



Article

# **Investigating the Welding Parameters in Friction Stir Welding of Yellow Brass 405-20**

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**Abstract:** This research presents the numerical and empirical efforts to investigate the effect of friction stir welding (FSW) parameters on the weld temperature, weld strength, and weld hardness for novel brass known as yellow brass 405-20. The numerical approaches used to measure the weld temperature and weld strength were studied for the first time for yellow brass 405-20 and their validations via empirical studies. Two numerical models were simulated including transient thermal analysis and static structural analysis. Thermal distribution leading to maximum weld temperature during FSW of yellow brass was investigated via both simulations and experiments. Moreover, the ultimate tensile strength, namely the weld strength, was measured numerically and validated from its empirical counterpart. Finally, weld hardness was measured empirically to explore the joint health. A maximum temperature of 598 °C was recorded, which was much below the melting point of brass. Joint strength of 228 MPa was observed, which is 83% of the base brass strength. Microscopic examination of the weldment revealed the underlying mechanisms of less weld strength as compared to the parent brass material strength.

Keywords: friction stir welding; brass; simulations; hardness; ultimate tensile strength; thermal distribution



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# 1. Introduction

Friction stir welding (FSW) is an eco-friendly and solid-state joining technology. Due to this reason, industries are keenly adopting this joining process in various applications, e.g., automobile, aerospace, marine, etc. Several materials have already been welded by FSW including aluminum, copper, steel, alloys of these materials, plastics, and composites. Friction stir welding is a famous joining technique in industry and research laboratories due to its various advantages, e.g., it is fumeless, the external medium melts less due to its solid-state nature, no protective equipment is required, etc. [1,2]. FSW was first used for aluminum and its alloys at the Welding Institute of the United Kingdom and patented by Thomas et al. in 1991 [3]. Now, it has become a state-of-the-art technique that is used to weld various other materials, e.g., steel, magnesium, copper, plastics, composites, and dissimilar materials [4].

To determine the effect of FSW factors (FSWFs), a few trial experiments with different combinations of FSW factors are usually conducted under the guidance of the most relevant literature. Sometimes, trial experiments seem essential in the absence of background knowledge when a research study is not found before in a particular field. In this context, numerical studies play an exceptional role in minimizing the cost and time required for trial experiments. For example, Memon et al. [5] performed thermal simulations towards

evaluating the suitability of weld factors, which may lead to very few trial experiments to validate the evaluation of weld factors' appropriateness.

Memon et al. [5] developed a new numerical approach based on computational fluid dynamics (CFD) to comprehend the mixing flow of materials during FSW. They strived to establish a link between the mixing materials and bonding of materials before and after FSW, respectively. Although the authors have provided the research community with a novel idea of applying CFD on FSW of Al-Mg-Si alloy T-joints, a numerical study based on CFD was not validated using appropriate empirical methods. Jia et al. [6] also described that joint microstructure and mechanical properties are the strong functions of both thermal processes and material flow, as they perceive the FSW process in terms of a complex interaction of thermal, mechanical, and geometrical effects. They found that the phenomenon of dynamic recrystallization is more available on the advancing side with tiny void defects. Another CFD study was conducted by Yang et al. [7] on aluminum material with an introduction of mechanical anisotropies in the material in terms of grain shape, grain orientation, and grain texture. The prediction was found accurate on the joint morphology. Other CFD studies were carried out by Yang et al. [8], Yang et al. [9], and Xiaoqing et al. [10] providing brief guidance about modeling the heat source development during FSW as a function of probe geometry, tool-workpiece interaction, affecting the FSW of dissimilar metal alloys when ultrasonic assisted FSW (UAFSW) is used, and affecting the overall welding of materials as a function of the stationary shoulder of tool, respectively.

Therefore, numerical studies may be divided into two types, namely computational solid mechanics (CSM) and CFD. Computational solid mechanics of welded joints is a better technique than computational fluid mechanics (as CFD has an emphasis on material flow only), e.g., to check the effect of introducing mechanical anisotropies in materials to be joined. Moreover, the flow of materials like fluids is not possible in FSW, since the melting of solid materials has never happened in FSW, which is a solid-state welding technique. Hence, prediction trials involving computational solid mechanics must proceed with more focus on brass materials instead of other materials such as aluminum materials. In other words, a transient thermal model using finite element analysis (FEA) is needed in the domain of CSM.

Many researchers have worked on mathematical modeling that involves an artificial neural network (ANN) model. This is a non-FEA numerical study, focusing mainly on the optimization of the FSW factor for metal alloys without considering the thermal distribution at the welded joint.

Alkayem et al. [11] established a relationship between FSW factors and the mechanical properties of aluminum alloy using an ANN model. The ANN model was employed to find the optimal FSW factors towards attaining a quality weld with both differential evolution for multi-objective (DEMO) and non-dominated sorting genetic algorithm-II (NSGA-II). The ANN DEMO was finally found to better deliver the optimal FSW factors more efficiently and effectively. Another ANN modeling approach was accomplished by Gupta et al. [12] for FSW of dissimilar AA5083-O and AA6063-T6 aluminum alloys. Design of experiments (DOE) based on four FSW factors, i.e., tool rotation speed, welding speed, shoulder diameter, and pin diameter, was executed using Taguchi's L27 OA. Joint efficiency was determined with three response parameters, which were tensile strength, micro-hardness, and grain size. A hybrid approach of the ANN mathematical model and GA was utilized to find the optimal FSW factors. A validation experiment promised a great improvement in the FSW process. Medhi et al. [13] also determined the optimal FSW factors using a hybridized approach of NSGA-II and TOPSIS. Weld quality was then determined with the corresponding mathematical model based on the ANN model. The fitness function for the NSGA-II technique was found employing the same ANN mathematical model.

