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Investigation of Exerted Force on Roller and Roller Width Effects on Residual Stresses in Direct and Indirect Rolling of FSW of SU304 Steel

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Abstract

In this paper, the effects of two parameters named width of the roller and exerted force on it in direct and indirect rolling, on residual stresses in Friction Stir Welding (FSW) process of SU304 steel have been studied. FSW numerical modeling has been performed by ABAQUS. In both direct and indirect rolling, five levels have been considered for each variable. Based on the results, it has been shown that both variables have significant effects on the pattern and maximum of residual stresses. In general, in both direct and indirect rolling, by increasing the rolling force, residual stresses decrease intensely. In direct rolling, tensile residual stresses decrement happens locally by using relatively narrow rollers and increasing the rolling force. While in wide rollers, the decrement in tensile residual stresses occurs constantly. Based on the results, using direct rolling causes more decrement in welding tensile residual stresses in comparison with indirect rolling. In direct and indirect rolling, the minimum tensile residual stresses take place when the width of roller is equal to diameter and half of the diameter of welding tool, respectively. In this situation, the maximum of tensile residual stresses decreases 97.4% for direct rolling and 57.3% for indirect rolling.

Nomenclature

Q_{pin}	Generated heat by pin	$Q_{shoulder}$	Generated heat by shoulder
w	Rotational speed	R_{pin}	Pin radius
H_{pin}	Pin height	μ	Friction
F_z	Downforce	σ_{yield}	Yield stress

1. Introduction

Friction Stir Welding (FSW) is a solid state joining method invented in 1991 at TWI institute [1]. Workpieces join together through pressure, high temperature and large plastic deformation. Although, in early years of its invention, this technique was only used for Aluminum alloys, nowadays it is also used to join Steel, Magnesium alloys, Titanium alloys and polymers. FSW has some advantages in comparison with other welding techniques like better mechanical properties and efficiency, lower residual stress, energy consumption and welding defects. Due to multiplicity of effective parameters on residual stresses in FSW

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process, one cannot use proper analytical methods to study the FSW process. In addition, experimental methods are expensive and time consuming. Numerical methods like Finite Elements Method (FEM) are appropriate alternative solutions to understand the effect of parameters on FSW Process.

Although residual stresses in FSW are lower than other welding techniques, they can affect the joint quality [2]. Tensile residual stresses usually have destructive effect on static and fatigue strength of workpieces. They also cause significant reduction in quality and mechanical properties of welded workpieces. In all welding processes, mechanical, thermal and metallurgical parameters are involved in the formation of residual stresses [3]. The magnitudes of residual stresses in FSW process depend on tool geometry, process parameters and mechanical and thermal treatments [4]. By proper weld design and use of thermal treatment, shot peening and vibrational stress relieving, one can highly reduce the residual stresses [5]. Many studies have been conducted on the effect of parameters on the residual stresses in FSW process. Richter-Trummer et al. [6] studied the effect of vertical and horizontal clamping forces on residual stress and distortion of workpiece in FSW of AA2189 Aluminum alloy. Six vertical and horizontal clamping forces were considered. The results showed that great clamping forces cause increment in residual stresses magnitudes and decrement in distortion and vice versa. Steuwer et al. [7] investigated the effect of process parameters on residual stress in FSW of AA5083 and AA6082 dissimilar alloys. They found that residual stresses in tool crossing route and surrounding are tensile and compressive, respectively. Based on the results, tool rotational speed in comparison with travel speed, has more significant effect on the magnitude of residual stresses. Brewer et al. [8] studied the travel speed and rotational speed of FSW in MA956 steel and found that in constant value of rotational speed, increasing the travel speed causes increment in residual stresses magnitude. Papahn et al. [9] investigated the underwater FSW of AA7075 and found that water cooling in comparison with air cooling causes more decrement in residual stresses, specially transverse ones. Farajkhah and Liu [10] studied the clamping area and travel speed effects on residual stresses in FSW of AA6061. Based on the results, by increasing the clamping area, the residual stresses decrease. Also clamping area has interaction with tensile stresses magnitude. Altenkirech et al. [11] investigated the effect of real-time rolling and post-rolling on the residual stresses of FSW. They used indirect real-time rolling and direct and indirect post-rolling. Based on the results, post-rolling has greater effect than real-time rolling on residual stresses. Wen et al. [12] studied the effect of three different types of rolling on FSW of AA2024 Aluminum alloy and found that rolling after cooling step until ambient temperature has the greatest effect on decrement of residual stresses.

Post-rolling is a novel method for decreasing the residual stresses and is used to enhance the mechanical and corrosion properties of welded joint. The important parameters in rolling are the method of rolling, number of rollers, width of rollers, exerted force on rollers, pattern of rollers and the distance of rollers from the weld-line, which have been addressed in a few studies. In this paper, FEM has been used to evaluate the effect of rolling method and the exerted force on rollers and roll width on the magnitude and distribution of residual stresses in FSW of 304L steel.

