Development of a Finite Element Model for Thermal Analysis of Friction Stir Welding (FSW)

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Abstract: Almost 2 decades ago, TWI had successfully introduced the Friction Stir Welding (FSW). During FSW, temperature increases because the friction and plastic deformation which begin at the same time. There are various reports on the assumptions and hypotheses in modelling the heat generation and the deformation of the material, however a consensus about modelling of the process is still to be reached. Over the years, scholars had proposed many numerical approaches, particularly Lagrangian, Eulerian and Arbitrary-Lagrangian-Eulerian (ALE). Researchers have deemed that choosing the most suitable numerical approach is one of the most challenging phases for FSW thermal modelling. This is because using the wrong numerical model could lead to issues such as divergence problems and high mesh distributions. Such problems could escalate when the welding transverse or rotational speeds increase. Thus, in this paper, global (structural component) level analysis was conducted, defining the problem in the Lagrangian setting. Meanwhile, an apropos kinematic framework was used at the local level. This framework uses the efficient combination Eulerian and Lagrangian descriptions for various welding speeds through the use of ABAQUS® software. The results from the temperature evaluation of the welding process are detailed in the paper. The result of the comparison between the experimental and simulated model indicates that the numerical model demonstrates the prospective methodology and its ability to accurately examine the FSW processes during different welding speeds.

Keywords: Friction Stir Welding (FSW), Eulerian, Lagrangian, Arbitrary-Lagrangian-Eulerian (ALE), Temperature Evaluation.

1. Introduction
Friction Stir Welding (FSW) is one of the newest welding techniques. However, this technique has several limitations, such as the applying of high forges, geometrical limitations and high process loads. There are existing FSW machines that are capable of operating it at different welding speeds, nevertheless there are few existing FSW machines that could operate it at high welding speeds. Basically, as the rotational welding speed gradually increases, the welding loads would significantly decrease. This reduces resulting the decrease of the clamping dependency, and the decrease of the need to large machines, and operating costs which these matters resulting the increase of the productivity. Furthermore, the size and the mass of the
machine and tooling forces will be reduced as the rotational speed increases, because most of the heat and the energy will be generated by the rotational speed.

Although some researchers have been focused on the experimental investigation of FSW, however the complexity of the thermal behavior of FSW hinders the ability of the analytical model to capture the details required for adequate quantitative prediction of the heat generated in the tool and workpiece. Consequently, researchers have proposed Finite Element Methods (FEMs) as an alternative method for decreasing the costly and time-consuming experimental tests. Therefore, FEM is known as a suitable method in order to solve the complicated governing equations and conduct a detailed investigation of the process.

Finite Element Modelling is a very appropriate approach for modelling the FSW process as shown by the massive number of published researches works on the thermal analysis of FSW since the last decade. Some of the pioneering works in done by Awang et al. and Meyghani et al. [1-3]. It should be mentioned that; the first step of the simulation is to choose between the explicit and the implicit time integration. As explicit time integration is less complicated, it is usually using to solve the transient problems where small-time step sizes are accepted. On the other hand, implicit methods are plagued with convergence problems, particularly when large plastic deformations and complicated contact behavior are available. Thus, the explicit method is advantageous in modelling the FSW process, as shown in other research [1, 4-10].

Another important selection that need to be done by a researcher is to choose between Lagrangian, the Eulerian and an ALE-formulation [11-16].

At first, the Lagrangian formulation seems to be an appropriate choice, because the finite element mesh follows the material deformation and it is attached to the material.

