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INFLUENCE OF WELDING PARAMETERS ON RESIDUAL STRESSES IN DISSIMILAR HSLA STEELS WELDS

E. Ranjbarnodeh[1*], M. Pouranvari[2], A. Fischer[3]

[1]*East Tehran Branch, Islamic Azad University, Tehran, Iran*
[2]*Dezful Branch, Islamic Azad University, Dezful, Iran*
[3]*Materials Science and Engineering, University Duisburg-Essen, Lotharstr.1, 47057 Duisburg, Germany*

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Abstract

For many years, the use of high strength steels in construction is increasing due to high ratio of strength to weight and cost considerations. These properties reduce the fabrication cost and time. To make use of these advantages of these modern steels, their weldability was extensively evaluated. In the present study a dissimilar patch welds between two high strength steels was investigated. A series of dissimilar steel joints based on the S600MC (as the base plate) and S355 (as the patch plate) were produced using robotic MIG welding. Residual stresses were determined using the X-ray diffraction (XRD).The effect of welding speed and sequence on residual stresses distribution in two different patch shapes was studied. Analysis of the results revealed that using of the welds in opposite directions reduces the welding stresses and the effect of welding speed is different in two patch shapes. It was found final state of residual stresses depends on all of theses parameters.

Keywords: Welding residual stresses, Dissimilar welding, HSLA steel, Heat input, Welding sequence

Introduction

High-strength low-alloy (HSLA) steels, or microalloyed steels, are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. HSLA steels have yield strengths greater than 275 MPa. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition. HSLA steels can be divided into many categories that one of them is microalloyed

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[*] Corresponding author: Estam Ranjbarnodeh, islam_ranjbar@yahoo.com

ferrite-pearlite steels, which contain very small (generally, less than 0.10%) additions of strong carbide or carbonitride forming elements such as niobium, vanadium, and/or titanium for precipitation strengthening, grain refinement, and possibly transformation temperature control. Applications of HSLA steels include oil and gas pipelines, heavy-duty highway and off-road vehicles, construction and farm machinery, industrial equipment, storage tanks, mine and railroad cars, barges and dredges, snowmobiles, lawn mowers, and passenger car components. Bridges, offshore structures, power transmission towers, light poles, and building beams and panels are additional uses of these steels [1]. In the recent passenger vehicles a broad variety of high strength steels has been introduced as an alternative for mild steel grades [2]. Due to this advantages and applications of high strength steels similar and dissimilar joint of these steels is inevitable and residual stresses are one the main concerning issues during the welding processes especially in the case of dissimilar welds. After finishing welding process, due to high thermal gradient, residual stresses are produced in the metal. Residual stresses in the weldment have been reported to cause problems, including brittle fracture, stress corrosion cracking and reduction in fatigue life [3]. Dissimilar weld is a term refers to joint between two different materials/alloys with significant differences in their chemical composition or metallurgical characteristics. When fusion welding processes such as Gas Tungsten Arc Welding (GTAW) or laser beam welding are used to make a dissimilar combination, alloying between the used base metals and filler metal, if any, is of utmost importance. The weld metal of dissimilar joint can exhibit different behavior during subsequent processing or in service rather than one or both base metals. Accordingly, selection of convenient welding process and parameters of dissimilar joints is more complicated than similar joints. Due to differences of thermo-physical, metallurgical and mechanical properties' welding of dissimilar metals has some special problems [4]. Some studies describing the research on dissimilar welding in various applications can be found in the literature. Sun [5] investigated the dissimilar weld between 1.4550 and low alloyed steel 1.7335 in a tubular joint and compared his results with TIG and plasma processes. Joseph et al [6] in their work on dissimilar welds between 2.25Cr–1Mo ferritic steel and AISI316 stainless steel with and without Inconel-82 buttering on the ferritic steel side found that the employed buttering layer and stress relief heat treatment were useful techniques to reduce the welding residual stresses which in turn would be beneficial to avoid in-service failures. Katasareas and Youtsos [7] studied the distribution of welding residual stresses in dissimilar joint between AISI 316 austenitic stainless steel and A508 low carbon steel using both experimental and numerical approaches. They concluded that a bead-by-bead simulation is necessary to obtain accurate prediction of residual stresses. Their results showed that the value of residual stresses at AISI 316 side is higher than A508 side. Anawa et al [8] used a statistical model to predict the relationship between process parameters and residual stress during CO_2 continuous laser beam for joining of AISI 316 stainless steel and low carbon steel plates. Ranjbarnodeh at al. [9] developed 2-D model to predict the effect of heat input on welding residual stresses in dissimilar welding between CK4 carbon steel and AISI 409 ferritic stainless steel. They found that the higher the heat input, the lower the residual stress are. Ranjabarnodeh et al. [10] in their work investigated the effect of welding current, the sample length and welding sequence on welding residual stresses in dissimilar joint between AISI 409 and CK4 steels. They found that CK4 side with the higher yield stress exhibit higher residual stresses and the increasing of sample length decreases the resulting residual stresses. There is limited open literature regarding residual stresses in dissimilar welds of high strength steels. Therefore, the work reported here addresses the residual stresses in dissimilar welding of two high strength steels. In the present study, S600MC (as the base plate) and S355 (as the patch plate) steel plates were patch welded using robotic MIG welding. Longitudinal residual stresses of the joints were evaluated by means of X-ray diffraction (XRD) method. The effect of welding speed, operation sequence and the patch shape on the residual stresses was studied.