2. Numerical Simulation

To study the effect of rolling parameters on residual stresses numerically, ABAQUS was used [13]. The process parameters, tool geometry and material were selected following Zhu and Chao's study [14] and numerical simulation was performed. Indirect analysis was used to simulate the FSW. In this method, the tool is not modeled and two equal volumetric and surface heat fluxes are exerted on workpieces and the results of heat solution is considered as input for mechanical analysis. In this paper, three different steps named welding, cooling and rolling steps in both heat solution and mechanical solution were used. The workpieces material was selected as 304L stainless steel alloy following Zhu and Chao's work [14]. Dimensions of workpieces were 200mm in width, 101.8mm in height and 3.18mm in thickness. The tool had a 19.05mm diameter shoulder and a pin with 6.35mm diameter and 3mm length. Due to experimental work, rotational speed, travel speed, downward force and friction coefficient were set at 500rpm, 101.6mm/min, 31138N and 0.3, respectively. Due to indirect analysis, only the workpieces were modeled and two moving fluxes were applied to workpieces to simulate the FSW thermal conditions. Moving fluxes were composed of two volumetric and surface ones used for pin and shoulder generated heats, respectively. To apply the fluxes, DFLUX subroutine was used and the fluxes were coded Schmidt equations [15]:

$$Q_{pin} = 2\pi w R_{pin} H_{pin} \frac{\sigma_{yield}}{\sqrt{3}} + \frac{2}{3} w \mu F_z \tag{1}$$

$$Q_{shoulder} = \frac{2}{3}\pi w \frac{\sigma_{yield}}{\sqrt{3}} (R^3_{shoulder} - R^3_{pin}) \tag{2}$$

In these equations, Q_{pin} and $Q_{shoulder}$ are the generated heat by pin and shoulder, respectively. The w, R_{pin}, H_{pin}, μ, F_z and σ_{yield} are rotational speed, pin radius, pin height, friction stir between tool and workpieces, downforce and yield stress of workpieces, respectively. Based on these equations, two volumetric and surface fluxes were coded by DFLUX subroutine and applied to whole and upper face of workpieces, respectively. It should be mentioned that entering and exiting phases of tool were ignored and only joining phase was considered. Thermal and mechanical properties of 304L stainless steel alloy have been illustrated in Table 1.

To apply the thermal boundary conditions, various convection heat transfer coefficients (h) were used for different parts of workpiece [16, 17]. For lower face, h was set at 200Wm^{-2} °C to compensate the lack of anvil simulation. In addition, for upper face, h was set at 15Wm^{-2} °C to simulate the convection heat transfer with ambient. Mechanical boundary conditions were selected as experimental work. DCC3D8 and C3DR elements were used for thermal and mechanical simulations, respectively. After mesh sensitivy analysis, the density of elements near weld line increased to improve the solution. The meshed model has been shown in Fig. 1.

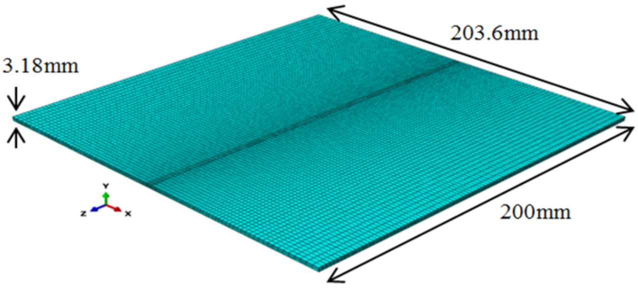


Fig. 1. Meshed model.

3. Design of Experiments (DOE)

In this paper, three rolling variables named type of rolling (direct or tensile), exerted force on roller. Roller width were considered as effective parameters and their effect on magnitude and pattern of residual stresses were studied. In all considered cases, roller diameter and travel speed were set at 30mm and 101.6mm/min, respectively. In direct rolling cases, roller crosses the weld line precisely, and in indirect rolling cases, two rollers cross paths parallel with a constant distance from the weld line. Fig. 2 illustrates the schematic pictures of direct and indirect rolling. The considered parameters and their levels are presented in Table 2. Based on full factorial design, experiments were designed and used for simulations shown in Table 3.

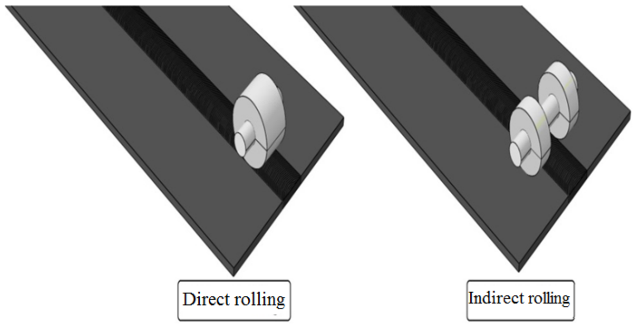


Fig. 2. Schematic of direct and indirect rolling.