FSW optimizations were further conducted using techniques other than ANN. For instance, Kundu and Singh [14] conducted an optimization study of using FSW to weld AA5083-H321 aluminum alloy. A Taguchi-based GRA technique was established to determine the solution of the corresponding multi-objective optimization problem. Pitchipoo

et al. [15] offered another way of optimizing the FSW factors for aluminum alloy by applying a multi-objective optimization technique based on the dragonfly algorithm (DFA). Rathinasuriyan and Kumar [16] presented the optimization of submerged FSW of 6061-T6 aluminum alloy. The RSM technique was used to develop the mathematical model, and optimal FSW factors were finally determined using the GRA application. Senthil et al. [17] again used the RSM-based DF approach to provide researchers with a solution to the multi-objective optimization problem regarding FSW of AA6060-T6 aluminum alloy pipes. Tamjidy et al. [18] studied the FSW of dissimilar welded joints to characterize their mechanical properties. FSWFs including tool rotational speed, tool traverse speed, tilt angle, and tool offset were set to determine their impact on characterizing the mechanical properties of the joint. Optimal FSWFs were later achieved using a mathematical modeling approach to characterize mechanical properties and a multi-objective optimization algorithm based on the biogeography optimization technique.

Zhou et al. [19] studied the effect of a rotational speed of 1200 rev/min and welding speed of 200 mm/min on 5 mm-thick AA6061-T6 aluminum welded joints using dual rotation FSW. The microstructure of the joints was enormously improved, and fracture occurred at the thermomechanically affected zone (TMAZ) and heat affected zone (HAZ) in a ductile fashion. The maximum tensile strength achieved was 215 MPa at 400 rev/min. Sathish et al. [20] studied the weldability of aluminum 8006 with the reinforcement of zirconia particles. The idea of zirconia reinforcement was to improve the weld quality with optimal levels of FSWFs. The maximum tensile strength was found to be 284 MPa with improved microhardness of 156 HV at a rotational speed of 1100 rev/min. Alam and Sinha [21] optimized the FSWFs using ANOVA and regression analysis when welding Al-Li alloy, which is widely used in the aerospace industry. Rotational speed, traverse speed, tool pin profile, and welding preheating conditions were optimized to maximize the tensile strength and minimize the tool wear rate. Optimum FSWFs were rotational speed 1500 rpm, welding speed 90 mm/min, tool profile cylindrical, and welding condition (80 °C preheated) at 5.32 and 1.65% to improve tensile strength and tool wear rate. Prabhu et al. [22] welded AA6061/TiO<sub>2</sub> composites using the FSW process. Their main emphasis remained on finding the relationships between response parameters that comprise hardness, yield strength, ultimate tensile strength (UTS), and FSWFs. They used the response surface methodology for relating the input variables and output responses. The appropriateness of models was investigated by ANOVA. They also used the teaching-learning based optimization (TLBO) algorithm to attain the optimal levels of FSWF, leading to a welded joint with satisfactory mechanical properties. An FSW joint with UTS of 174 MPa, yield strength of 120 MPa, and hardness of 126HV was achieved by using TLBO. There was also a close agreement between TLBO and experimental results. Kahhal et al. [23] performed a multi-objective optimization of AA1050 A-H12 aluminum alloy using the response surface methodology together with a swarm optimization algorithm.

However, a research gap still exists, motivating the researchers to perform a thermal numerical study based on FEA to investigate the effect of FSW factors on the thermal distribution at the welded joint and joint strength. The FSWFs utilized were tool pin geometry, rotational speed, welding speed, tool tilt angle, and shoulder diameter. The output responses included the hardness, yield strength, fracture strain, and impact toughness on both advancing and retreating sides. The yield strength and hardness reached their maximum values when keeping the rotational speed lower and the welding speed higher.

Likewise, Kumar et al. [24] optimized FSWFs that consisted of setting rotational speed, axial force, tool tilt angle, and tapered pin tool pin profile. An extensive empirical optimization study was conducted towards joining AA6061 and AA7075 dissimilar aluminum alloys to enhance the joint quality in terms of its hardness, tensile, and impact strengths. The Taguchi DOE was employed in this study. Rotational speed and tilt angle of the FSW tool were found to be the most significant FSWFs. Rajesh et al. [25] joined aluminum alloys and ceramics-reinforced aluminum composites using the FSW process. Alumina and silicon carbide were used as ceramic reinforcements. The UTS was optimized using