Materials and experimental methods

Materials and welding procedure

Geometry of joints was circular and rectangular patches on rectangular base plates. S600MC was used for base plate and S355 for patch plate, 4 and 3 mm in thickness. The chemical compositions, mechanical and thermo physical properties of the used materials at room temperature are represented in Table 1, 2, and 3, respectively. Laser cutting was used for preparation of all base and patch plates. After laser cutting, rectangular patches were tacked on all four corners and circular patches in four places. After preparation, patch welds were produced between S600MC and S355 using ER70-S6 as filler metal. Welding operation was carried out using VALK robotic MIG/MAG welding machine. Ar-17%CO_2 shielding gas with flow rate of 15 L/min was used during welding process. The weld type for rectangular patch was edge fillet on two sides and for circular, continues weld all around. Fig. 1 shows the dimensions of the used samples. Fig. 2 presents the used set-up for robotic welding operation. The current, voltage and wire speed are measured during the trials welding with ALX unit (data logger). Fig. 3 shows a close view of welding operation. The process parameters were changed as shown in Table. 4. The effect of welding speed was studied for both patch and the effect of welding direction was investigated for rectangular patch in addition too. In Fig. 4 the welded samples are shown.

Table 1. Chemical compositions of the used materials (wt %)

Steel	C	Si	Mn	Nb	Ti
S355	0.065	0.011	1.034	0,023	0.009
S600MC	0.071	0.012	1,609	0.054	0,072
ER70S-6	0.1	0.9	1.5	-	-

Table 2. Mechanical properties of the used materials at room temperature

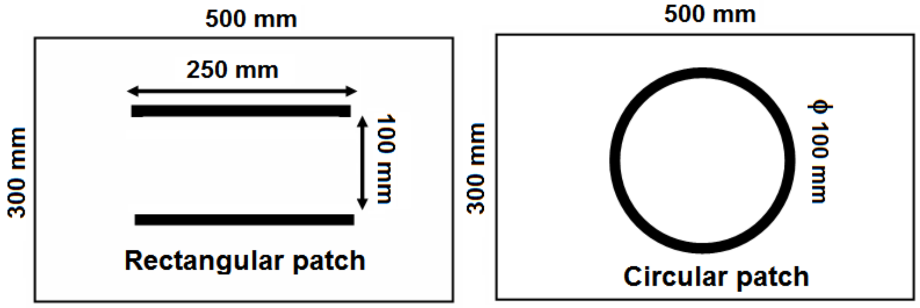
Steel	α (1/K)	E (GPa)	σy (MPa)
S355	10E-6	210	355
S600MC	11.9E-6	212	600
Filler Metal(ER70S-6)	11E-6	200	470