4. Results and Discussion

4.1. Validation of Model

Due to numerical solution procedure, one must validate the model. Thus, numerical temperature history and residual stresses diagrams in a surface point located at 14mm from weld line in workpiece were drawn and compared with experimental ones which are shown in Fig. 3.

Table 1
Thermal and mechanical properties of SUS304 [15].

T (°C)	E (Gpa)	Yield stress (MPa)	C_p (Wm^{-2}K^{-1})	ρ (kgm^{-3})	α (10^{-6} °C^{-1})	k (Wm^{-1} °C^{-1})
25	193	290	484	7926	17	14.04
100	190	270	522	7829	17.1	16.08
200	183	234	542	7765	18	17.12
300	172	210	552	7702	18.6	18.82
400	162	197	563	7638	19.1	20.86
500	155	183	586	7575	19.6	21.57
600	147	166	590	7511	20.2	23.94
700	133	109	592	7481	20.7	25.98
800	128	45	597	7418	21.1	28.36
900	128	32	598	7387	21.6	28.39
1000	128	29	599	7391	21.8	28.09

Table 2
Considered variables and their levels.

Variables	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Rolling force	KN	2.5	5	7.5	10	12.5
Roller width	mm	10	15	20	25	30
Rolling scheme	-	Direct	Indirect	-	-	-

Table 3
Table of design of experiment (DOE).

Run order	Rolling technique	Rolling force (KN)	Roller width (mm)
1	Direct	2.5	10
2	Direct	2.5	15
3	Direct	2.5	20
4	Direct	2.5	25
5	Direct	2.5	30
6	Direct	5	10
7	Direct	5	15
8	Direct	5	20
9	Direct	5	25
10	Direct	5	30
11	Direct	7.5	10
12	Direct	7.5	15
13	Direct	7.5	20
14	Direct	7.5	25
15	Direct	7.5	30
16	Direct	10	10
17	Direct	10	15
18	Direct	10	20
19	Direct	10	25
20	Direct	10	30
21	Direct	12.5	10
22	Direct	12.5	15
23	Direct	12.5	20
24	Direct	12.5	25
25	Direct	12.5	30
26	Indirect	2.5	10
27	Indirect	2.5	15
28	Indirect	2.5	20
29	Indirect	2.5	25
30	Indirect	2.5	30
31	Indirect	5	10
32	Indirect	5	15
33	Indirect	5	20
34	Indirect	5	25
35	Indirect	5	30
36	Indirect	7.5	10
37	Indirect	7.5	15
38	Indirect	7.5	20
39	Indirect	7.5	25
40	Indirect	7.5	30
41	Indirect	10	10
42	Indirect	10	15
43	Indirect	10	20
44	Indirect	10	25
45	Indirect	10	30
46	Indirect	12.5	10
47	Indirect	12.5	15
48	Indirect	12.5	20
49	Indirect	12.5	25
50	Indirect	12.5	30

Based on Fig. 3, the FSW simulation method is accurate enough and can predict the temperature history and residual stress pattern. Therefore, this method was used to simulate the rolling numerically and study the effect of parameters on residual stresses.

4.2. Direct Rolling

Based on the process described in previous sections, two parameters named the width of roller and the rolling force were considered as input variables in both direct and indirect rolling positions and residual stresses were considered as output of the process. Residual stresses were drawn across mid-plane of workpiece in all situations. Longitudinal residual stresses diagrams in various width of roller and rolling force are shown in Fig. 4 and the maximum value of them are listed in Table 4.

