Parametric study of the nugget growth in spot welding of 304L stainless steel sheets having equal and unequal thicknesses

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Abstract

In this paper, an experimental and analytical study of the weld nugget development in resistance spot welding process of 304L stainless steel sheets having equal and unequal thickness is presented. Experimentally, the metallographic technique has been used to determine the size and location of different weld nuggets realized under a given welding parameters which varies from no nugget formation to expulsion. Two stainless steel sheet thicknesses (1 mm and 1.5 mm) were investigated. The effects of welding current intensity and time on nugget growth are studied. Moreover, the influence of the electrode applied load in weld nugget displacement has been also investigated. Analytically, a two dimensional thermal model was developed with ability to predict the electrical contact resistance and nugget size during spot welding of equal sheet thicknesses. The maximum nugget thicknesses are reached when the electrical contact resistance becomes maximal, contrary to nugget diameter which is less influenced by the electrical contact resistance. For a given sheet thickness ratio (1/1.5), the nugget displacement induced during spot welding of unequal sheet thicknesses remains not influenced by the variation of the welding parameters.

Keywords Resistance spot welding · Weld nugget · Metallographic technique · 304L stainless steel · Thermal analysis

List of symbols

A	Surface (m^2)
C	Specific heat of the metal sheet ($J/kg\ K$)
e	Sheet thickness (m)
ΔH	Latent heat of fusion (J/kg)
I	Weld current intensity (A)
J_0	Bessel function
k	Thermal conductivity ($W/m\ ^\circ C$)
Q	Generated heat flux at the faying surface (J/m^2)
Q_0	Heat quantity generated by joule effect (J)
q	Heat quantity generated in the infinite metal sheet (J)
R_c	Electric contact resistance (Ω)
T	Temperature ($^\circ C$)
t	Time (s)
V_n	Nugget volume (m^3)
x, y, z	Spatial coordinates (m)

Greek symbols

α	Thermal diffusivity (m^2/s)
λ	Integration parameter
ρ	Density (kg/m^3)
δ	Electrical resistivity ($\mu\Omega\ m$)
θ	Angle (rad)

1 Introduction

The size and location of the weld nugget realised in resistance spot welding process of similar and dissimilar thickness stainless steel sheets is one of weldment quality parameters. Due to their easy weldability and corrosion proprieties [1], the 304L stainless steel is largely used in various industrial applications [2]. The nugget development in RSW process has been investigated through several experimental, analytical and numerical studies. During

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Table 1 Chemical composition of the employed 304L stainless steel

Element	C	Cr	Ni	Mn	Si	S	P	Cu	Fe
wt%	0.014	18.3	10.4	1.62	0.34	0.005	0.015	0.03	69.91

spot welding of two metal sheets, the faying surface asperities increase the weld current density [3] and induced a fast rise in interface temperature [4], causing a molten nugget [5]. The thermal analysis shows that the peak temperature [6] is reached at the sheets contact surface center. By using the metallographic technique, the nugget size is measured and weld parameters effects [7–10] on its growth were treated. Result show that the nugget growth is most influenced by the welding current compared to the other welding parameters. Numerical thermal models using finite element method [6, 11–15] and finite difference method [7, 16–18] have been developed in order to predict the nugget size and investigate the various effects of welding parameters. The expulsion phenomenon of liquid metal from the weld nugget which is difficult to eliminate [19] has been experimentally studied by using the scanning acoustic microscopy [20]. It was useful for weld quality improvement in spot welding process. During the spot welding of unequal sheet thicknesses it was found that, the weld nugget displaces into the thickest metal sheet [21, 22]. This axisymmetric displacement is largely affected by the thickness ratio of the two welded sheets than other welding parameters. Resistance spot welding of dissimilar materials such as AISI 316L–DIN EN 10130-99 steels [23], DP600 and DC54D steels [24], DP600 and AISI 304 steels [25] were investigated. Results show that the size and nugget quality in welding of dissimilar metals are significantly different from welding of similar metals for equal or unequal thicknesses. In this study, the phenomenon of nugget growth in spot welding of equal and unequal sheet thicknesses is presented. The metallographic technique has been used in order to determine the nugget sizes of different welded samples. The effects of welding time, welding current and electrode applied load on the nugget development were investigated. A coupled thermal-electrical model was analytically developed to predict the nugget thickness. The predict results were compared with those obtained in experiments.