Appl. Sci. **2023**, 13, 2433 4 of 23

weighted aggregated sum product assessment (WASPAS). A UTS of AA1000 alloy and AA6061 5% alumina was found to be the highest. Of the WASPAS optimization techniques, AA6061 5% alumina and AA1100 5% alumina were ranked as the best in terms of corrosion resistance. Sasikala et al. [26] optimized different combinations of Al-Cu alloys using the Taguchi method to maximize again the UTS. Among the results, a spindle speed of 700 rpm, a transverse speed of 15 mm/min, and D/d ratio of 3 were found as the optimal levels of FSWF. Bhushan and Sharma [27] optimized aluminum matrix composites (AMCs) with ceramic reinforcement of silicon carbide and silicon nitride. The objective function of the optimization was to maximize the hardness of AMCs. The results showed that optimal FSWF resulted in maximum hardnesses for both composites. However, the hardness of SiC-reinforced AMCs was higher than that of Si3N4-reinforced AMCs.

Mishin et al. [28] presented the idea of performing thermal analysis numerically as well as experimentally with aluminum alloys. In their study, weld temperatures and thermal strains were measured while welding aluminum as a function of FSW factors. Although numerical and empirical results agreed, aluminum was again used, which should be replaced with a novel material such as brass. In a similar study on aluminum alloy, Essa et al. [29] found the numerical effect of an eccentric cylindrical pin on heat development during FSW. Though thermal simulation was in good agreement with that of the experimental work, the same approach may be used for brass to see whether there still exists a good agreement between numerical and empirical results.

Brass is an alloy of copper and zinc. Brass properties are determined from the careful configuration of the percentage of copper and percentage of zinc. It is widely used as an engineering and industrial material due to its various striking properties, such as high strength, high corrosion resistance, and high electrical and thermal conductivities. Brass may easily be formed when processing and it is nice looking before and after processing. Brass presents difficulties when it is subjected to fusion welding since the melting of brass usually involves the evaporation of zinc. Hence, novel joining processes should be employed which do not cause melting and the brass remains in its solid state during and after welding. FSW may be used to weld brass, keeping in mind that brass must not be melted. Only one research paper was found in the past five years on the FSW of brass, showing the very limited research efforts towards joining brasses, and it could become part of a great body of literature on FSW over the last decade. For example, Xu et al. [30] successfully welded 2 mm-thick brass plates using FSW subjected to rapid cooling. When comparing the improvements in the yield strength and the UTS for conventional FSW, the rapidly cooled FSW showed an improvement of up to 31 and 24%, respectively. Although a group of researchers has finally broken the non-welding silence on brass, no numerical efforts are evident focusing on the FSW of brass as a solid function of FSW factors.

Heidarzadeh et al. [31] reported the formation of defects in their study on the microstructure of 63/37 brass. They employed an optical microscope, scanning electron microscope (SEM), and scanning transmission electron microscope (STEM) to study the microstructure of brass under investigation. It was revealed that the alpha grains resulted in dynamic recrystallization (DR) after FSW. However, the beta phase split between the alpha grains without DR. Liu et al. [32] joined AA6061-T6 aluminum sheets of 0.8 mm thickness using high-speed FSW with rotational speed equal to 8000 rev/min and welding speeds of 300–1200 mm/min. Grain refinement was achieved under these levels of FSWFs settings, as compared to the conventional FSW. However, Mg<sub>2</sub>Si, Al<sub>8</sub>Fe<sub>2</sub>Si, and Al<sub>2</sub>CuMg precipitated and re-precipitated in the weld nugget, resulting in lessening the weld softening and brittle fracture of welded joints. Although researchers have made their best efforts to reveal various phenomena that are happening at the weld zone, a thorough understanding of microstructural phenomena has not been extensively revealed for brass materials.

From the literature review, it is quite evident that very few researchers have currently focused on welding brass via FSW. Researchers have looked at FSW using various materials and process parameters. They have done substantial numerical and empirical studies. Many

Appl. Sci. **2023**, 13, 2433 5 of 23

numerical studies were experimentally validated for various materials other than brass. Most of the researchers used non-standardized samples too. Temperature distributions during welding and their predictions through numerical studies are extremely important, since these give both excellent indications of the effect of FSW weld factors on the thermal changes and assurance of temperature reach, i.e., it must remain below the melting point of the material under consideration. In this context, researchers have already validated temperatures via k-type thermocouples. Therefore, thee aim of this study was to perform numerical studies for FSW of brass with their proper validation for thermal distribution at HAZ using a thermal imager that is more reliable than k-type thermocouples. In many engineering applications such as structures, bridges, joined structures, etc., predictions of both strength and temperatures are usually important where welding processes are extensively used. This was another motivation for us to conduct numerical studies for joint strength with their proper validations. Numerical and empirical investigations pertinent to friction stir welding of brass 405-20 joint strength and thermal distributions have never been carried out. In fact, the thermos-mechanical couple field numerical analysis was conducted in this study along with its validation. Moreover, the hardness of the welding joint of novel brass was also studied in this research.

#### 2. Materials and Methods

Materials and methods for the FSW process can be divided into two categories to make it more eloquent. One is relevant to simulation work known as numerical FSW and the second is relevant to experimental investigation known as empirical FSW. These two categories are further equally divided into three subcategories named preprocessing, processing, and postprocessing. A hierarchical diagram of the research methodology for numerical as well as experimental studies is shown in Figure 1.