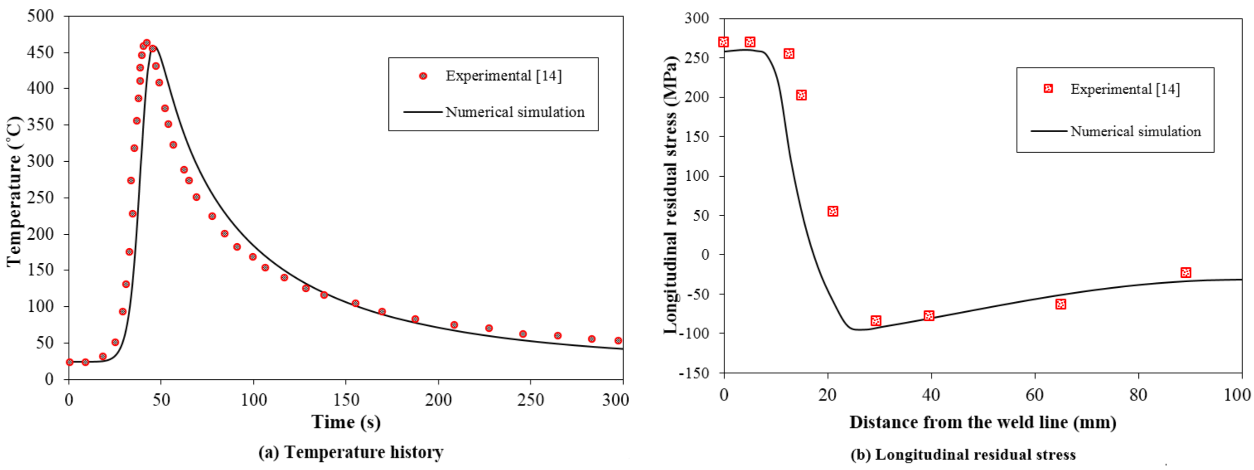


Fig. 3. Numerical and experimental temperature history and longitudinal residual stress diagrams.

Table 4
Comparison of maximum longitudinal stress magnitude for before and after direct rolling.

Input parameters		Maximum longitudinal residual stress (MPa)		Reduction rate (%)
Rolling force (KN)	Roller width (mm)	Before rolling	After rolling	
2.5	10	246	196	20.3
2.5	15	246	183	25.6
2.5	20	246	159	35.3
2.5	25	246	170	30.8
2.5	30	246	180	26.8
5	10	246	132	46.3
5	15	246	129	47.5
5	20	246	102	58.5
5	25	246	132	46.3
5	30	246	142	42.2
7.5	10	246	82	66.6
7.5	15	246	83	66.2
7.5	20	246	73	70.3
7.5	25	246	106	56.9
7.5	30	246	116	52.8
10	10	246	81	67.1
10	15	246	54	78.1
10	20	246	34	86.1
10	25	246	86	65.1
10	30	246	92	62.1
12.5	10	246	67	72.7
12.5	15	246	36	85.3
12.5	20	246	13	94.7
12.5	25	246	55	77.6
12.5	30	246	77	68.7