In this light, some FSW models have considered the Lagrangian mesh [17, 18] and used it to globally study the process. The models were able to predict the deformation of the structure and the welding temperature successfully. Dialami et al. [19] created a model of FEM with a Lagrangian mesh. In the model, the material visco-plastic law is assumed which had temperature-dependent properties. Between the parts, a frictional interface was used. The values determined by using the pressure and the velocity between the interfaces which were gain from the experimental data. In the meantime, the finite volume method was used for simulating the friction weld [20]. The study is done to investigate the flow of the material in the plasticized region. They had analyzed both similar and dissimilar welds. For the former one, the viscosity was obtained from a heuristic relationship which was not dependent on the temperature. Meanwhile, for dissimilar welds, the Eulerian-Lagrangian mesh and a transient thermal model with a complicated viscosity relationship were used. Furthermore, Dong et al. [21] thermomechanically studied the FSW. The model used an axis-symmetrical FE Lagrangian formulation. A 3D FSW model for aluminum thick plates was developed by Ulysse [22]. The study focused on computing the forces on the tool across different welding and rotational velocity. Here, the deviatoric stress tensor was employed to model the FSW process by using a 3D visco-plastic model. Parametric studies had done to identify the tool velocity influence on the workpiece temperature. The comparisons were used for validating the existing predicted measurement in the model. The study found that the increase in welding transverse speed increases the pin forces, however, when the rotational speeds were increased, the pin forces decrease. Unfortunately, a closer investigation reveals that the drawbacks dominate over the advantages. As the advantages, it is easy to understand the theory and the result. In this regard, there are more drawbacks compared to advantageous. These drawbacks include large strains distortions and the passes of the shear plane by the material which decreases the accuracy and significantly reduce the critical time step size. Consequently, a majority of available computer program are based on Lagrangian formulation.

Meanwhile, for the Eulerian formulations, the material flows through the faces of the element and the mesh is fixed in space. This could prevent numerical problems when large strains are available in the model. Besides, the element distortions do not affect this strategy and allows the simulation to have a steady state behavior. However, the separation of the element is not allowed in the Eulerian approaches, hence, the proper modelling of the convection terms which are related to the material properties is required. Furthermore, prior knowledge of workpiece/tool contact length and the geometry was needed by this formulation. This issue restricts the range of its application. Thus, to overcome this shortcoming, many researchers have adjusted the workpiece/tool contact length and the geometry by adopting iterative procedures. As an advantage of the Eulerian method is the use of flow boundary condition; hence only the small region around the tool needs to be modelled resulting the reduce of the simulation time. There are two main steps in the simulation process. The first, adopts the Eulerian description of the thermo-mechanical, along with a steady-state algorithm [23]. This step needs to be done to prevent remeshing as a result of pin motion. The next step estimates the
residual state created during the process by using a steady-state algorithm based on the constitutive law of elasto-viscoplastic. Meanwhile, Bendzsak et al. [24] adopted the Eulerian code Stir3D to model the flow around the tool, including the tilt angle and thread of the tool to obtain the flow patterns. However, this model neglects the influence of the temperature in the viscosity. The model created by Cho et al. [25] is an example of distinctive local level study. The study used the Eulerian approach which comprises thermomechanical models, but the transient temperature did not take into account. The study also studied the hardening of the strain and evolution of texture in the stainless-steel friction stir welds. Meanwhile, some studies [26, 27] adopted the Lagrangian approach with intensive re-meshing, which were not numerically efficient.

Some studies [11-16, 28-30] had proposed the combination of Lagrangian and Eulerian formulations which could model FSW process and combine advantages of both as a mixed method, recognized called Arbitrary Lagrangian–Eulerian formulation (ALE). This method uses an ‘operator split’ and sequentially applies the Eulerian and Lagrangian steps, as shown in Figure 1. During the initial step, it is assumed that the mesh follows the material flow, because the displacement issue in the Lagrangian is solved subsequently. In this regard, the mesh is repositioned to move, and the Eulerian approach is used for solving the velocities advection problems. Despite the fact that ALE methods decrease the distortion of the element, however in this method a suitable numerical treatment of the advection terms is required.

![Figure 1. The ALE operator schematic view](image_url)

On the other hand, selecting the suitable method to model the process is still challenging. Thus, this paper presents the individual aspects of simulation techniques and numerical strategies to provide an accurate simulation of the FSW thermal analysis.

2. Methodology

2.1. Geometry

The model comprises of a welding tool with a pin and a shoulder, the welded plates has 200 mm length and 100 mm width with the thickness of 10 mm. The diameter of the welding tool is 8 mm with a pin with the length of 6 mm, and the shoulder has the diameter of 18 mm. It is assumed that the workpiece is made from a deformable material (AA6061-T6) and has temperature and displacement degrees of freedom. The tool meshes are assumed to be coarser, because
there is no significant deformation in it. The C3D8RT elements are used to discretize the workpiece and the tool. This element type possesses a coupled temperature-displacement formulation which includes trilinear displacement and temperature, hourglass control and 8-node thermally coupled brick, which allows the decrease integration with hourglass control. As mentioned earlier the deformation of the tool is not significant compared to the anticipated deformation in the welded workpiece plat, therefore the tool was modelled as a rigid body. Figure 2 illustrates the undeformed configuration of the model used.