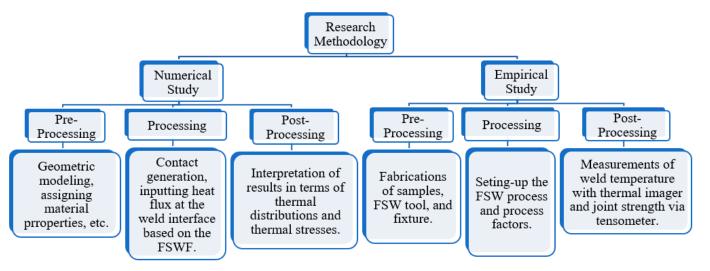


Figure 1. Research methodology for numerical and empirical studies.

## 2.1. Numerical FSW

In this category of materials and methods, simulation work completed and investigated is presented regarding FSW of brass with the following subcategories:

In the preprocessing step of the numerical study, two finite element analyses (FEAs) were performed, namely transient thermal and static structural analysis in Ansys Workbench 19.2. Moreover, later FEA (FEA\_B), i.e., static structural, was coupled to the first FEA (FEA\_A), i.e., transient thermal. In other words, results from FEA\_A were input to FEA\_B. FEA\_A was used to predict the maximum temperatures at the joint interface whereas FEA\_B was utilized to determine the numerical shear stresses at the joint interface. Numerical shear stresses were assumed to be equal to the numerical shear strengths based on the shear strength definition, which is the capability of a material to withstand or resist

Appl. Sci. 2023, 13, 2433 6 of 23

the shear loads imposed on the heat affected area up to a certain maximum numerical value of shear stresses before failure.

Geometric modeling was conducted in SolidWorks software based on the American Society for Testing and Materials (ASTM) standard (E8/E8M-13a), as shown in Figure 2. The geometry was imported then to Ansys Workbench software. Brass material with its chemical composition and mechanical and thermal properties was assigned to the imported geometric model. For instance, Table 1 shows the chemical composition of novel brass material with copper and zinc, which share high percentages by volume. The mechanical properties of brass, including yield strength, ultimate tensile strength, Young's modulus, and hardness, are shown in Table 2. Likewise, the thermal properties of brass required for numerical work are shown in Table 3, comprising melting point, coefficient of thermal expansion, specific heat, thermal conductivity, and emissivity.

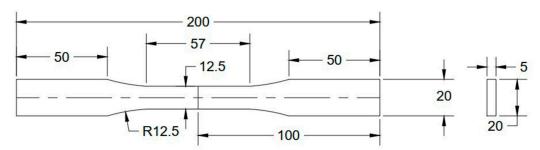


Figure 2. ASTM Standard (E8/E8M-13a) for weld specimen design (all dimensions are in mm).

**Table 1.** Chemical composition of brass.

Material	Cu	Zn	Pb	Sn
	Percentage (%)			
Brass 405-20	63.0	34.7	1.0	1.0

**Table 2.** Mechanical properties of brass.

Material	UTS (MPa)	Yield Strength (MPa)	Young's Modulus (GPa)	Hardness (HR-15N)	Elongation (%)
Brass 405-20	275	250	103	82 avg.	15

**Table 3.** Thermal properties of brass.

Material	Specific Heat (C)  J/kg °C	Thermal Conductivity (K) W/m °C	Coefficient of Thermal Expansion ( $\alpha$ ) ( $f^{\circ}$ C)	Density (ρ) Kg/m³	Emissivity (ε) (600 °C)	Melting Point (T <sub>m</sub> ) °C
Brass 405-20	380	119	$20.9 \times 10^{(-6)}$	8800	0.61	940

The meshing of the geometry was accomplished after the geometrical model was assigned with brass material properties, as mentioned in Tables 1–3. Moreover, mesh verification was completed with low, medium, and high quality of meshing. The maximum temperatures found for these three qualities of meshing were almost similar. For instance, the maximum temperature value was found to be 563.91 °C (after setting FSWF levels from Table 4) for DOE No. 4 of Table 5 for three mesh qualities. Hence, mesh quality was selected as medium levels.

Appl. Sci. **2023**, 13, 2433 7 of 23

Table 4. Factor levels for FSW of brass.

Weld Factors	Level 1	Level 2	Level 3
Rotational/Spindle Speed (rpm)	1600	1450	1300
Traverse/Welding Speed (mm/min)	60	50	40

Table 5. L-9 DOE based on full factorial method.