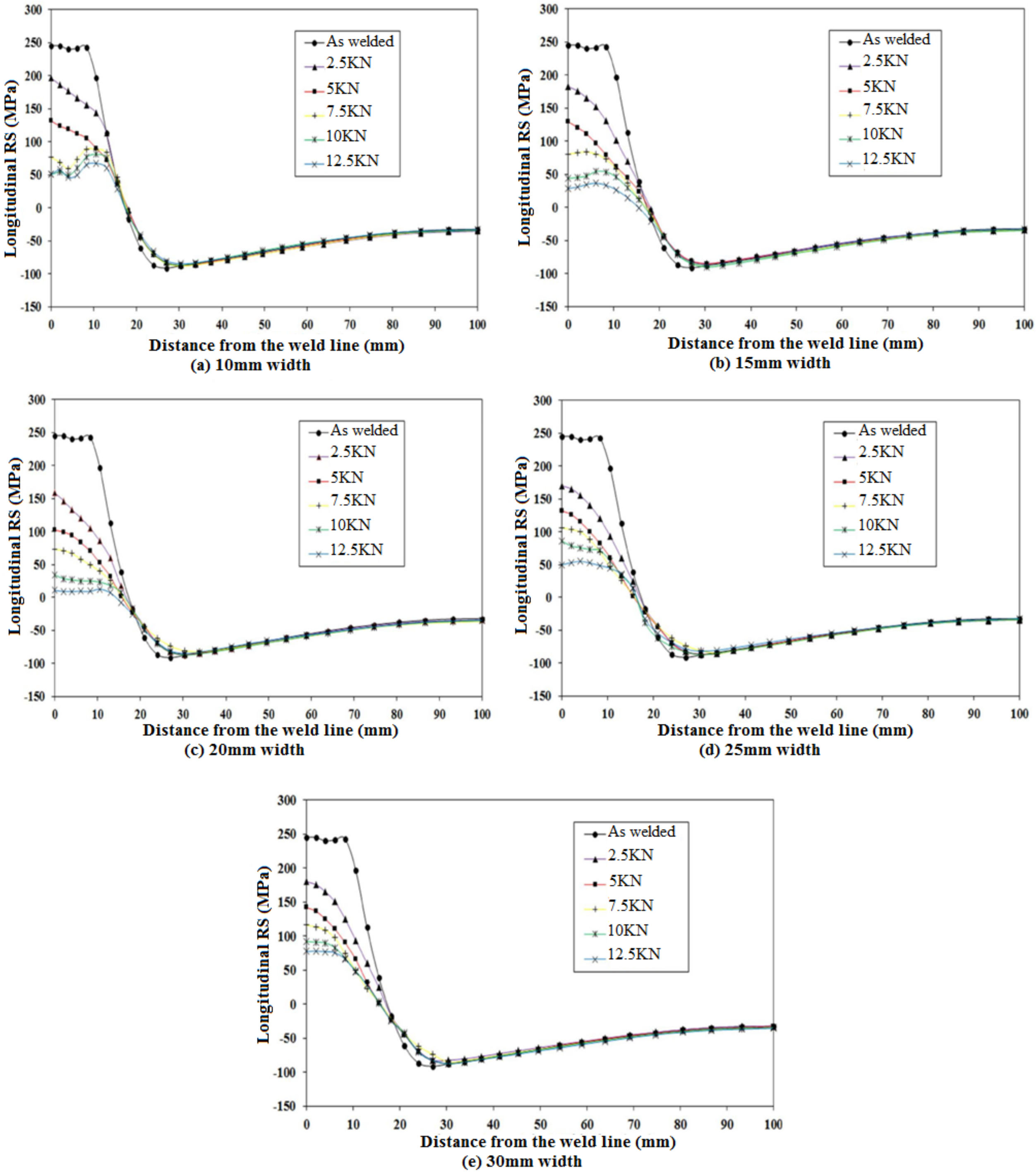


Fig. 4. longitudinal residual stress in direct rolling for various roller widths a) 10mm, b) 15mm, c) 20mm, d) 25mm, e) 30mm.

As shown in Fig. 4 and Table 4, using rolling results in changing the pattern and maximum magnitude of longitudinal residual stresses. Increasing the rolling force and the width of roller results in increment and decrement in the stress exerted on workpiece from the roller. Based on Fig. 5, in constant roller width, residual stresses decrease intensively by increasing the rolling force. This is due to the significant increment in compressive exerted stress of the roller. In all situations, rolling compressive stress reduces maximum of tensile residual stresses and changes their pattern. It was also observed that the pattern and the amount of longitudinal tensile residual stress are dependent on the width of roller. In cases with lower roller width (5mm and 10mm), compressive stress increases intensely by increasing the rolling force which is because of the relatively small area. This increment causes local decrement in longitudinal tensile residual stresses along the roller moving path while further points do not experience such decrement.

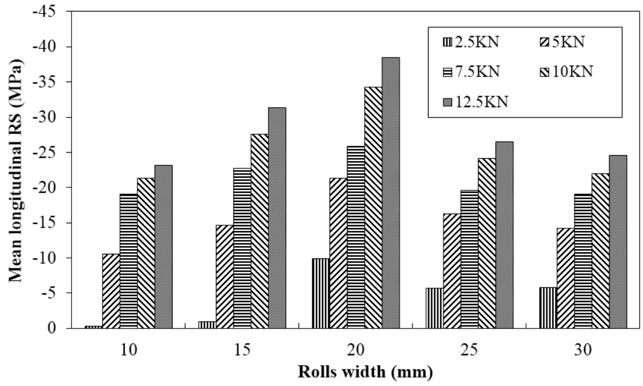


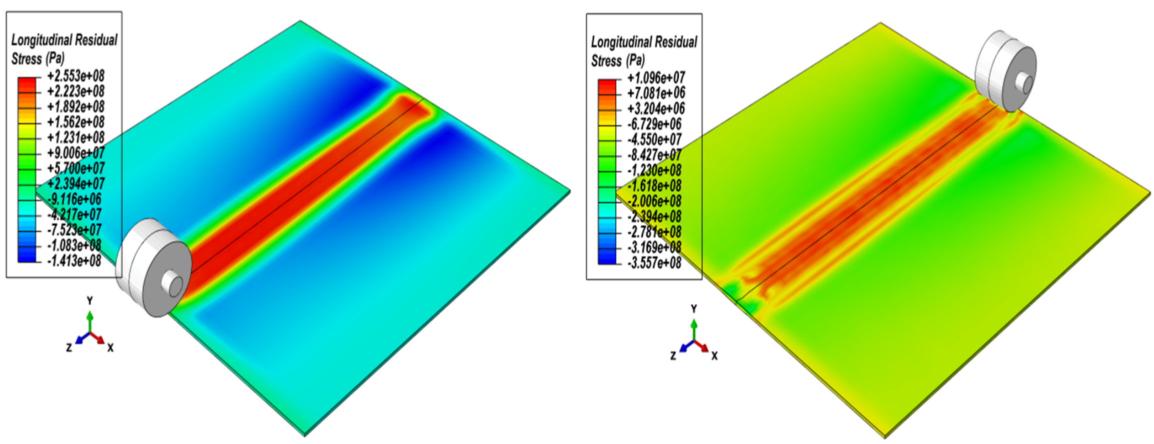
Fig. 5. Average longitudinal residual stress of weld section after direct rolling.