![Figure 2. The mesh and the boundary condition](image)

2.2. Material Properties

Table 1 and Table 2 present the thermal and mechanical properties. It needs to be mentioned that based on the literature, the temperature dependent values of the Young Modulus were used except the Poisson’s Ratio which is assumed to be constant (0.34).

| Temp (°C) | Thermal Conductivity (W/mK) |
|----------|-----------------------------|
| 148.9    | 162                         |
| 204.4    | 177                         |
| 260      | 184                         |
| 315.16   | 192                         |
| 371.1    | 201                         |
| 426.7    | 207                         |
| 148.9    | 217                         |
| 204.4    | 223                         |
Table 2. Material properties and heat coefficients of AA6061-T6

| Temp (°C) | Density (kg/m³) | Coefficient of Thermal Expansion (°C) | Specific Heat Capacity (J/Kg °C) |
|----------|----------------|--------------------------------------|----------------------------------|
| 37.8     | 2685           | 2.345x10^{-5}                        | 95                               |
| 93.3     | 2685           | 2.461x10^{-5}                        | 978                              |
| 148.9    | 2667           | 2.567x10^{-5}                        | 1004                             |
| 204.4    | 2657           | 2.669x10^{-5}                        | 1028                             |
| 260      | 2657           | 2.756x10^{-5}                        | 1052                             |
| 315.6    | 2630           | 2.853x10^{-5}                        | 1078                             |
| 371.1    | 2630           | 2.957x10^{-5}                        | 1104                             |
| 426.7    | 2602           | 3.071x10^{-5}                        | 1133                             |

2.3. Thermal Boundary Conditions

During the process, the heat is rapidly propagated into the workpiece. It should be noted that, the convection and radiation of the heat caused the heat loss into the ambient on the front edge and the top surfaces of the workpiece. Moreover, conduction losses need to be considered from the workpiece bottom surface to the backing plate or the clamp. In the literature [31] the data suggested for the film condition in a range of 0 to 25 W/m² °C. As shown in Figure 3 and Table 3, the width and the length surfaces of the workpiece the film coefficient was applied. Figure 4, and Table 4 illustrate the workpiece top surface, where the film coefficient values are set between 0 to 13.66 (W/m² K⁻¹), while at the bottom surface film coefficient is assumed as a constant value of 1000 W/m² K⁻¹. To model conduction losses, the bottom surface is treated as a convection surface. It should be noted that the constant value of the film coefficient at the bottom surface reminds a high overall heat-transfer coefficient which is assumed for the conductive heat loss through the surface. As shown in Figure 5 and Table 5, the convection coefficient value ranged from 0-20 W/m² K⁻¹ for the interfaces between the tool and the workpiece. Moreover, it is significant to note that the model output temperature would be increased when lower coefficient is applied. The radiation heat losses are ignored due to the low percentage of heat lost from radiation. Here, the initial temperature of 25 °C is applied to the model.
Figure 3. Width (a) and length (b) surfaces of the workpiece

Table 3. Film coefficient applied in the width and length sides of the workpiece

| Temp ºC | Film coefficient W m⁻² K⁻¹ (Width) | Film coefficient W m⁻² K⁻¹ (length) |
|---------|-----------------------------------|-------------------------------------|
| 25      | 0                                 | 0                                   |
| 40      | 13.8991                           | 13.9992                             |
| 60      | 16.8327                           | 16.9539                             |
| 80      | 18.5058                           | 18.6391                             |
| 100     | 19.7069                           | 19.8488                             |
| 120     | 20.5985                           | 20.7469                             |
| 140     | 21.3248                           | 21.4785                             |
| 160     | 21.9613                           | 22.1195                             |
| 180     | 22.4379                           | 22.5995                             |
| 200     | 22.8662                           | 23.0309                             |
| 250     | 23.7139                           | 23.8847                             |
| 300     | 24.4014                           | 24.5772                             |
| 350     | 24.8169                           | 24.9957                             |
| 400     | 25.1348                           | 25.3158                             |
Figure 4. Top (a) and bottom (b) surface selected for applying film condition