DOE. No	Rotational Speed (Revolution per min)	Traverse Speed (mm/min)	Revolutionary Pitch (Revolution per mm)
1	1600	60	26.67
2	1600	50	32.00
3	1600	40	40.00
4	1450	60	24.17
5	1450	50	29.00
6	1450	40	36.25
7	1300	60	21.67
8	1300	50	26.00
9	1300	40	32.50

The preprocessing details of the first FEA, i.e., FEA\_A, finishes here. All three steps are explained for the second FEA, i.e., FEA\_B. Temperature distribution at the joint interface was aimed to be found resulting from heat estimates for FSW. The temperature distribution results were then coupled to static structural analysis where the thermal results were imported to the processing setup of static structural analysis, as can be seen in Figure S1 of the supplementary information file. The geometry, meshing, and connections were kept the same for both FEA\_A and FEA\_B. This FEA\_B was performed to find the stresses developed at the joint interface due to temperature variations that result in thermal expansions/contractions. The fundamental mathematical expression for these stresses due to thermal loads is detailed in Equations (1)–(3) [33].

$$\delta_{\rm T} = \alpha \times L \times \Delta T \tag{1}$$

where  $\delta_T$  is the change in length due to the temperature variations (mm),  $\alpha$  is the coefficient of thermal expansion (/°C), L is the original length (mm), and  $\Delta T$  is the change in temperature (°C).

$$\varepsilon_{\rm T} = \alpha \times \Delta T$$
 (2)

where  $\varepsilon_{\rm T}$  represents the thermal strains

$$\sigma_{\rm T} = {\rm E} \times \varepsilon_{\rm T} \tag{3}$$

where  $\sigma_T$  stands for the thermal stresses and E is known as Young's modulus.

The processing phase of simulation is also called the solution of the steps that are executed after the preprocessing phase. In this phase of simulations, the initial temperature was assigned to be equal to room/ambient temperature for all the nodes and elements. Additionally, the time-dependent load in the form of heat flux, as calculated from Equation (5) [34], was applied at the joint interface by dividing it into time steps that were further based on the combination of factor levels from each DOE from 1 to 9. Contact status was defined as bonded contact in the connection's definitions of preprocessing phase of Ansys.

Equation (4) [35] is the governing differential equation for calculating temperature numerically.

$$k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} + k \frac{\partial^2 T}{\partial z^2} + Q - \rho c \frac{\partial T}{\partial t} = 0$$
 (4)

Appl. Sci. 2023, 13, 2433 8 of 23

where T is temperature,  $^{\circ}$ C (to be determined by solving Equation (4)), K is isotropic thermal conductivity, W/m.  $^{\circ}$ C,  $\rho$  is density, Kg/m³, c is specific heat capacity, J/Kg.  $^{\circ}$ C, and Q is the volumetric heat generation rate, W/m³  $^{\circ}$ C.

Volumetric heat generation rate (Q) was given as an input heat flux at the joint interface in the FEA simulation to predict the temperature at HAZ. Average power generation (q) during friction stir welding can be calculated by Equation (5) and heat flux per unit area (Q) was calculated by Equation (6) [34].

$$q = 2\pi \times k \times \omega \times Rs^3/3 \tag{5}$$

where k is the yield stress of brass (MPa),  $\omega$  is rotational speed (rad/s), and  $R_S$  is the shoulder radius.

$$Q = \frac{3 \times q \times Rs}{2\pi \times (Rs^3 - Rp^3)}$$
 (6)

where q is average power generation and R<sub>P</sub> is pin radius.

Moreover, when putting q in Equation (6), we obtain a relationship for heat flux per unit area that is shown in Equation (7) [34].

$$Q = \frac{k \times \omega \times Rs^4}{Rs^3 - Rp^3} \tag{7}$$

Since Equation (7) considers only the heat flux for its conduction at the solid interface of FSW joint areas, heat losses due to convection from the solid areas into the environment or air were calculated using the fundamental equation of convection heat flow, as shown in Equation (8) [36].

$$Q_{convection} = h \times (Ts - Ta)$$
 (8)

where h is film coefficient, Ts = surface temperature at the weld interface, and Ta is air/ambient temperature.

Moreover, the surface temperature at the weld interface was measured using transient thermal analysis and validated with the utilization of the thermal imager supplied by the Testo company, as shown in Figure S5. The value of emissivity is 0.61, which was assigned to the thermal imager as a potential input. After assigning the emissivity value, the thermal images were taken for the calculation of surface/weld zone temperatures and the film coefficient (h) was calculated by making Q from Equation (7) equal to  $Q_{convection}$  from Equation (8). A proper working distance of 3 feet was maintained between the thermal imager and FSW setup. All the thermal images were taken by maintaining the same distance of the thermal imager from the FSW setup.

Q<sub>convection</sub> calculated previously was subtracted from the heat generated from Equation (7). The final heat calculated was given as heat flux load at the weld interface area in the form of time steps. The total number of steps and step end time were defined for the transient thermal analysis. These time steps were again based on the weld factor levels for each DOE, as shown in Table 5. Convection heat transfer was activated with the definition of film coefficient and room temperature. Therefore, processing requirements were completed at this stage. After this, the defined thermal transient system was solved under the influence of geometrical, boundary, and loading conditions.

Additionally, the geometry of ASTM specimens was fixed at its boundaries to restrict it to remain stationary during FSW, as shown in Figure 3, for the fixture. Thermal outputs from FEA\_A were imported from FEA\_A to FEA\_B to fully set up the FEA\_B. The FEA\_B was now solved to find numerically the weld strength of brass.