2 Materials and methods

2.1 Welding steel description

The 304L stainless steel sheets used was selected as the base metal in this experimental study for its high corrosion resistance and reasonable weldability as well as its good ductility and toughness in a broad interval of exploitation

Table 2 Thermo-physical Properties of the used 304L stainless steel

Temperature (°C)	Density (kg/m ³)	Thermal conductivity (W/m °C)	Specific heat (J/kg °C)	Electrical resistivity (μΩ m)
20	7900	14.6	462	0.664
200	7830	16.1	512	0.774
600	7660	20.8	577	1.001
1200	7370	32.2	676	1.210
1480	7370	120	700	–

Fig. 1 The spot welding machine used in experiments

temperature (–30 °C to 1000 °C) [26]. These metallurgical properties make possible to use it in numerous industrial applications [10]. The investigated steel sheets used in this study have respectively a thickness of 1 mm and 1.5 mm. In Tables 1 and 2 are illustrated the chemical composition and thermo-physical properties of the used stainless steel.

2.2 Experimental process

The spot welding operations were realised using a resistance spot welding machine presented in Fig. 1 operating at 50 Hz and an effective weld current varying from 0 to 15 kA. The two conical copper electrodes as indicated in Fig. 1 having a same contact surface with a diameter of 6 mm were manufactured and used in all realised spot welds under different electrode forces. In Table 3 are illustrated the physical proprieties of the electrodes material.

Table 3 Physical proprieties of the copper electrodes at 300 K

Thermal conductivity (W/m °C)	355.1
Specific heat (J/kg °C)	431
Density (kg/m ³)	8930
Electrical resistivity (μΩ m)	50.5
Thermal expansion coefficient (°C ⁻¹ × 10 ⁻⁵)	1.72

Table 4 Welding parameters used in different formed weld nuggets (sheet 1 mm/sheet 1 mm)

Current intensity (A)	Electrodes applied load (2.5 kN ≈ 22 MPa)		
	Welding time (cycle)		
	5	10	15
	Series 1	Series 2	Series 3
4000	S11	S21	S31
5000	S12	S22	S32
6000	S13	S23	S33
7000	S14	S24	S34
8000	S15	S25	S35
9000	S16	S26	S36

2.2.1 Welding of equal sheet thicknesses

In order to investigate the weld current effect and weld time on the size of the formed nugget during spot welding of two sheets having a same thickness of 1 mm, three series of spot welding were carried out under a constant electrodes applied load of 2.5 kN. As indicated in Table 4, each series of test is carried out under the same weld time with variation in the intensity of the weld current. It should be noted that the upper and lower limits of the weld time and current are deduced from the weldability diagram of the 304L stainless steel according to the American Welding Society [9]. Once the weld spots are realised, the various samples were sectioned diametrically and prepared for standard metallographic observation in order to obtain a better visualization which allows the size apparition of the formed weld nugget as shown

Fig. 2 Micrographs of cross sectioned welded samples (sheet 1 mm/sheet 1 mm) **Fig. 3** Mechanism of weld nugget visualisation and measurement

in Fig. 2. The recommended chemical etchant for metallographic examination of stainless steel is composed of 100 ml HNO₃, 200 ml HCl and 200 ml of glycerine. This stage is followed by a fine mechanical polishing of the weld nugget surface before measuring its size (diameter and thickness) using an optical microscope interfaced to PC as indicated in Fig. 3 (ZEISS with camera AXIO-CAM).

In Table 4 appear the different welding parameters used in the realisation of the various weld samples.

2.2.2 Welding of unequal sheet thicknesses

In this experimental part, two stainless steel sheets having an unequal thickness of 1 mm and 1.5 mm were welded under various welding parameters. The first series of samples as illustrated in Fig. 4a are welded under a constant electrodes applied load of 2.5 kN while the weld time and current vary respectively from 5 to 15 cycles and from 4000 to 9000 A as indicated in Table 5.

As shown in Fig. 4b and Table 6, the second series is realised under a weld time of 10 cycles and weld current intensity of 7000 A for an electrode applied load varying from 1 to 2.5 kN.