α: Thermal Expansion Coefficient, E: Elastic Modulus, σ_y: Yield strength

Table 3. Thermophysical properties of used materials at room temperature

Steel	ρ (kg/m3)	C(J/kg.K)	K(W/m.K)
S355	7815	430	46
S600MC	7840	461	49.4
Filler Metal (ER70S-6)	7800	447	40

ρ: Density, C: Specific Heat, K: Thermal conductivity



(a) (b)

Fig. 1. The dimensions of the samples and joints (a) rectangular path (b) circular path

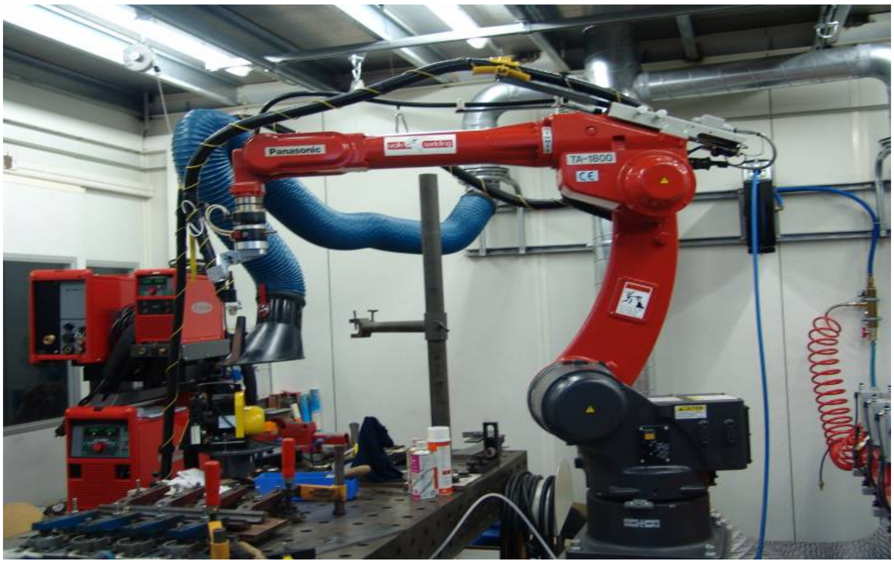


Fig. 2. VALK welding robot used for welding

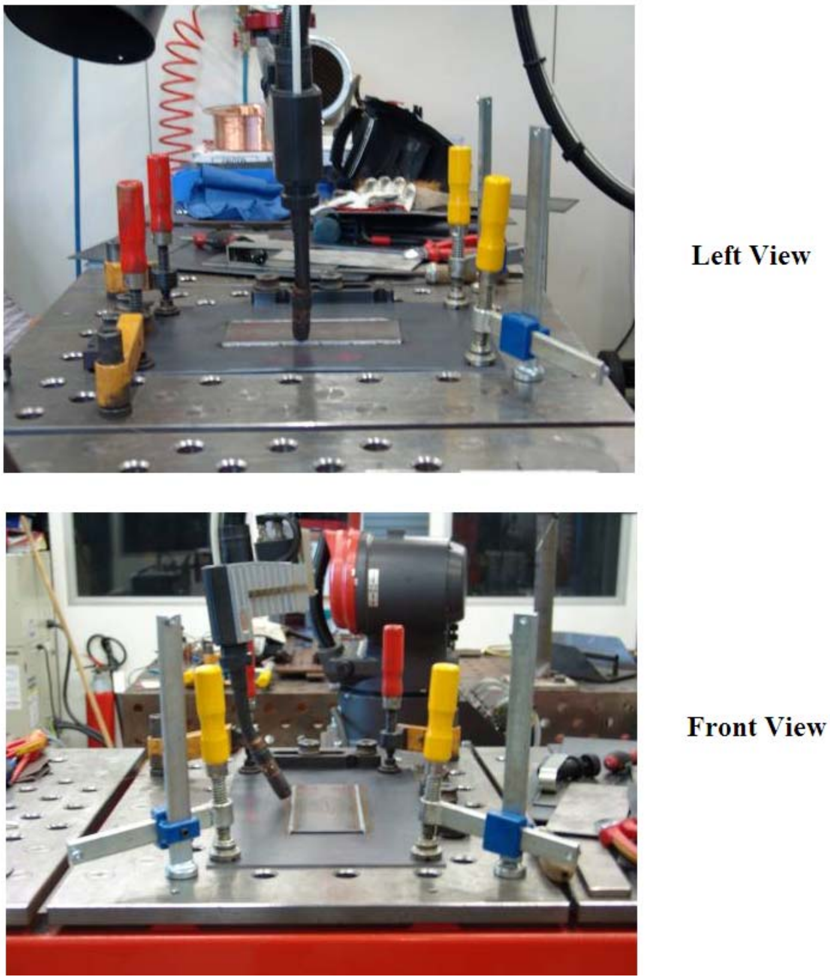
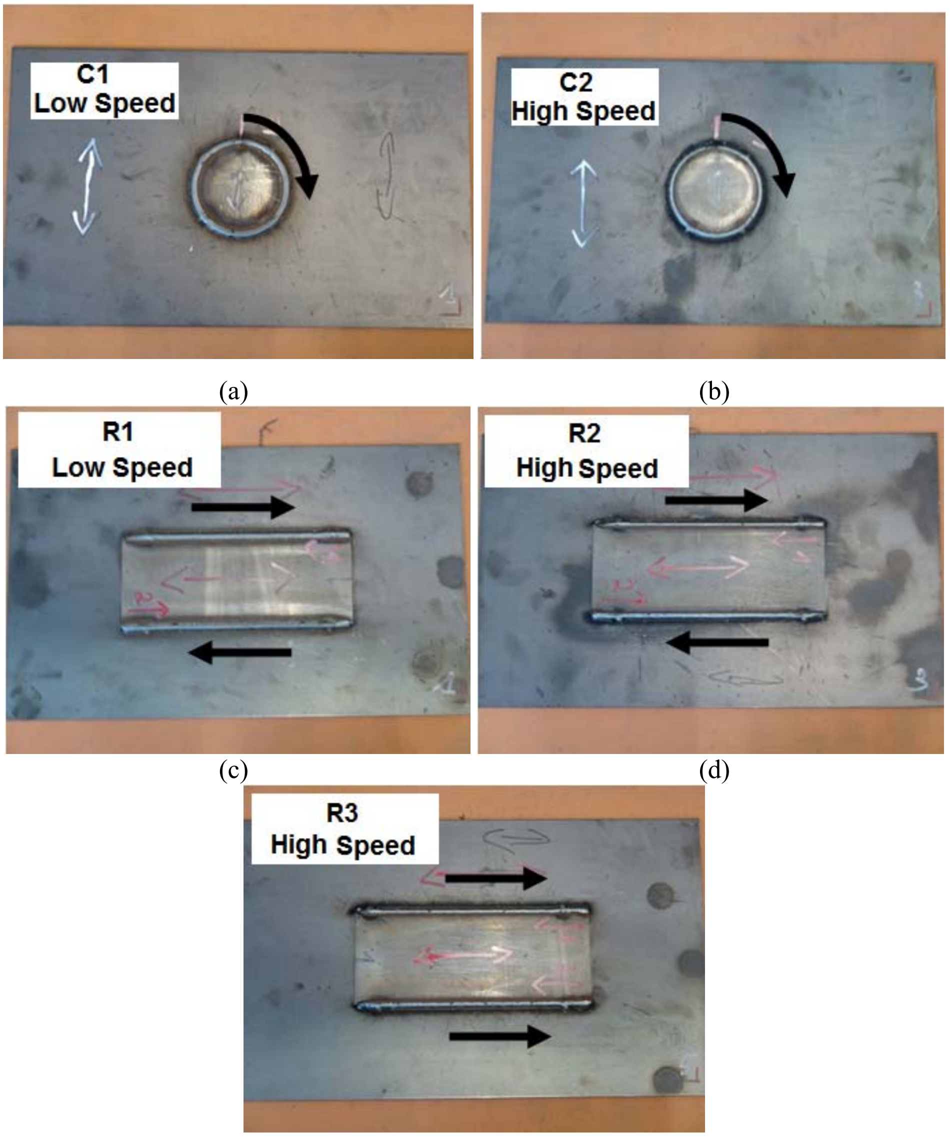