Moreover, the elemental formulation for heat transfer in general FEA settings (Equations (9)–(13)) [37] can be described as follows in Figure 4, which represents a thermal

Appl. Sci. 2023, 13, 2433 9 of 23

element that has two nodes, i and i + 1. Therefore, the heat is transferred from the high region (node i) to the low temperature region (node i + 1).

$$Q = U \times A \times (T_{i+1} - T_i)$$
(9)

where Q is the heat transfer rate  $(W/m^3)$ , A is the area of thermal gradients, and U is the thermal transmittance coefficient or U-factor that is defined as the thermal transmission through a unit area. Conduction and convection modes of heat transfer may easily be addressed by the U-factor:

U = K/l (for conduction)

U = h (for convection)

where K is thermal conductivity, l is the length of the element, and h is the film coefficient.

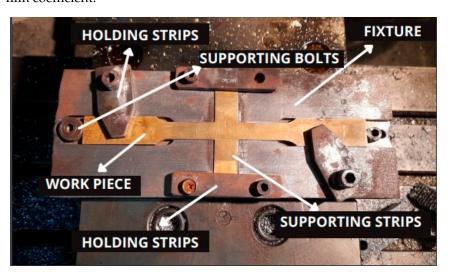


Figure 3. Fixture holding the specimen for FSW.



Figure 4. Finite element with two end notes.

According to the law of conservation of energy, heat generation from FSW due to conduction must be equal to the heat loss to the surroundings by convection. Considering the two end nodes of the finite element shown in Figure 4, the summation of heat generation and heat loss must be zero.

$$Q_i = Q_{i+1} \tag{10}$$

Heat flow matrix may be found as follows

where  $[K]^e$  = thermal conductance matrix/thermal convection matrix

$$[Q] = [K]e \times [T] \tag{12}$$

where [Q] is the heat flow matrix,  $[K]^e$  is the elemental heat transfer matrix via conduction or convection, and [T] is the temperature matrix.

Appl. Sci. 2023, 13, 2433 10 of 23

As we are interested in finding the highest weld temperature at the HAZ by inputting the heat flux (Q), Equation (12) may be rewritten as follows

$$[T] = [[K]e]^{-1} \times [Q]$$
 (13)

In the postprocessing step, the maximum temperature was then found numerically for empirical validation from FEA\_A, as shown in Figure 5. Shear strengths were also measured numerically from FEA\_B where maximum shear stresses were accounted for in the weld strength of the FSW weld, as shown in Figure 6.

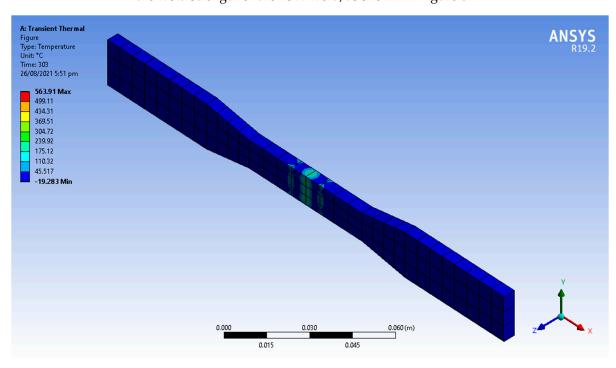


Figure 5. Numerical results showing maximum and minimum temperatures.

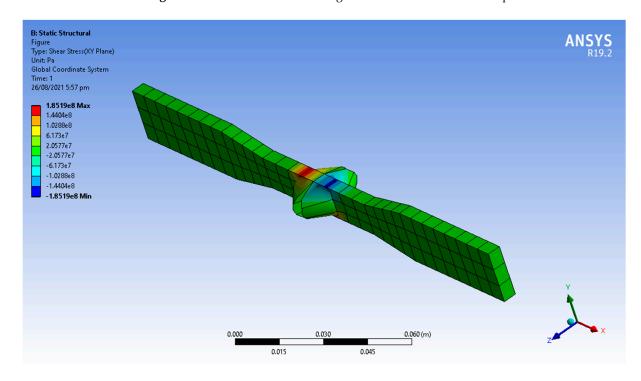
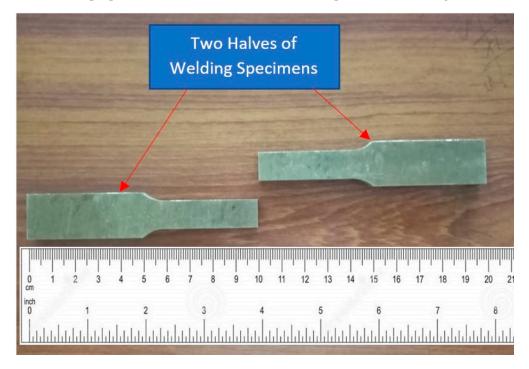


Figure 6. Numerical results showing maximum and minimum shear strengths.

Appl. Sci. 2023, 13, 2433 11 of 23

#### 2.2. Empirical FSW

In this empirical study of materials and methods, a detailed experimental investigation is elaborated considering the FSW of brass. Yellow brass 405-20 is an alloy of copper 63%, zinc 34.7%, and a trace percentage of lead and tin. This alloy has good corrosion properties. In the preprocessing step of the empirical study, novel yellow brass rectangular plates having  $250 \times 200$  mm dimensions were purchased as raw materials. These brass plates were later used to prepare specimens as per ASTM standards. Specimens were manufactured in two halves according to ASTM standard E8/E8M-13a, as shown in Figure 7. Wire electric discharge machining (EDM) was used to fabricate the samples. Filing and emery tapes were used to prepare the surfaces of the fabricated samples before welding.