Table 4. Film coefficient applied in the top surface of the workpiece

| Temp °C | Film coefficient W m²K⁻¹ (Top surface) |
|---------|----------------------------------------|
| 25      | 0                                      |
| 40      | 7.5568                                 |
| 60      | 9.1518                                 |
| 80      | 10.0614                                |
| 100     | 10.7144                                |
| 120     | 11.1992                                |
| 140     | 11.5941                                |
Figure 5. Tool workpiece surface selected for applying the film condition

Table 5. Film coefficient applied in the workpiece/tool interfaces

| Temperature ºC | Film coefficient W m⁻² K⁻¹ (Tool/ workpiece interfaces) |
|---------------|----------------------------------------------------------|
| 25            | 0                                                        |
| 40            | 10.5586                                                  |
| 60            | 12.7871                                                  |
| 80            | 14.0561                                                  |
| 100           | 14.9705                                                  |
| 120           | 15.6478                                                  |
| 140           | 16.1996                                                  |
| 160           | 16.6831                                                  |
| 180           | 17.0452                                                  |
| 200           | 17.3705                                                  |
| 250           | 18.0145                                                  |
| 300           | 18.5368                                                  |
| 350           | 18.8524                                                  |
| 400           | 19.0939                                                  |
2.4. Mechanical Boundary Conditions
The plates portions were constrained in all directions (Figure 6). All of the bottom nodes are constrained in the perpendicular direction (z direction). Meanwhile, the loading of the FSW comprise of three primary phases (i.e. plunging, where the tool plunged slowly into the workpiece). Dwelling in which the friction between the workpiece and the rotating tool generates the heat. It can be defined as the starting tool position until the temperature of the workpiece shows the value required for the traverse velocity, where the rotating tool transfers along the weld seam. The temperature at the welding line region would rise during the traverse phase, however, the maximum temperature values did not exceed the workpiece melting point. Moreover, a solid continuous joint appeared between the plates as the temperature declined. Table 6 illustrates the modification details in each step.

![Figure 6. Mechanical boundary that are applied to the workpiece](image)

**Table 6.** Step modifications and definitions

| Step name Time period | Kind of step                     | Mass scaling type                                                                 | Quadratic viscosity parameter | bulk viscosity parameter |
|-----------------------|----------------------------------|----------------------------------------------------------------------------------|-------------------------------|-------------------------|
| Plunging (8)          | Dynamic Temperature-displacement, Explicit | Semi-automatic, Target time increment (scale: 0.0001)                             | 1.2                           | 0.06                    |
| Welding (12.5)        | Dynamic Temperature-displacement, Explicit | Use scaled mass and throughout step definition from the previous step             | 1.2                           | 0.06                    |
| Plunging out (4)      | Dynamic Temperature-displacement, Explicit | Use scaled mass and throughout step definition from the previous step             | 1.2                           | 0.06                    |

2.5. Material Model and Properties
The study had chosen an Aluminum alloy AA6061-T6 as the workpiece material. The strain hardening, the strain rate hardening and the temperature softening material law (Johnson-Cook) is used to model the behavior of the material.
\[ \sigma_p = [A + B(\varepsilon_p)^n] \left[ 1 + C \left( \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right)^m \right] \left( 1 - \frac{T_{FSW} - T_{room}}{T_{melt} - T_{room}} \right)^m \]  

(1)

Based on the elastic-plastic Johnson-Cook material model, \( \varepsilon_p, \dot{\varepsilon}_p \) and \( \dot{\varepsilon}_0 \) represent the effective plastic strain, the effective plastic strain rate and the normalizing strain rate, respectively. Table 7 explains the input parameters for Johnson-Cook model.

| Parameter                          | Value  |
|-----------------------------------|--------|
| Yield stress (A)                  | 546    |
| Strain factor (B)                 | 678    |
| Strain exponent (n)               | 0.71   |
| Strain rate factor (C)            | 0.024  |
| Room temperature \( T_{room} \) (°C) | 25     |
| Temperature exponent (m)          | 1.56   |
| Melting temperature \( T_{melt} \) (°C) | 582    |

