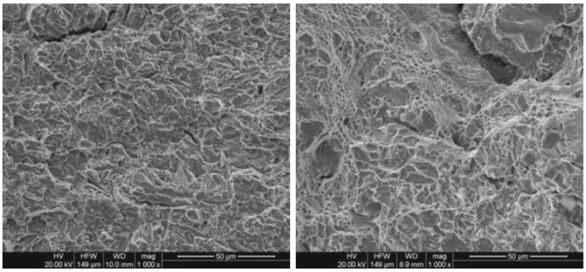
Table 6. Diameter of nugget and failure mode.

No.	Diameter/mm	Failure mode	
		IF/PCS	PF/PCS
1	4.59	3	0
2	4.88	2	1
3	5.18	1	2
4	5.60	0	3
5	5.65	0	3
6	5.68	0	3
7	6.13	0	3
8	6.06	1	2
9	6.36	0	3



(a) Inter-facial fracture (IF) (b) Pull-out fracture (PF)

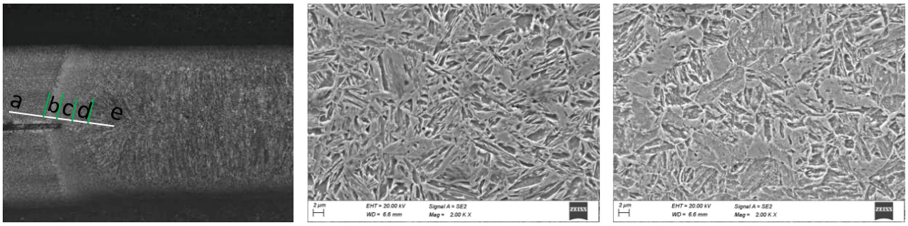
Fig. 5. Macroscopic and sectional morphology of fractured samples.



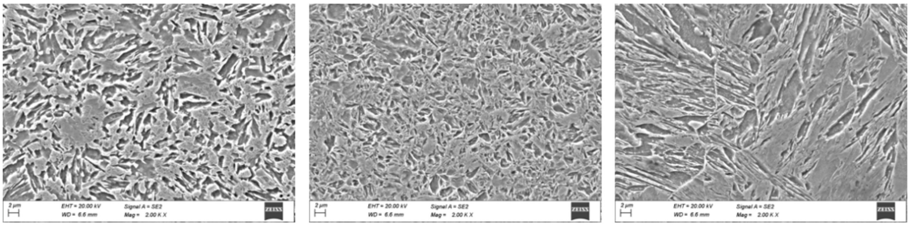
(a) Inter-facial fracture (IF) (b) Pull-out fracture (PF)

Fig. 6. Fracture morphology.

Observe the fracture morphology, as shown in Fig. 6. The interface fracture fracture is brittle fracture with a large number of tearing edges and cleavage plane. The dimples with uneven distribution of the pull-out fracture are ductile fracture.



(a)Macrostructure (b) Position a (c) Position b



(d) Position c (e)Position d (f) Position e

Fig. 7. Microstructure of spot welded joint.

3.3 Microstructure and Microhardness Analysis

The microstructure and microhardness of the spot welded joint under the above optimal welding process A3B3C1 are analyzed, as shown in Fig. 7. The welded joint consists of five regions, a base metal zone, b tempering zone, c softening zone, d critical zone and e nugget zone.

The base metal zone is full martensite structure obtained at 930 °C for 4 min quenching heat treatment of die. In a welding cycle, the temperature of the weld nugget center in the position e is the highest, reaching 1500 °C. Under the cooling effect of the electrode perpendicular to the surface of the steel plate, the crystal appearance from the surface of the steel plate to the center of the weld nugget, which forms columnar crystals, and the microstructure is coarse lath martensite. The heating temperature of d critical zone is between Ac1 and the melting temperature of base metal, belonging to the transition zone. The temperature distribution in this position leads to the formation of incomplete recrystallization region, fine grain region and coarse grain region. The microstructure is martensite and a small amount of ferrite, fine grain martensite and coarse grain martensite, respectively. Softening zone c is far from the weld nugget center, and the maximum temperature in this region is lower than Ac1 temperature when heating. Due to the instability of the original martensite structure, some martensite is decomposed into ferrite and carbides, and the retained microstructure is martensite and ferrite. The generated ferrite makes the microhardness of this region decrease significantly. The heated temperature of tempering zone b is between 350 °C to 600 °C when martensite occurred structure tempering.

The microhardness distribution was tested along the direction shown in Fig. 7 (a) from the base metal, and the results are shown in Fig. 8. The hardness distribution is extremely uneven along the direction. The microhardness value of the base metal zone is about 490 HV, and that of the critical zone is about 530 HV, and that of the nugget zone

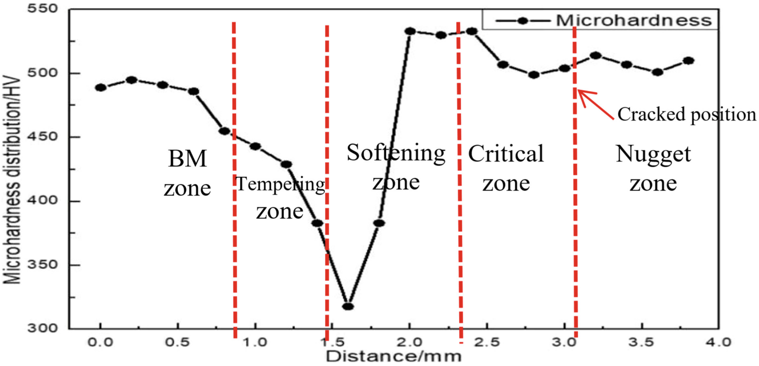


Fig. 8. Microhardness distribution of welded point.

is about 510 HV. The hardness of the softening zone is the lowest, and that of the critical fine grain zone is the highest. Combined with Fig. 5 and Fig. 7, it can be seen that the microstructure of the bonding line position (nugget zone) is brittle and hard martensite, and there is a serious stress concentration, which is a dangerous area for the failure of the press-hardened steel spot welded joint.

4 Conclusions

(1) In the spot welding parameters of press-hardened steel, the order of priority affecting the mechanical properties of spot welded joint is welding current, electrode pressure and welding time. The influence of welding current on the spot welded joint is significant. The optimal process parameters for spot welding of 1.2 mm 22MnB5 hot-formed steel are as follows: welding current 8.5 kA, electrode pressure 4 kN, and welding time 525 ms.

(2) The fracture position of press-hardened steel spot welded joint is located in the nugget zone. The fracture of pull-out fracture samples is ductile fracture, and the fracture of interface fracture specimen is flat, which is brittle fracture.

(3) The spot welded joint of press-hardened steel is composed of base metal zone, tempering zone, softening zone, critical zone and nugget zone. The hardness of softening zone is the lowest. There is a serious stress concentration in the bonding line position, which is a dangerous area for the failure of press-hardened steel welded joints.

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