**Figure 7.** Specimens manufactured as per ASTM Standard E8/E8M-13a in two halves.

Molybdenum high-speed tool steel (M2 HSS) was used as tool material. M2 HSS includes 5–9.5% molybdenum, about 4% chromium, 1.5–6.5% tungsten, and smaller amounts of vanadium. This tool steel is almost similar in properties to those of the H20 to H26 steels, with the economic advantage of the lower initial cost. Among those properties, this steel has increased resistance to thermal fatigue, i.e., resistance to high-temperature softening over an extended period of time. Therefore, this tool material was deemed appropriate for FSW of brass and even other materials.

M2 HSS was purchased in the form of cylindrical rods. These rods were then turned on a conventional lathe machine with operations for cutting off, facing, and turning to generate the shoulder diameter and pin diameter, as shown in Figure 8.

A fixture was also designed and manufactured on a conventional machining center to hold the specimens so that specimens would not be allowed to move in x, y, and z directions, as shown in Figure 3.

The processing phase of empirical FSW was accomplished on a computer numerically controlled (CNC) machining center. A general FSW process is shown in Figure 9 and a customized FSW setup using a CNC machining center is depicted in Figure S4. A CNC program was written with spindle speed function (S) to account for the rotational speed of the FSW tool. Feed function (F) was also specified in the CNC program for the traverse speed of the FSW tool. Therefore, three levels of rotational and traverse speeds were employed, as shown in Table 4, to investigate their impact on response parameters and deduce optimal combinations for response parameters. The range of variability of the

FSW factors in Table 4 was partly taken from the FSW past studies on copper and its alloys (because brass is an alloy of copper and due to the unavailability of FSW studies on brass in the current context) and partly from the experimental trials at initial stages of the current study. The penetration depth of the FSW tool pin was also mentioned in the program by specifying its value in the z-axis. In the same way, nine experiments were conducted with amendments in values of S and F of the CNC program as per the design of experiments (DOE) based on the full factorial method and factor levels, as shown in Table 5. Furthermore, the revolutionary pitch was also computed, which can be defined as a ratio of rpm and mm/min, as shown in the last column of Table 5.

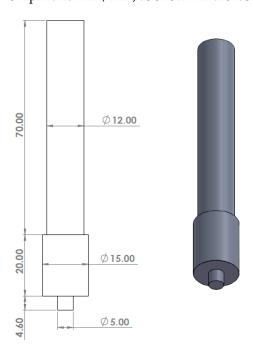
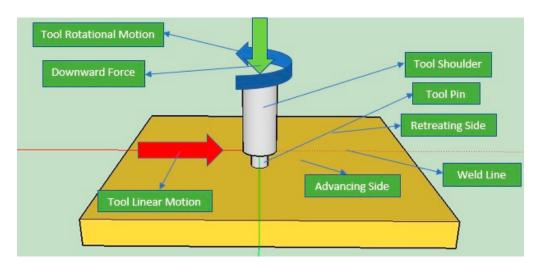


Figure 8. FSW tools' geometry (all dimensions are in mm).



**Figure 9.** Friction stir welding.

Moreover, a thermal imager supplied by Testo with model number 868 was also used while welding brass specimens to measure the temperature at various locations of the weld line, as shown in Figure S6 of the supplementary information file. In addition, three specimens were repeated for each welding experiment to measure weld temperature, which was finally averaged. This model of the imager was excellent in measuring not only the maximum temperature during FSW but also the numerous values of temperatures at any

location HAZ. Since researchers use k-type thermocouples for measuring the temperature at one point of the weld zone, which is not only time-consuming but also does not provide an opportunity to measure the joint strength and hardness due to the embedment of tiny thermocouple wires at HAZ, a thermal imager seems competent in resolving the time and effort issues during welding. Testo's IRSoft software version 4.7 was used for image processing, allowing us to measure the temperatures at multiple locations of HAZ, as shown in Figure 12 for DOE 4. In this image, there were four interfaces; the top left interface shows the multiple locations of the hot spot (HS) and cold spot (CS), which are the maximum and minimum temperatures respectively during welding. The top right shows the temperature scale or maximum and minimum values of the scale in which temperature can be measured. The bottom left interface shows the values of CS and HS. The bottom right shows the actual welding scenario schematic. Various HS can be measured along with CS using a thermal imager simply through gentle mouse clicks at different locations of the top left window. The recorded HS was the maximum possible value of HS at the HAZ obtained from FSW.

Supporting strips were used to support the joint location for effective welding. In other words, the tool entered the supporting strips on one side, transversed while rotating along the weld line of specimens, and exited again from the supporting side on the other side, as shown in Figure 10.