In higher roller widths, the compressive stress arising from rolling is applied more balanced to upper face of workpiece which causes more balance in residual stresses decrement across the weld section. It should be mentioned that optimum roller width selection leads to maximum decrement in longitudinal tensile residual stresses across the weld section and by inappropriate selection of roller width, performance of roller decreases extremely. Generally the (micro) cracks occur in the areas with maximum tensile residual stresses [1]. With optimum rolling situation, one can decrease these stress. Based on Table 4, in all rolling force cases, the greatest decrement occurs while using 20mm in width roller. In addition, it was observed that by selecting 20mm width and 12.5KN rolling force, optimum situation takes place among all direct rolling cases and the longitudinal tensile residual stress decreases to 97.4%.The average residual stress in the weld section is one of the effective parameters in residual stresses of welding. Fig. 5 shows all direct rolling situations. It should be mentioned that in the case of non-use of roller, the average residual stress in the weld section is +16.8MPa.

As illustrated in Fig. 6, in all direct rolling situations, the average longitudinal residual stress changes from +16.8MPa to compressive values by changing the width of roller and rolling force. In addition, the optimum width of roller is equal to the diameter of the welding tool. In FSW process, the major part of tensile residual stress occurs in the tool-crossing path because of existence of plastic flow and high thermal stresses. Therefore, using a roller whose width is equal to FSW tool diameter results in applying rolling stress in the mentioned area and rolling becomes more effective in reducing residual stresses. In narrower or wider roller widths, the rate of tensile residual stress decrement declines which is due to the lack of overlap between the rolling area and the area in which the maximum of tensile residual stress occurs. Fig. 6 shows the longitudinal residual stress contour for before and after the direct rolling with 20mm in width of roller and 12.5KN rolling force.

4.3. Indirect Rolling

In indirect rolling, similar to the direct rolling, the width of the roller and rolling force was considered as parameters affecting the longitudinal residual stresses. Their relative diagrams across the weld section were drawn. In general, in indirect rolling, the rollers crossing path and weld-line experience the compression and tension, respectively. After rollers cross, the area surrounding the rolled area compresses the weld-line because of the stress released which leads to compressive residual stress in the weld-line. Due to the exerted compressive rolling stress, welding tensile residual stresses are partially balanced at the weld cross section and decrease. Longitudinal residual stresses diagrams in various width of roller and rolling force are shown in Fig. 7 and the maximum value of them are listed in Table 5.



(a) Before direct rolling (b) After direct rolling

Fig. 6. Longitudinal residual stress contour for before and after direct rolling with 20mm width roller and 12.5KN rolling force.

