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IMPACT OF FRICTION COEFFICIENT VARIATION ON TEMPERATURE FIELD IN ROTARY FRICTION WELDING OF METALS – FEM STUDY

Abstract

A mathematical model is presented for investigating the temperature field caused by the rotary friction welding of dissimilar metals. For this purpose, an axisymmetric, nonlinear, boundary value problem of heat conduction is formulated with allowance for the frictional heating of two cylindrical specimens of finite length made of Al 6061 aluminium alloy and 304 stainless steel. The thermo-physical properties of materials change with increasing temperature. It was assumed that the coefficient of friction does not depend on the temperature. The mechanism of heat generation due to friction on the contact surface with the temperature field of samples is considered. The boundary problem of heat conduction was reduced to the set of nonlinear ordinary differential equations at time t relative to the values of temperature T at the finite elements nodes. The numerical solution of the problem was obtained with the inverse 2nd order differentiation method implemented in COMSOL FEM system (finite element method), with time step $\Delta t=0.1$ (s). The influence of various values of friction coefficient is presented.

1. INTRODUCTION

Friction welding is a widely used solid-state joining process. Metallic and nonmetallic materials with different thermomechanical properties can be welded Simoes et al. (2014), Uday et al. (2012) and Taban et al. (2010). The friction welding processes can be divided into the following types: continuous drive friction welding (CDFW) or rotary friction welding (RFW), inertia friction welding (IFW), linear friction welding (LFW), orbital friction welding (OFW) and friction stir welding (FSW). The CDFW is the oldest and most used method. One of the most effective numerical method for structural and thermal

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problems is the finite element (FE) method. Several studies have so far been made to investigate the thermal problem of friction welding. A review papers on this question was presented for example in the works by Maalekian (2007), Uday et al. (2010), Gooch T. G. (1973) and Bhamji et al. (2011). In work of Pinheiro (2019) the welding of aluminum ASTM A6351-T6 and SAE 1020 steel was carried out aiming at evaluating the effects of the initial contact geometry on the mechanical properties of the welded joint in detail.

In work by Uday et al. (2012) axisymmetric FE model of the CDFW has been developed to analyse a temperature field of friction pair: Al 6061 aluminium alloy and 304 stainless steel. The same pair (Al 6061 + AISI 304) was experimentally tested by Senkathir and Siddharth (2020). Taban et al. (2010) analysed dissimilar friction welding of 6061–T6 aluminum and AISI 1018 steel, properties and microstructural characterization. Effect of energy input on tensile strength of 304-304 bars during CDFW was examined in the paper developed by Wang et al. (2018).

Influence of varying rotational speed on the tensile static strength and tension-compression fatigue behaviours for AA7075/AA5083 aluminium alloys pair carried out using RFW was performed by Sasmito et al. (2022). Linear and rotary friction welding in detail are analysed by Li et al. (2016). FSW process (Rajak et al. 2020) and study on grain boundary and microtexture evolutions during FSW of aluminum alloys (Shamanian et al. 2016) were analysed. Fatigue performance of Al2024 alloy performed by FSW process in a different corrosive environment were studied by Thapliyal and Dwivedi (2020), Ross and Sorensen (2013) as well as by Chen and Cui (2018). Optimization of parameters in RFW process of dissimilar austenitic and ferritic stainless steel using finite element analysis were analysis in Mattie et al. (2023). Many researchers deal with the friction welding of aluminum alloys in great detail, for example: Ghias et al. (2019), Mehta (2019). Livingston (2019) in their PhD thesis presented comparison of heat generation models using finite element analysis during friction welding process.

The aim of this paper is to show the influence of friction coefficient’s values for temperature distribution in frictional heating stage in RFW process. The present work is a continuation of the research carried out by Łukaszewicz (2018, 2019). In these studies, the nonlinear numerical model using FEM for simulate temperature field near contact zone in the RFW process for metals alloys were developed, modelled and analysed.

2. MATERIALS AND METHODS

A friction stage of CDFW process is considered (Fig. 1). Assembly of two cylindrical parts by rotational friction when applying a compression, constant pressure p_0 generates heat at the contact zone. One part is stationary while the second is rotating with constant value ω_0 in predetermined time t_s. After this stage the rotation is stopped and final forging pressure is applied to make the weld. It is assumed that the properties of materials are temperature dependent.