Fig. 3. View of welding operation

Table 4. The applied welding parameters

sample	S(Speed) (mm/min)	I(Current) (A)	V(Voltage) (V)	Heat input* (J/mm)
C1	500	187	20.9	398.8
C2	1000	187	20.9	199.4
R1	500	187	20.9	398.8
R2	1000	187	20.9	199.4
R3	1000	187	20.9	199.4

$^{*}\text{Heat Input} = \eta \frac{VI}{S}$, Welding efficency=0.85



(a) (b)

(c) (d)

(e)

Fig. 4. The welded samples: C1 (low speed), C2 (high speed), R1 (low speed with opposite welding directions), R2 (high speed with opposite welding directions), R3 (high speed with the same welding directions).

Residual stress measurements

The method of residual stress measurements using XRD technique is well established. In this technique, strain in the surface layers of a material is estimated by measuring the shift in the position of the diffraction peak of a set of planes. These strains are then converted into stresses analytically [6]. In the present study, the equipment used for the XRD based residual stress measurements was portable X-ray stress analyzer STRAINFLEX. A multiple ψ method, where ψ is the angle between the specimen normal (z-axis) and the direction of strain measurement was used for the stress measurements. The used ψ angles steel were 10, 15, 25 and 35º and the radiation used for the measurements was Cr Kα. The set of planes considered was {211}, having a peak at the 2θ value of 156.08º. Using the described method, the residual stress profiles of longitudinal (acting parallel to the welding direction) stresses of the dissimilar weld joints were measured. The setup of the x-ray measurement system is depicted in Fig. 5. The center of S600MC was chosen as reference point (zero) of coordination system for measurement (Fig. 6) and the unit of horizontal axis is centimeter. It means that x = 5 cm is equal to the weld line.

Fig. 5. The equipment for the x-ray measurement

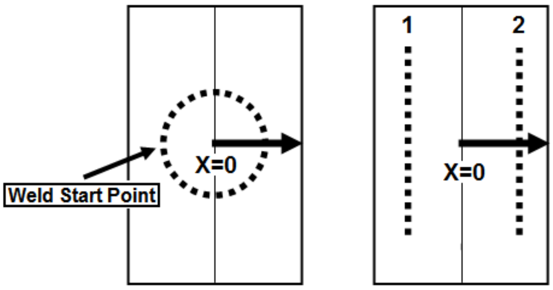
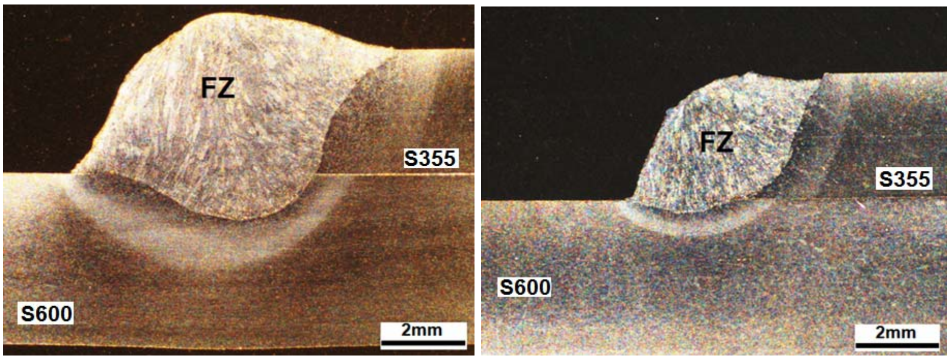