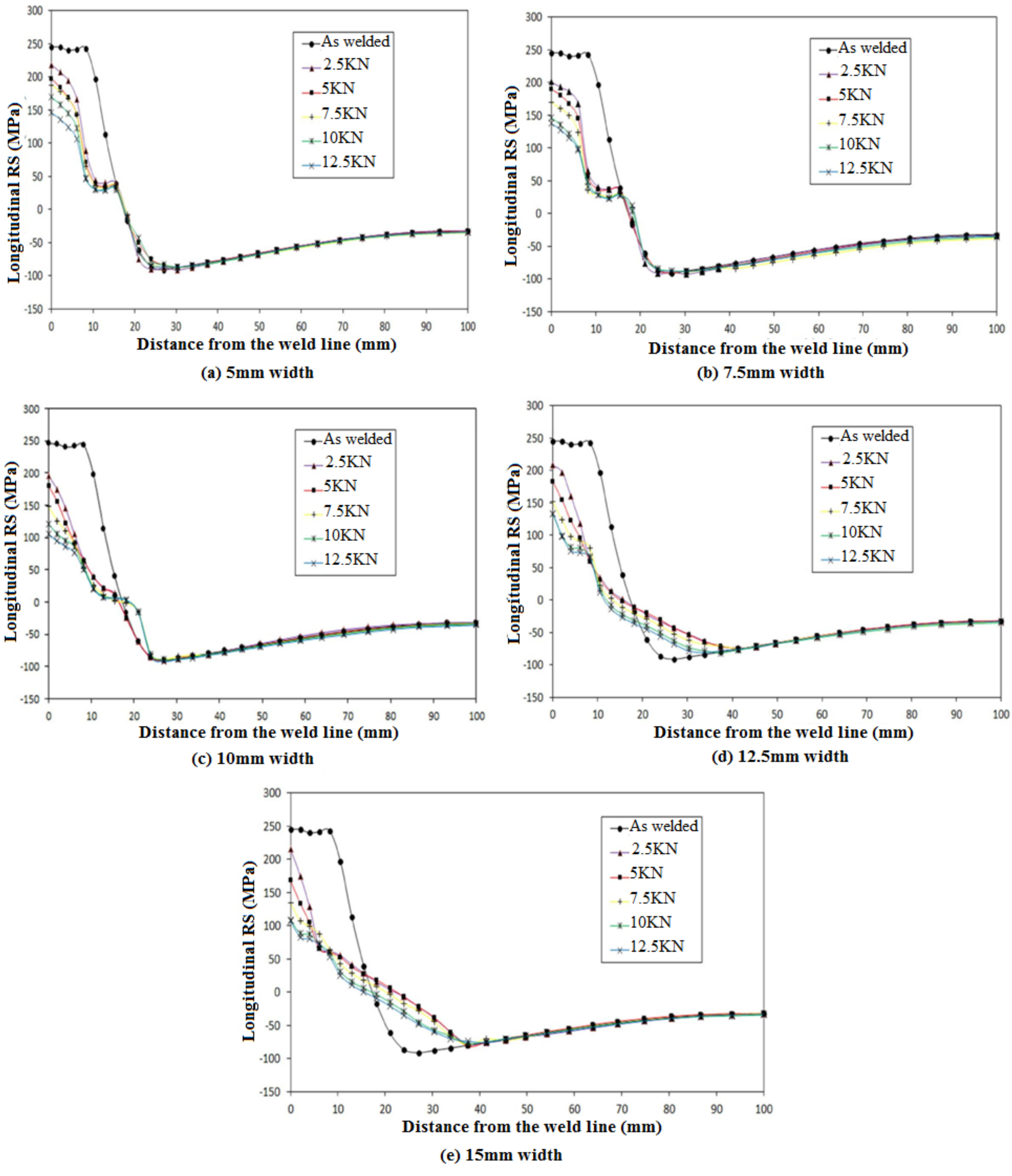


Fig. 7. Longitudinal residual stress contour for before and after direct rolling with 20mm width roller and 12.5KN rolling force.

Similar to direct rolling, in indirect rolling, the residual stresses pattern change by changing the rolling force and width of rollers. Based on Fig. 8, in roller widths of 5mm and 7.5mm, tensile longitudinal residual stresses decrease locally by increasing the rolling force. This is because of the low width of rollers as well as applying compressive rolling stresses to a rather small area. Although rollers width increment results in decrement in applying compressive stress to workpiece, it leads to stress being distributed uniformly in the weld section. Based on the obtained results shown in Table 5, it was observed that, unlike direct rolling, in various rollers width and rolling forces, the maximum of tensile residual stresses in weld-line path decreases. Based on Table 5, it is clear that the optimum situation (decreasing the maximum of tensile residual stress) occurs at 10mm in width of roller and 12.5KN rolling force and the maximum of tensile residual stress decreases to 57.3%. Average longitudinal residual stress in weld section for all indirect rolling situations is shown in Fig. 8.

Table 5
Comparison of maximum longitudinal stress magnitude for before and after indirect rolling.

Input parameters		Maximum longitudinal residual stress (MPa)		Reduction rate (%)
Rolling force (KN)	Roller width (mm)	Before rolling	After rolling	
2.5	5	246	218	11.3
2.5	7.5	246	201	18.3
2.5	10	246	196	20.3
2.5	12.5	246	208	14.4
2.5	15	246	215	12.6
5	5	246	197	19.9
5	7.5	246	190	22.7
5	10	246	181	26.4
5	12.5	246	183	25.6
5	15	246	168	31.7
7.5	5	246	188	23.5
7.5	7.5	246	170	30.9
7.5	10	246	148	39.8
7.5	12.5	246	152	29.2
7.5	15	246	135	45.1
10	5	246	169	31.3
10	7.5	246	147	40.2
10	10	246	121	50.8
10	12.5	246	134	45.5
10	15	246	107	56.5
12.5	5	246	146	40.6
12.5	7.5	246	138	43.9
12.5	10	246	105	57.3
12.5	12.5	246	134	45.5
12.5	15	246	107	56.5

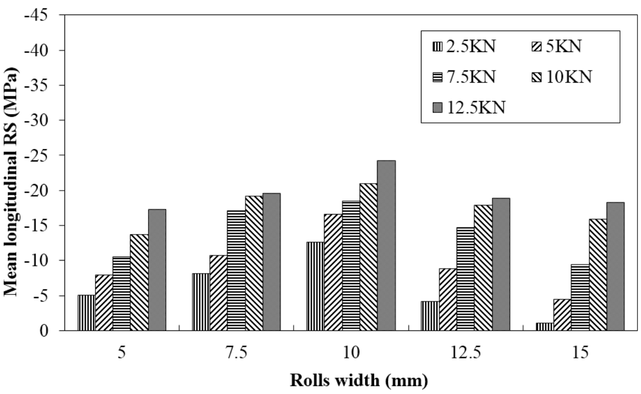


Fig. 8. Average longitudinal residual stress of weld section after indirect rolling.

Similar to direct rolling and based on Fig. 8, using indirect rolling leads to average residual stress change from tensile to compressive which shows that it is an effective method to balance the welding residual stresses. As shown in Fig. 8, the maximum decrement in average longitudinal residual stress takes place at 10mm in width of rollers. Longitudinal residual stress contour for indirect rolling with 10mm in width of rollers and 12.5KN rolling force is illustrated in Fig. 9.