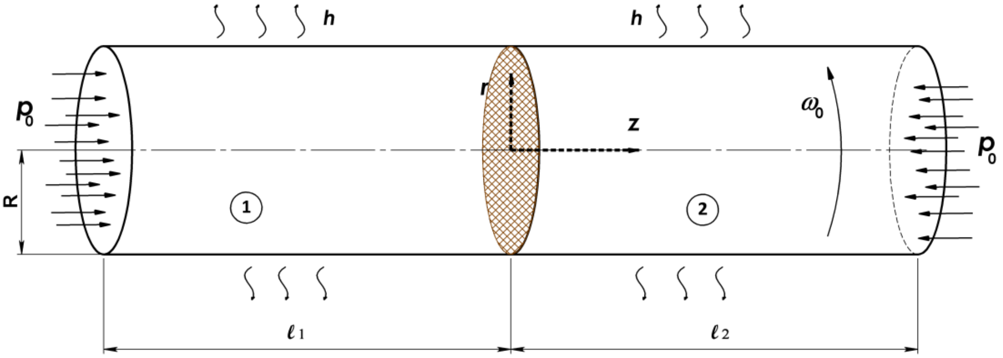

Fig. 1. Schematic diagram of frictional system in CDFW process

Axisymmetric transient temperature field $T(r, z, t)$ will be obtained from the solution of the following boundary value problem of heat conduction in the cylindrical coordinate system (if $l_1 = l_2 = l$) (Łukaszewicz, 2018):

$$\frac{1}{r}\frac{\partial}{\partial r}\left[rK_1(T)\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial z}\left[rK_1(T)\frac{\partial T}{\partial z}\right]=\rho_1(T)c_1(T)\frac{\partial T}{\partial t}, 0<r<R, 0<z<l, 0<t\leq t_s, \tag{1}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left[rK_2(T)\frac{\partial T}{\partial r}\right]+\frac{\partial}{\partial z}\left[rK_2(T)\frac{\partial T}{\partial z}\right]=\rho_2(T)c_2(T)\frac{\partial T}{\partial t}, 0<r<R, -l<z<0, 0<t\leq t_s, \tag{2}$$

$$K_2\frac{\partial T}{\partial z}\bigg|_{z=0^-}-K_1\frac{\partial T}{\partial z}\bigg|_{z=0^+}=q(r,t),\ 0\leq r\leq R, 0<t\leq t_s, \tag{3}$$

$$T(r,0^-,t)=T(r,0^+,t), 0\leq r\leq R, 0<t\leq t_s, \tag{4}$$

$$K_1\,(T)\frac{\partial T}{\partial r}\bigg|_{r=R}=h[T(R,z,t)-T_0], 0\leq z\leq l, 0<t\leq t_s, \tag{5}$$

$$K_2\,(T)\frac{\partial T}{\partial r}\bigg|_{r=R}=h[T(R,z,t)-T_0], -l\leq z\leq 0, 0<t\leq t_s, \tag{6}$$

$$\frac{\partial T}{\partial z}\bigg|_{z=\pm l}=0, 0\leq r\leq R, 0<t\leq t_s, \tag{7}$$

$$T(r,z,0)=T_0, 0\leq r\leq R, -l\leq z\leq l, \tag{8}$$

Temperature dependencies of thermal conductivity K_i, specific heat c_i and density ρ_i, $i = 1, 2$; of specimen materials have the form:

$$K_i(T)=K_{0,i}K_i^*(T), c_i(T)=c_{0,i}c_i^*(T), \rho_i(T)=\rho_{0,i}\rho_i^*(T), \tag{9}$$

$$K_{0,i}=K_i(T_0), c_{0,i}=c_i(T_0), \rho_{0,i}=\rho_i(T_0). \tag{10}$$

where: $K_i^*(T)$, $c_i^*(T)$, $\rho_i^*(T)$ are dimensionless functions of temperature.