Fig. 6. Coordination system for residual stress measurement

Results and discussion

Circular patch

Welding speed is one of main welding process parameters that can change the heat transfer and final stress state of weldment. Macro sections of dissimilar weld are shown in Fig.7. It can be seen that due to higher thermal conductivity of S600MC, heat transfer in this material is faster than S355 and therefore the weld and HAZ size of S600MC will be smaller than S355. Another important point is the effect of welding speed on cooling rate and welding residual stresses. Distribution of longitudinal (circumferential) residual stresses for circular patch is demonstrated in Fig. 8. It is shown that welding speed has different effects on residual stresses in weld metal and HAZ. Higher welding speed will cause smaller weld pool size and higher cooling rate, consequently magnitude of stresses in weld center will be increased. But in HAZ welding speed has opposite effect. The reason for this phenomenon is that high welding speed results in low heat input per unit length of weld in HAZ. It means that HAZ experiences lower temperatures and therefore relatively smaller stresses will be produced. Of course HAZ of S600MC, due to higher yield strength, has higher stress. Away from the HAZ, the stress profiles of two samples are going to be same.



(a) (b)

Fig. 7. Effect of welding speed on weld pool shape in circular patch (a) Low speed,C1 (b) High speed,C2

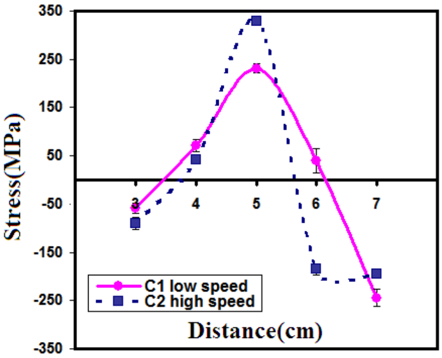
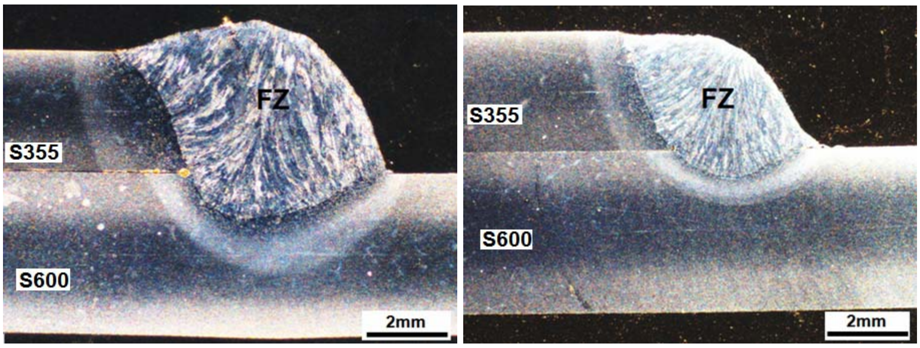


Fig. 8. Distribution of longitudinal residual stresses for circular patch

Rectangular patch

The effect of welding speed

Macro sections of dissimilar weld are shown in Fig. 9. Again due to above mentioned reasons, the weld and HAZ size of S600MC will be smaller than S355. Distribution of longitudinal residual stresses for rectangular patch is shown in Fig.10.The diagram in the HAZ is similar to circular patch but there is completely different behavior in the weld metal. It means that, in addition to welding speed there is another affecting factor on residual stresses. This is difference between acting constraints in this case comparing with the circular patch. Weld 1(left hand) acts such as an external constraint on the weld 2 (right hand). Constraints during welding usually reduce deformations significantly but give higher stresses. Logically this effect should be more pronounced in highly constrained structures (rectangular patch) comparing with circular patch. Increasing the welding speed reduces the reaction time for weld 1, as an external acting force. The result of lack of enough reaction time is reduction in the magnitude of residual stresses.