By comparing Fig. 5 and Fig. 8, it is clear that direct rolling is more effective in decreasing the FS welded longitudinal residual stress as, in direct rolling, the roller passes along the maximum tensile residual stress area and the maximum decrement takes place. A comparison between average longitudinal residual stresses for both direct and indirect rolling processes has been done and shown in Fig. 10. It should be noted that, in Fig. 10, the sum of the two rollers width in indirect rolling is equal to the width of roller in direct rolling.

5. Conclusions

In current research, the impact of using direct and indirect rolling in FSW process, on residual stress distribution was studied numerically. In both rolling cases, the width of roller and rolling forces were considered in five levels and their effect on welding longitudinal residual stresses was studied. The following results were obtained:

- In both rolling cases, by increasing the rolling force in constant width of roller (s), tensile residual stresses decrement rate decreased.
- In both rolling cases, by increasing the width of the roller (s) in constant rolling force, tensile residual stresses decrement rate increased because of the decrement in the applied roller compression stress.

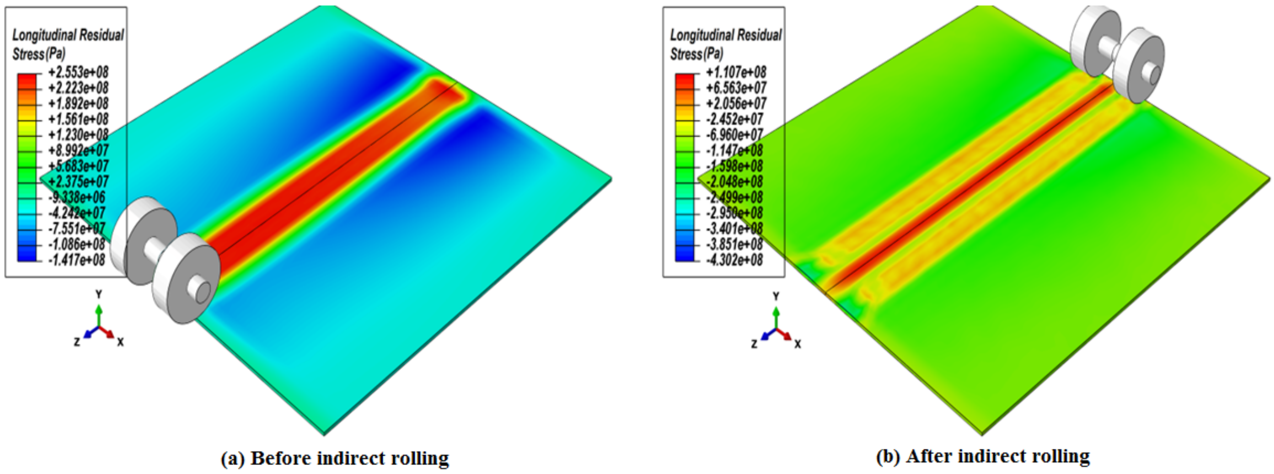


Fig. 9. Longitudinal residual stress contour for before and after direct rolling with 10mm width roller.

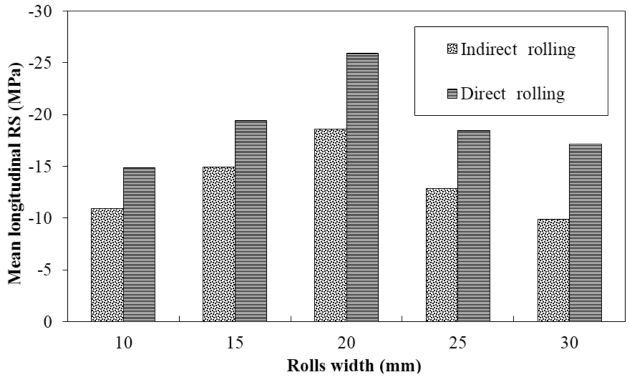


Fig. 10. Comparison of average longitudinal residual stress of weld section in direct and indirect rolling.

- In both rolling cases, in small widths of roller (s), by increasing the rolling force, tensile residual stresses decrement occurred locally and discontinuously. On the other hand, in larger widths of roller (s), because of the larger area covered, tensile residual stresses decreased more uniformly in the weld section.

- Based on the results, it was observed that the optimum value of roller width in direct rolling is equal to tool diameter (20mm). In this situation, the maximum of tensile residual stress decreased to 97.4% which was due to complete covering (overlapping) of the weld area with the width of the roller.

- The optimum width of the roller for indirect rolling was 10mm for each of rollers and the maximum of residual stress decreased to 57.3 %.

- Based on the obtained results, direct rolling is more effective in residual stresses decrement than indirect rolling given that it covers maximum tension stresses area.

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