In general case, owing to the high temperatures on the contact surface, the friction coefficient f should be dependent on the temperature:

$$f(T) = f_0 f^*(T), f_0 = f(T_0). \tag{11}$$

The specific friction power, taking into account equation (3), equals (Łukaszewicz, 2019):

$$q(r,t) = q_0 q^*(r,t), q_0 = f_0 p_0 R \omega_0, q^*(r,t) = rR^{-1} f^*[T(r,0,t)], 0 \le r \le R, 0 \le t \le t_s. \tag{12}$$

3. RESULTS

Simulation of frictional heating in a couple during friction process with parameters: $f(T) = f_0 = 0.1; 0.2; 0.4$, $p_0 = 40$ (MPa), $\omega_0 = 146.6$ (rad/s), $h = 40$ (W/m2K), $t_s = 1$ (s) using FE based software (COMSOL Multiphysics v.5.2a) was carried out. The calculations were performed for two specimens of radius R =12.5 (mm) and length $l = 50$ (mm) each, made of Al 6061 aluminium alloy and 304 stainless steel. The 2D axisymmetric FE mesh of the friction couple is shown in Figure 2.

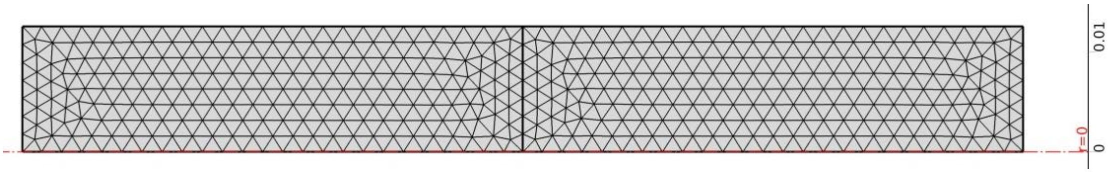

Fig. 2. FE mesh of the friction pair

Changing the properties of Al 6061 aluminium alloy with temperature increase is shown in Figure 3, and the properties of temperature dependence of 304 stainless steel is presented in Figure 4 (Rothman, 1988). On Figure 3 and 4 following units are applied: $K_i(T)$ (W/(m K)), $c_i(T)$ (J/(kgK)), $\rho_i(T)$ (kg/m^3); x axis: T (K).