Fig. 4 Micrographs of weld nuggets **a** first series realised under welding parameters as indicated in Table 5. **b** Second series realised under welding parameters as indicated in Table 6

Table 5 Welding parameters used in different formed weld nuggets (sheet 1 mm/sheet 1.5 mm)

Current intensity (A)	Electrodes applied load (2.5 kN $\approx$ 22 MPa)		
	Welding time (cycle)		
	5	10	15
	Series 1	Series 2	Series 3
4000	SA11	SA21	SA31
5000	SA12	SA22	SA32
6000	SA13	SA23	SA33
7000	SA14	SA24	SA34
8000	SA15	SA25	SA35
9000	SA16	SA26	SA36

Table 6 Welding parameters used in weld spots under various electrode applied loads (sheet 1 mm/sheet 1.5 mm)

Electrodes applied load (N)					
Current intensity (7000 A)					
Welding time (10 cycles)					
1000	1250	1500	1750	2000	2500
SB1	SB2	SB3	SB4	SB5	SB6

It should be noted that, the nugget surfaces of all weld samples realised in this experimental part have undergone the same preceding chemical treatment in order to ensure a good visualization of the weld nugget sizes. As shown in Fig. 5, diameter, thickness and the axisymmetric displacement of the nugget were measured.

3 Analytical development

3.1 Electrical contact resistance

The contact resistance generated at the faying interface between the two sheets has a dominant effect on the weld nugget formation. Its evaluation remains as one of the significant parameters in the process of resistance spot welding. It makes possible to quantify the heat quantity necessary [7] to the nugget weld formation, and consequently an adequate adjustment of weld current and weld time [27]. The heat generated quantity Q_0 by Joule effect at the faying surface as shown in Fig. 6 is expressed by Eq. (1) and reached its maximum at the place where contact resistance is highest.

$$Q_0 = R_c I^2 t \quad (1)$$

The generalized relation for electric contact resistance between two sheets was given by Greenwood [28].

$$R_c = \underbrace{(\delta_1 + \delta_2) \left(\frac{1}{4na} + \frac{3\pi}{32nl} \right)}_{\text{Constriction effect}} + \underbrace{\delta_f \left(\frac{s}{A_c} \right)}_{\text{Surface contaminant effect}} \quad (2)$$

where δ_1 and δ_2 are the bulk resistivities of the contacting workpieces, δ_f is the resistivity of contaminant surface, n is the number of contacting asperities per unit area, a is the average contacting radius of asperities, l presents the average center to center distance between the contacting asperities and s is the contaminant thickness.

Fig. 5 Weld nugget; **a** descriptive scheme, **b** formed weld nugget under $I = 7000$ A, $t = 5$ cycles and $F = 2.5$ kN, **c** enlarging

Fig. 6 Representative scheme of welding process during the weld nugget formation

A_c is the total surface of existing asperities at the two sheets interface. This surface is given by the following expression:

$$A_c = \pi a^2 n \quad (3)$$

It should be noted that, through the investigation study of Fenech and Rohsenow [29] the asperities number varies from 20 to 1473 for mild steels under a pressure from 6 to 177 bars.

During first cycles of spot welding, the generated heat quantity by Joule effect at the faying surface causes fusion and formation of the weld nugget. The very short passage times of the welding current as well as the thermal capacitive phenomenon of electrodes and sheets metal makes it possible to suppose that, the thermal dissipation through

the electrodes and sheets to be neglected in this time duration. To this end, the electrode-sheet contact resistances and the electric sheet resistances are neglected compared to the sheet-sheet contact resistance. The thermal balance equation can be written in the following form:

$$\underbrace{R_c I^2 t}_{\text{Joule effect}} = \underbrace{\rho C (T_f - T_i) V_n}_{\text{Heating process}} + \underbrace{\rho V_n \Delta H}_{\text{Fusion process}} \quad (4)$$

where $(T_f - T_i)$ is the variation between the initial temperature of the faying surface and its melting point ΔH is the fusion latent heat of metal and V_n is the nugget volume determined in experiment. From where:

$$R_c = \frac{\rho V_n (C \Delta T + \Delta H)}{I^2 t} \quad (5)$$

3.2 Nugget temperature distribution

An analytical development has been introduced to predict the temperature field during the spot welding of two similar (nature and thickness) sheets. Several authors proposed numerical models [8, 27, 30] simulating the process of nugget formation, but little of them treated the analytical techniques [31]. These expressions are established through the classical theory of resolution partial derivative equations based on assumptions which simplify the physical phenomena. This distribution is a solution of governing differential equation of heat conduction expressed in cylindrical coordinates as follows:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} + q = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (6)$$