2.6. Finite Element Techniques

The model presented in this study used the Arbitrary Lagrangian – Eulerian (ALE) adaptive meshing. In general, it would control the mesh distortion when large deformation occurs. As the process involved analyses such as geometric nonlinearities, thus, it is expected that at high welding rotational speeds, the model would undergo large deformations. ALE is defined as a mixture of Eulerian in which the nodes remain fixed in space and the material flows through the elements, and Lagrangian in which the node motion is similar to the material motion [32]. Adaptive meshing is used for the welding seam, due to the significance of the area while the tool is modelled as a rigid body, because it is not expected to face large deformations. In order to optimize the position of the node at the plunging step, the study has set the adaptive meshing frequency of 3 after each increment, and each adaptive meshing comprises of 15 mesh sweeps. Whereas, in the welding step the values were increased to 5 and 50, respectively. In addition, mass scaling was defined in the analysis, because when the explicit central difference method is used for integrating the equations in time, the mass matrix employed for the equilibrium equations has a significant role in both the accuracy and the computational efficiency of the model. Moreover, because of the dynamic nature of the FSW process and the importance of the natural time scale, the rate-dependent properties of the workpiece material need to be used. Several trial runs had shown that in comparison to the workpiece, the geometry of the pin caused it to contain very small elements which leads to have stable time increments substantially lower than the average, resulting to a very small-time increment for the whole model. To overcome this issue, a constant time increment, equal to 0.0001 sec was specified for the whole model, at the beginning of the step (fixed mass scaling).

3. RESULTS AND DISCUSSION

First of all, a model without the ALE modification was simulated to investigate the influence of the ALE method on the final results. It was found that after studying the temperature field, the model was aborted. Figure 7 shows the result of the model in which the pure Lagrangian mesh is employed for the entire workpiece structure. It was observed that after the plunging step (after the step time of 8), there is an irregular temperature pattern indicating that the model cannot be sufficiently accurate for temperature modelling. Moreover, the Figure indicates that the temperature had spiked to 580 °C which seems to be unrealistic for the model according to the literature, because the melting point for aluminum 6061-T6 is around 580 °C which will never be achieved during FSW [33]. Therefore, the model without the ALE modifications presents an inaccurate model.
Figure 8, Figure 9 and Figure 10 illustrate that compared to the upper surface the temperature is significantly lower at the mid-thickness of workpiece and the temperature rapidly declines across the plate thickness. Moreover, a higher temperature at the top surface is observed, because the tool shoulder produced most of the heat and the conduction at the workpiece bottom surface of the workpiece that are in contact with the backing plate and the clamp is relatively higher. Therefore, the created temperature at the bottom surface is significantly lower. The temperature is also observed more intense at the retreating side, which leads to the high plastic dissipation at the advancing side. This issue also affects the behavior of the plastic deformation and also produces better fluidity at the advancing side. Therefore, as shown in Figure 11, Figure 12 and Figure 13, there is an asymmetrical temperature contour between the retreating and the advancing side. It is also observed that, the temperature goes up rapidly when the tool penetrates inside the workpiece, while the temperature behavior starts to fluctuate as the tool moves through the welding seam. This issue happens because, the shear friction factor is negatively correlated with the temperature and the variation of the friction heat affects the temperature. To clarify the point, the action of the shear friction force caused the deformation of the materials from the advancing side to the retreating side.

It should be noted that, the cavity caused by the welding transverse speed is filled by the rotation movement of the materials to the retreating side. It is also observed that, the plasticized material around the tool rotates together with the tool head.
Figure 8. Cross section during constant rotational velocity of 800 RPM
a) 40 mm/min, b) 70 mm/min and c) 100 mm/min
Figure 9. Cross section during constant rotational velocity of 1200 RPM
a) 40mm/min, b) 70 mm/min and c) 100 mm/min
Figure 10. Cross section during constant rotational velocity of 1600 RPM
a) 40mm/min, b) 70 mm/min and c) 100 mm/min
Furthermore, a "V" shape temperature gradient was observed at the cross section of the weld. This indicates the presence of a high-intensity heat flow at the interface layer between the workpiece and the tool shoulder. The "V" pattern is also formed due to the larger diameter of the shoulder in comparison to the pin. This difference leads to higher heat generation on the upper surface than the bottom. Meanwhile, the convection heat transfer between the top surface of the workpiece and the atmosphere is smaller in comparison to the convection heat at the bottom surface to the backing plate. Consequently, the mentioned discrepancy between the coefficient of the convective heat transfer caused the formation of the "V" shaped temperature pattern. The results also illustrate that the process rapidly reaches to a steady state condition as the tool laterally moves to join the plates together.