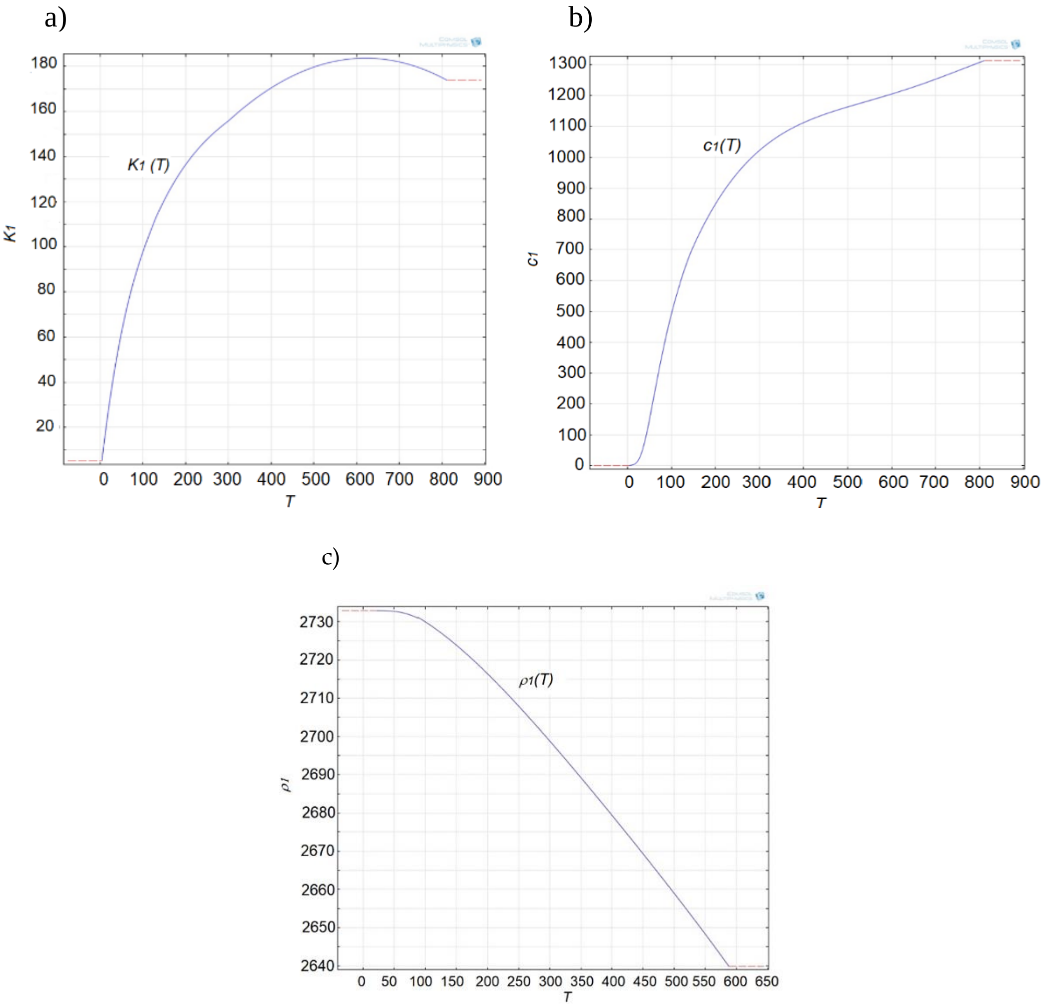

Fig. 3. Functions $K_1(T)$ (a), $c_1(T)$ (b), $\rho_1(T)$ (c) for Al 6061 aluminium alloy

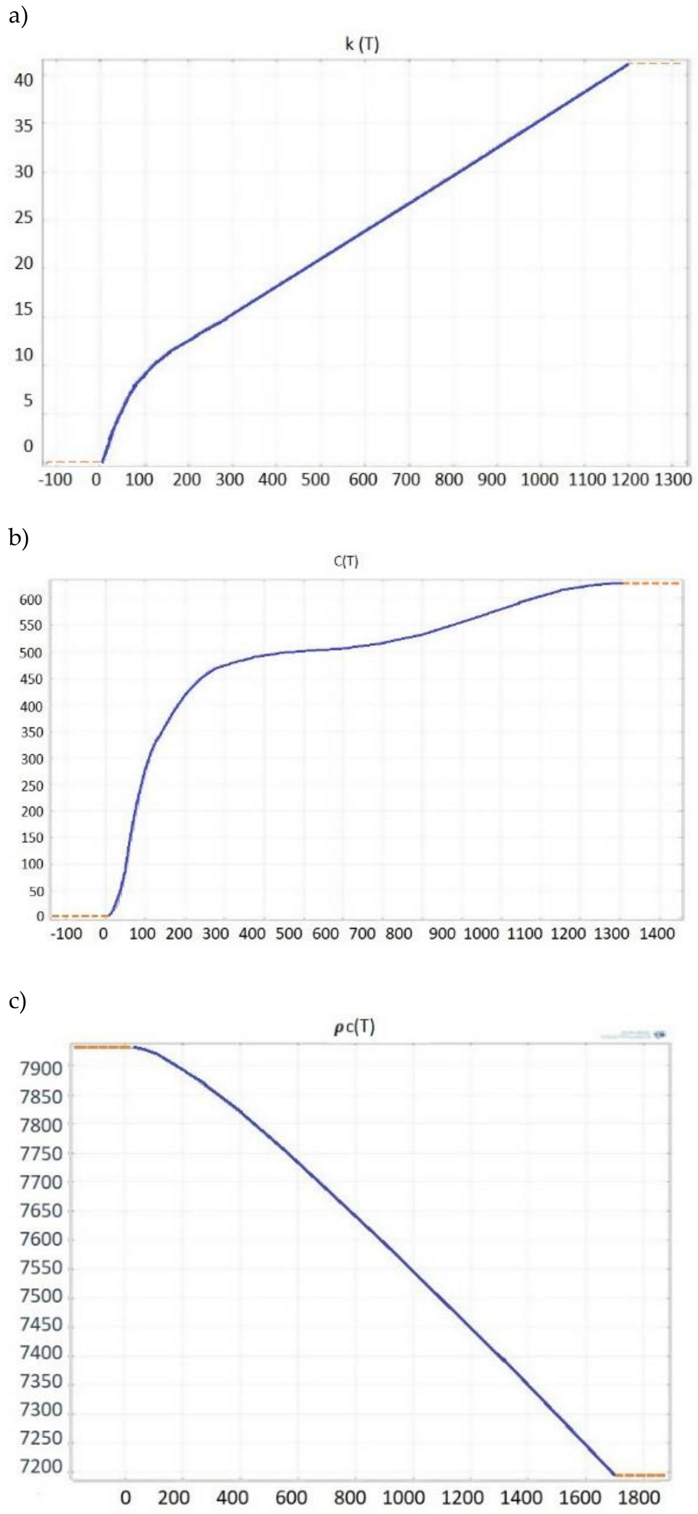

Fig. 4. Functions $K_2(T)$ (a), $c_2(T)$ (b), $\rho_2(T)$ (c) for 304 stainless steel