The increase of the temperature at point P due to the initial heat quantity generated by the instantaneous point source P' located at the faying surface between the infinite

homogeneous sheets as indicated in Fig. 7 is given by the elementary solution of heat conduction equation, under the boundary conditions as given in Eqs. (7) and (8).

$$r \rightarrow \pm l \quad \frac{\partial T}{\partial r} = 0 \quad (7)$$

$$z = \pm e \quad -k \frac{\partial T}{\partial z} = h(T - T_{\infty}) \quad (8)$$

where h is the convective heat transfer coefficient and α is the thermal diffusivity of the metal sheet.

The quantity of heat stored in the infinite solid at any moment $t > t_0$ is expressed by:

$$q = \int_0^r \int_0^{2\pi} \int_{-e}^{+e} \rho C (T - T_0) r dr d\theta dz \quad (9)$$

In Eq. (9), ρ and C are respectively, the metal sheet density and its specific heat. The variation in the temperature at the point $P(r, \theta, z)$ due to the generated heat at point $P'(r', \theta', z)$ can be deduced through the solution of the heat conduction equation which gives the following temperature distribution:

$$T - T_0 = \frac{Q}{8(\pi \alpha t)^{3/2}} \text{EXP} \left[-\frac{r^2 + z^2 + r'^2 - 2rr' \cos(\theta - \theta')}{4\alpha t} \right] \quad (10)$$

If, instead of the point source, we consider an elementary surface $r' dr' d\theta'$ of the circular disc as illustrated in Fig. 7 generating a heat quantity $dq = Q\rho c r' d\theta' dr'$, the

rise in the corresponding temperature takes a following expression:

$$d(T - T_0) = \frac{Qr' d\theta' dr'}{8(\pi \alpha t)^{3/2}} \text{EXP} \left[-\frac{r^2 + z^2 + r'^2 - 2rr' \cos(\theta - \theta')}{4\alpha t} \right] \quad (11)$$

The integration of Eq. (11) through the disc surface gives the following thermal distribution:

$$T - T_0 = \frac{Q}{8(\pi \alpha t)^{3/2}} \int_0^{r_0} r' dr' \int_0^{2\pi} \text{EXP} \left[-\frac{r^2 + z^2 - 2rr' \cos(\theta - \theta')}{4\alpha t} \right] d\theta' \quad (12)$$

By introducing of the Bessel functions of first species and zero order, the Eq. (12) takes the following expression:

$$T - T_0 = \frac{Q_0}{2\pi r_0 (\pi \alpha t)^{1/2}} \text{EXP} \left[\frac{-z^2}{4\alpha t} \right] \int_0^{+\infty} \text{EXP}[-\alpha t \lambda^2] J_0(\lambda r) J_0(\lambda r_0) d\lambda \quad (13)$$

where $Q_0 = \pi r_0^2 Q$ and r_0 is the faying disc radius.

Along axis Z ($r=0$) the temperature distribution is given as follows:

$$T - T_0 = \frac{Q_0}{2\pi r_0^2 (\pi \alpha t)^{1/2}} \text{EXP} \left[\frac{-z^2}{4\alpha t} \right] \left(1 - \text{EXP} \left(-\frac{r_0^2}{4\alpha t} \right) \right) \quad (14)$$

4 Results and discussion

4.1 Equal sheets thickness

In resistance spot welding, the weld nugget quality is closely related to the weld current intensity, weld time and electrode applied load. Through the Fig. 8a–c which illustrate the effect of weld current and welding time on nugget sizes realised under welding parameters as given in Table 4, it appears clearly that, the incubation zone characterized by no apparition of spot welds is located at weld current intensity lower than 4000 A for all weld times. In this zone, the generated heat at the two sheets contacting surface causes a rise in faying surface temperature of the 304 stainless steel without reaching its melting point.