**Figure 11.** Top surface view for the welding during the constant rotational speed of 800 RPM
a) 40mm/min, b) 70 mm/min and c) 100 mm/min
Figure 12. Top surface view for the welding during the constant rotational speed of 1200 RPM
a) 40mm/min, b) 70 mm/min and c) 100 mm/min
Figure 13. Top surface view for the welding during the constant rotational speed of 1600 RPM a) 40mm/min, b) 70 mm/min and c) 100 mm/min

Table 8 indicates the validation of the peak temperature distribution for different process parameters between experiments and numerical simulation. As observed, a higher temperature was obtained at higher tool rotational speeds due to the higher friction heating, and more intense mixing and stirring of the material. Furthermore, it should be mentioned that the frictional coupling of the tool surface and the workpiece is governed the generation of the heat.

| Process Parameter | EXP (ºC) | FEM (ºC) |
|-------------------|----------|----------|
| 800 RPM-40 MM/Min | 295.828  | 301.267  |
| 1200 RPM-40 MM/Min| 304.592  | 305.529  |
As observed, at the transverse velocity of 40 mm/min with the rise of the rotational velocity an increase in the temperature occurs. This caused by the increase in plastic dissipation and strain rate in the stir zone. A change in the temperature is observed when the rotational velocity is increased from 800 RPM to 1200 RPM around 8.7 ºC, this rise continues as the welding speed increased to 1600 RPM (around 60 ºC). The similar behavior for the temperature is observed for the transverse speeds of 70 mm/min and 100 mm/min.

The variation of transverse speed is also affected the work piece temperature profile as illustrated in the Table 8. The results show that the increase in the transverse speed would radically decrease the temperature at the stir zone. A significant variation was also detected in the thermal behavior, where the maximum temperature of 357.146 ºC is obtained at the transverse velocity of 40 mm/min and the rotational velocity of 1600 RPM. This finding is in-consistent with what reported by other studies [1, 15, 34, 35]. Moreover, certain amount of heat is required to plasticize the material in FSW that allows enough material mixing for achieving a high-quality weld. As mentioned, the frictional heat between the workpiece and the tool would cause heat generation in FSW. In addition, plastic deformation of the material depends on the contact area and the shear friction factor. It is also notable that, during the simulation, large deformation of the material normally happens on those elements that are located adjacent to the tool. Since the decrease of the particular element length, increase the simulation time, the decline in the mass can inherently decrease the computational costs of the analysis.

### 4. CONCLUSIONS

This study had developed a three-dimensional finite element analysis of FSW including the investigation of the temperature evolution and thermal behavior of AA-6061-T6 alloy. The study is validated by the experimental values reported in the published results. As a result of the adoption of the ALE technique, there is a narrow gap between the experimental measurements and the numerical results. Based on the results obtained from the workpiece cross-section, taken at different rotational speed ratio, it was observed that a large proportion of the heat was generated by the shoulder. Furthermore, the FSW process achieved the temperature between 60% to 90% of the aluminum alloy melting temperature. It was observed that, temperature changes are highly influenced by the rotational speeds and welding transverse. As the rotational speed increased, the joint maximum temperature was also increased to 365.044 ºC at the rotational velocity of 1600 RPM and the transverse velocity of 40 mm/min. Conversely, the welding temperature was decreased as the transverse speed increased.

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| RPM | Transverse | Temperature |
|-----|-------------|-------------|
| 1600 | 40 MM/Min   | 357.146     | 365.044     |
| 800  | 70 MM/Min   | 285.366     | 287.57      |
| 1200 | 70 MM/Min   | 295.828     | 290.034     |
| 1600 | 70 MM/Min   | 338.173     | 344.461     |
| 800  | 100 MM/Min  | 247.956     | 248.565     |
| 1200 | 100 MM/Min  | 296.551     | 288.301     |
| 1600 | 100 MM/Min  | 308.893     | 318.005     |
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