The two-dimensional region was filled by triangular finite 2nd order element. Number of finite elements was 844. Influence of number of FE in similar axisymmetric problem to calculation results is described in paper by Łukaszewicz (2018). Difference between results of T_{max} (°C) on whole contact surface for two identical specimens made of AISI 1040 steel (l_1 = l_2 = 30 (mm), R = 6 (mm)) in case of numbers of FE equal respectively 460 and 6062 was less than 0.015 %. In presented paper, the impact of quantity of FE was not discussed. However, according to previous author calculation experiences, the relative error in the specified amount of FE (i.e. 844) certainly will not be greater than 0.1% if the amount of FE will increase to about 10 times (e.g. 10000).

As a result of described discretization, the boundary problem of heat conduction was reduced to the set of nonlinear ordinary differential equations on time t relative to the values of temperature T in the finite elements nodes. The solution was obtained with the inverse 2nd order differentiation method implemented in COMSOL FEM system, with time step
Δt=0.1 (s).

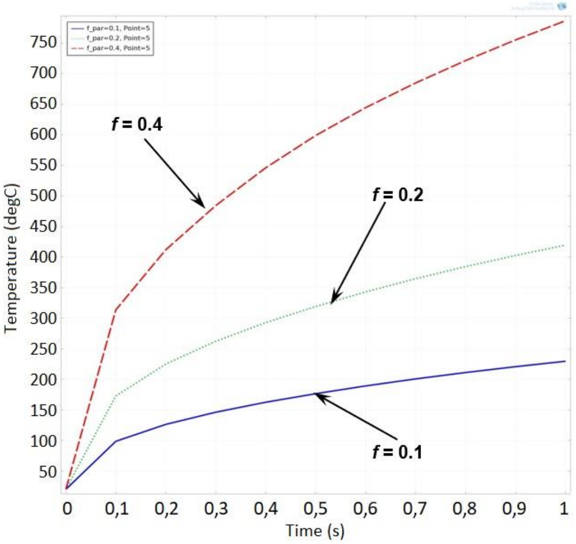

Fig. 5. Evolution of temperature *T* (°C) with time *t* (s) on the contact surface *z* = 0, *r* = R for three values of friction coefficient *f*

The effect of various values of friction coefficient on temperature was considered. It was found that an increase in the parameter f leads to an increase in the temperature in contact surface (z = 0) for r = R during the entire heating process (Fig. 5). The temperature increases the most at the outer surface (r = R) for t = ts (Fig. 6). This is due to the higher linear velocity v=ω0(r) as the radius r increases, and thus the higher value of the specific friction force q(r,t).

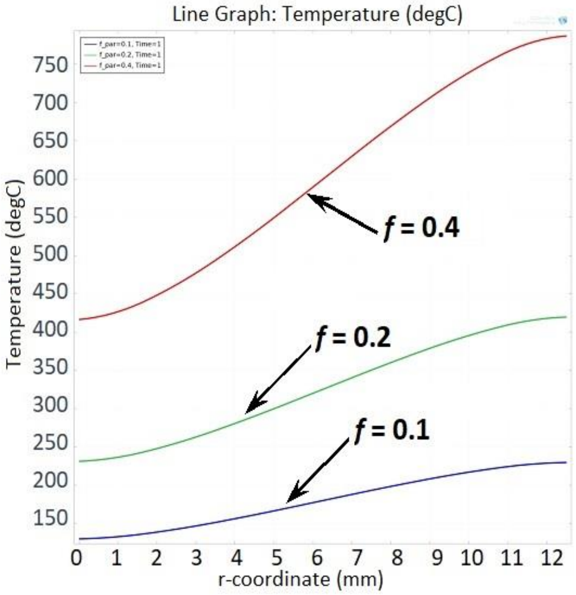

Fig.6. Change of temperature *T* (°C) on the contact surface *z* = 0 in the radial direction *r* (mm) at time *t* = *t*$_s$