Figure 8a presents the nugget diameter and thickness evolution according to the weld current intensity with welding time of 5 cycles. From 4000 to 6000 A, the nugget size is characterized by a fast development reaching its maximum thickness of about 1.5 mm. The nugget diameter continues to increase in the interval of current intensity going from 6000 to 8000 A until its maximum of 5.80 mm while the thickness records a reduction of

Fig. 7 Descriptive scheme of thermal boundary conditions and instantaneous point source during spot welding

Fig. 8 Nugget size variation according to the weld current **a** weld time = 5 cycles, **b** weld time = 10 cycles, **c** weld time = 15 cycles

34% compared to its maximum value. It is noticed that beyond 8000 A, the weld nugget size remains without significant growth.

Figure 8b shows the growth of the nugget size welded under a weld time of 10 cycles. It appears that, the nugget thickness reached a maximum value of 1.2 mm under a weld current intensity of 6000 A while its diameter records 4.4 mm. Once the weld current increases from 6000 to 8000 A, the nugget thickness decreases but the diameter recorded an increase until its maximum of 5.90 mm reached at 9000 A. Through the Fig. 8c which illustrates the nugget development obtained under weld time of 15 cycles, it observed that, the maximum nugget diameter of 6.4 mm is reached under an intensity of 9000 A, while the maximum thickness of 1.2 mm is recorded under 6000 A.

Analytical results of the contact resistance as illustrated in Fig. 9 were obtained through the Eq. 5. It shows that the contact resistance decreases quickly when the weld time increases for all weld current intensities. For a weld time of 5 cycles, the contact resistance reached its maximum value of $8.8 \mu\Omega$ at 6000 A then decreases with the increase in weld current until $2.8 \mu\Omega$ recorded at 9000 A. It appears clearly that for 10 cycles and 15 cycles, the contact resistance records respectively its maximum values of $4.6 \mu\Omega$ and $3.28 \mu\Omega$ under a same current intensity of 5000 A. By comparison between Figs. 8 and 9, it appears that the maximum nugget thicknesses are reached when the electrical contact resistance becomes maximal, contrary to nugget diameter which remains less influenced by the electrical contact resistance.

Fig. 9 Variation of the electrical contact resistance according to the weld current intensity

The temperature field along Z axis as indicated in Fig. 10 is schematized through the obtained results from Eq. (14) during spot welding of two stainless steel sheets having a same thickness of 1 mm. The nugget thickness is determined through the isothermal contour of 1427 °C assumed as the melting point which appears under a violet color. In this analytical approach, it appears that the weld nuggets are formed at the first cycles of welding time. For example, the weld spot nugget realised under a welding time of 10 cycles and welding current of

6000 A as shown in Fig. 10, finishes its transversal growth at the 7th weld cycle. Beyond this time, the temperature decreases quickly inducing a cooling of the molten zone. This physical phenomenon [32] can be explained by the significant effect of the electrical contact resistance on the nugget formation during first weld cycles.

Figure 11a–c show the comparison between experimental nugget thicknesses and those predicted theoretically through the developed analytical model. It appears that for a weld time of 5 cycles as illustrated in Fig. 11a, no weld nugget formation below 5000 A while its fast development is observed between 5000 and 9000 A without radial expulsion. When the weld time passes to 10 cycles as indicated in Fig. 11b, the theoretical weld nugget growth begins at 4000 A followed by a fast development until 7000 A. A good agreement is observed between the predicted nugget thicknesses and those given experimentally in the interval of weld current from 4000 to 6000 A. The expulsion of the molten metal is appeared starting from 8000 A.

Through Fig. 11c, it observed that the analytical and experimental thicknesses increase according to the same pace with an average difference of 23% in the zone of the weld currents between 4000 and 5000 A. The nugget grows until its metal expulsion which appears at an intensity of 6000 A.