(a) (b)

Fig. 9. Effect of welding speed on weld pool shape in rectangular patch: (a) Low speed,R1 (b)High speed,R2

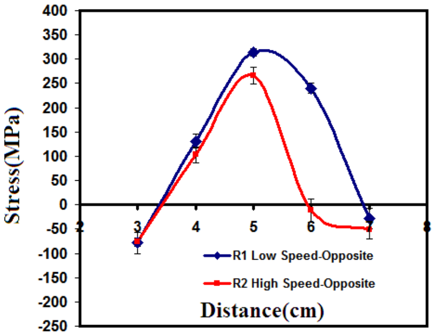


Fig. 10. The effect of welding speed on residual stresses for rectangular patch

The effect of welding direction

Reducing the residual stresses in welded structures during an early stage of design and fabrication is of priority concern. For this reason, the effects of welding sequence on the residual stresses are characterized in the following. This research investigates the effect of parallel and opposite welding on residual stresses. Fig. 11 shows the effect of welding direction on distribution of longitudinal residual stresses in two samples with the different welding directions. When welding the second weld, if the opposite welding method is adopted, the trend of residual stress distribution is opposite to that in the first weld. Thus, the two welds' resultant effect makes a relatively low peak value. This is reason that the converse welding method is better.

In Fig.12 is presented simultaneous effect of welding speed and direction on distribution of residual stresses for rectangular patch. This figure indicates that, in the rectangular patch the minimum magnitude of residual stresses in the weld zone correspond to high speed welding in opposite direction. The sensitivity of residual stresses in HAZ shows direct relationship to yield strength of base metal .In all cases (circular and rectangular) residual stresses in S600MC with higher strength exhibit more sensitivity to welding parameters and variables. Therefore, it could be said that welding parameters alone are not enough to judge about the final stress state in patch welded structures. The shape, size of patch and welding direction are important to anticipate final residual stresses.

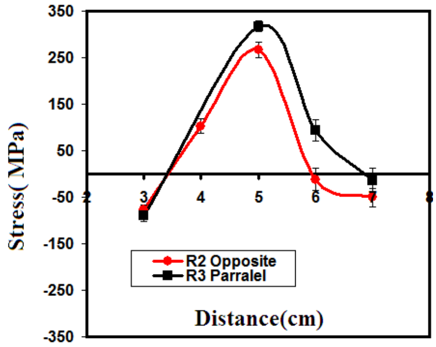


Fig. 11. The effect of welding direction on residual stresses for rectangular patch

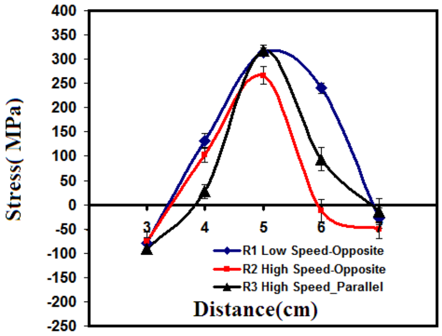


Fig. 12. The effect of welding speed and direction on residual stresses for rectangular patch

Conclusion

In this work a series of dissimilar patch welds based on the S600MC (as the base plate) and S355 (as the patch plate) were generated and the effect of welding speed and direction on residual stresses distribution in two different patch shapes was studied using X-ray diffraction. Analysis of the results revealed that:

1. For the circular patch, higher the welding speed will cause smaller weld pool size and higher cooling, consequently magnitude of stresses in weld center will be increased. But in HAZ welding speed has opposite effect and results in lower residual stresses.
2. Same as circular patch, there is a reveres relationship between welding speed and residual stresses in HAZ of rectangular patch. In the both cases the magnitude of residual stresses depends on yield strength of the base material.
3. The mechanical behavior and residual stresses of weldments could be readily manipulated through size and shape of the welded patch.
4. The optimum case for welding of rectangular patch is using high welding speed and welding in two opposite directions.

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