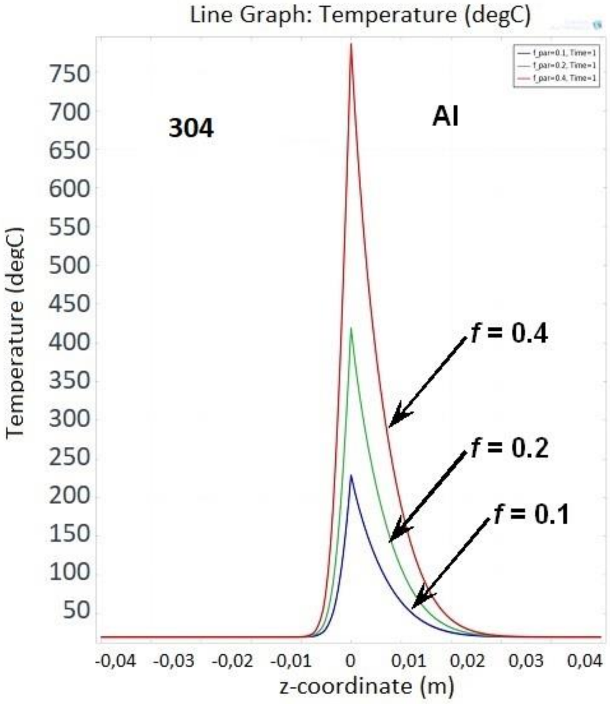

Fig. 7. Change of temperature *T* (°C) along *z* axis (m) at *t* = *t*$_s$ for *r* = R for three values of friction coefficient *f*

Figure 7 shows the effect of the value of the friction coefficient f on the temperature distribution in the axial direction z at the end of fictive heating (t = ts) for r = R. It was observed that an increase in the value of *f* leads to an increase in the temperature in contact surface (*z* = 0) for *r* = R at the end of friction heating stage of welding process. Due to the higher thermal conductivity values for the aluminum alloy, the temperature influence zone on the Al 6061 side is wider than on the steel side.

Temperature obtained in contact zone for value of friction coefficient *f* = 0.4 and at the time $t = t_s$ (Fig. 6 and 7) is the most suitable to achieve a steel-aluminum friction pair joint, over the entire contact surface. However, the simulation would need to be verified experimentally to confirm whether this value of *f* allows for correct numerical results.

In fact, the value of the coefficient of friction during the friction welding process is not constant. However, obtaining the temperature characteristics of the friction coefficient for a given friction pair is not easy and requires specialized instrumentation. For this reason, many mathematical models often assume a constant value of this parameter for numerical simulations. In investigations carried out by Łukaszewicz (2018, 2019) it was assumed temperature-dependent characteristics of friction coefficient for similar friction steel pair AISI 1040/AISI 1040 find from work by Bouarroudj (2017). However, there is no database for the temperature characteristics of the friction coefficient *f* (*T*) for dissimilar friction pairs.

4. CONCLUSIONS

A mathematical model is proposed for investigating the temperature field caused by the rotary friction welding of dissimilar metals. For this purpose, an axisymmetric, nonlinear, boundary value problem of heat conduction is formulated with allowance for the frictional heating of two cylindrical samples of finite length made of Al 6061 aluminum alloy and 304 stainless steel. It is assumed that the both materials of specimens are thermally sensitive, but the friction coefficient is independent of temperature. The numerical solution of the problem is obtained by the finite element method. The influence of various values of friction coefficient has been considered. For this friction pair value of friction coefficient *f* = 0.4 is the most suitable to obtain the realistic temperature, allowing to achieve a steel-aluminum friction pair joint, over the entire contact surface. Presented results are important and significant not only in the scientific but also in the utilitarian sense. They allow optimizing the parameters of the friction welding process and affect the energy parameters of the process.

Author Contributions

The authors confirms sole responsibility for the following: study conception and design, analysis and interpretation of results, and manuscript preparation.

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Conflicts of Interest

The authors declare no conflict of interest.

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