4.2 Unequal sheets thickness

Knowledge of weld nugget location and size in spot welding of unequal metal sheets thicknesses is of a great

Fig. 10 Temperature distribution along the thickness of the two stainless steel sheets during their spot welding using the analytical development

Fig. 11 Experimental and analytical results of the weld nugget thickness **a** weld time=5 cycles, **b** weld time=10 cycles, **c** weld time=15 cycles

importance in order to evaluate its quality. The effect of weld current and weld time on weld nugget growth and its axisymmetric displacement under a same mechanical pressure of 22 MPa (2.5 kN) is illustrated in Fig. 12. It is observed that for a weld time of 5 cycles as indicated in Fig. 12a, the nugget thickness reached a maximum value of 1.6 mm at 6000 A before its decrease up to a minimal value of 1.1 mm recorded under a weld current of 9000 A. However, the nugget diameter grows differently comparing to thickness growth in the same weld current interval in which a maximum value of 5.4 mm is obtained at 9000 A. Results show that the nugget axisymmetric displacement records 0.3 mm into the thickest stainless steel sheet independently of the weld current intensity.

When weld time increases to 10 cycles, the nugget thickness passes to its maximum of 1.9 mm recorded under weld current of 6000 A as presented in Fig. 12b. It is noticed that the weld time rise from 5 cycles to 10 cycles induced a growth of 18.75% in maximal nugget thickness welded under a same weld current. However,

the nugget diameter grows until its maximum value of 5.9 mm obtained at 9000 A, recording a rise of 9.25% compared to that obtained under a weld time of 5 cycles. It appears clearly that the axisymmetric displacement of the weld nugget remains not influenced by the increase in weld current from 5 to 10 cycles for weld current intensity going from 4000 to 9000 A.

As shown in Fig. 12c, the maximum nugget thickness takes a value of 1.4 mm recording a reduction of 31% than that recorded during weld time of 15 cycles, contrary to the maximum nugget diameter which recorded a rise of 17%. The constant value of 0.3 mm which axisymmetric displacement records during a weld time of 15 cycles shows that the nugget location is not influenced by the welding time as well as the welding current intensity. Results show that the nugget thickness development is appreciably affected by weld time than weld current, contrary to the nugget diameter growth which is most influenced by weld current.

Fig. 12 Experimental weld nuggets sizes obtained during spot welding of unequal sheet thicknesses (1 mm/1.5 mm). **a** Weld time = 5 cycles, **b** weld time = 10 cycles, **c** weld time = 15 cycles

The effect of electrode applied load on nugget size and its location during spot welding of unequal thickness under a given weld time and current is illustrated in Fig. 13. Results indicate that the maximum values of nugget thickness and its diameter are reached under the same applied load of 1250 N. It may be concluded that the reason for this result is more likely due to the higher electrical contact resistance recorded under the given welding parameters.

Beyond 1250 N, the thickness and diameter of the spot weld nugget decrease and become almost constant from 2000 N to 2500 N. It appears that the axisymmetric displacement of the weld nugget maintains a constant value of 0.3 mm for all applied loads. This result shows that the

nugget location welded under a constant weld time and current is independent of the electrode applied load.

5 Conclusion

Nugget development in spot welding of 304L stainless steel sheets having an equal and unequal thickness has been investigated in this study. The effect of different welding parameters such as weld time, weld current intensity and electrode applied load on the weld nugget growth was experimentally analysed. A thermal analytical model has been also developed with aim to predict the nugget size development during spot

Fig. 13 Experimental weld nugget size according to electrode applied load (weld time of 10 cycles and weld current of 7000 A)

welding process. Through the experimental process, it was found that, the nugget growth passes by four stages which are; incubation, fast development, slowed down development and expulsion. The obtained results in spot welding of equal and unequal sheet thickness emphasize that, the nugget thickness growth is appreciably affected by weld time than weld current, contrary to the nugget diameter growth which is most influenced by the weld current. It is useful to notice that the nugget thickness reached its maximum when the electrical contact resistance is maximal, contrary to nugget diameter which remains less influenced by the electrical contact resistance. Quantitatively, there were a significant deviation between the predicted sizes given by the developed analytical than those obtained experimentally, but remains in a qualitative adequacy and indicates that the weld nuggets are formed at the first cycles of welding time. Through the results of spot welding of unequal sheet thickness, it was observed that nugget displaces into the thickest sheet and its location is independent of the weld time, weld current and electrode applied load. This nugget location is more likely affected by the sheets thickness ratio than other parameters.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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