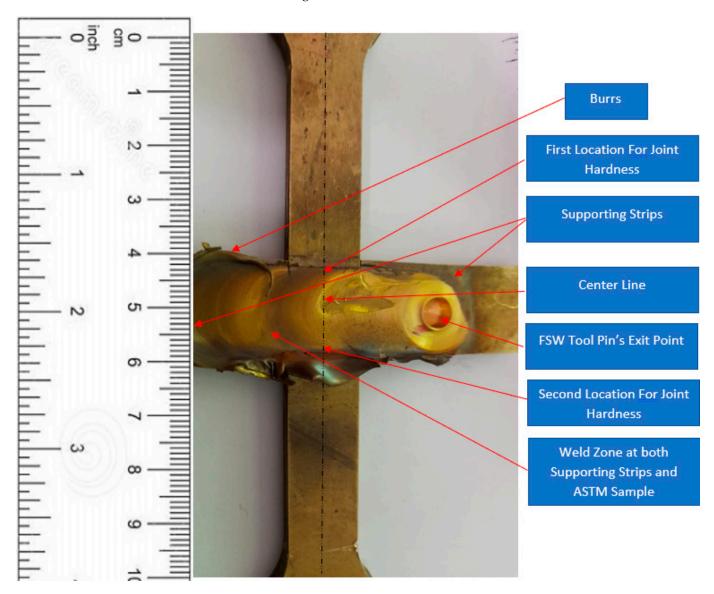


Figure 10. A friction stir weld.

After the specimens were welded in the processing phase of empirical FSW, specimens were tested for their joint strength and hardness to accomplish the postprocessing research activities. Side strips welded with the specimens were cut using an electric saw, as shown in Figure S2. A sample cut by the electric saw is shown in Figure S3. Joint strength was tested using a tensometer with a crosshead speed of 1 mm/min, as shown in Figure S7, under the guidelines of ASTM standard (E8/E8M-13a) Three samples were tested for each welding experiment, as per the DOE Table 5, and weld strengths were averaged accordingly. A broken FSW sample is also shown in Figure 11. Hardness was tested on the Rockwell hardness testing machine at various points of samples, shown in Figure S8. A diamond cone was used as an indenter with a pre-load of 29.42 N and a total applied load of 147.1 N by placing the welded specimen on the Rockwell hardness tester platform, as shown in Figure S8. The weld zone was especially exposed to the indenter to measure the weld hardness. The average value of hardness value was then computed and hardness values were recorded as the average of two values at the two joint hardness locations of HAZ, as shown in Figure 10. Welded brass burrs can be seen in Figure 10, which were removed from welded specimens before tensile testing of specimens. A simulation in Figure 6 showing the burr, as achieved from its experimental counterpart, is shown in Figure 10. The burrs in simulated Figure 6 are coming out of the top or bottom sides of the weld zone due to the reason that the whole specimen was fixed in all three axes as necessary boundary conditions for the current FSW problem theme. However, experimental burrs were forcefully moved at the outer edges of the specimen due to the combined (traverse and rotational) movements of both the pin and shoulder of the FSW tool, as shown in Figure 10.

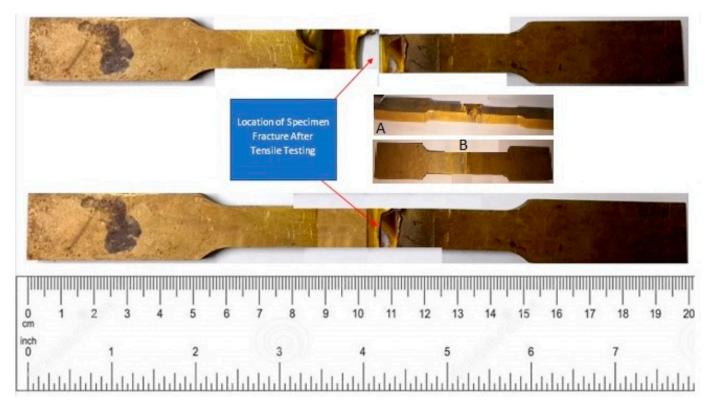


Figure 11. A top view of broken FSW sample with (A) side view and (B) bottom view.

#### 3. Results and Discussion

Figures 12–14 show the numerical and empirical results for weld temperature, weld strength, and weld hardness (empirical only), respectively. These results show that there exists an overall good agreement between them, as shown in Figures 12 and 13. Moreover, the maximum temperature and joint strength were found to be the highest for DOE4, implying that 1450 rpm and 60 mm/min were optimal levels of FSWFs with a revolutionary

Appl. Sci. 2023, 13, 2433 15 of 23

pitch of 24.17 revolutions per mm, as shown in Table 5. This value of the revolutionary pitch is evaluated to be smaller in Table 5.

Revolutionary pitch can be defined as a ratio of rotational speed (rpm) and traverse speed (mm/min). It seems that the smaller the value of the revolutionary pitch, the greater will be the weld quality in terms of both temperature and strength. In Figure 12, temperature distribution indicates that the maximum temperature achieved experimentally and numerically during FSW of brass was 598 °C again for DOE4. Hence, the maximum weld temperature was again possible with the smaller revolutionary pitch, i.e., for DOE4. Interestingly, the lowest weld temperature of 430.39 °C was obtained at DOE3, which had the highest revolutionary pitch.

The maximum temperature was found to be lower than the melting point of brass, i.e., 940  $^{\circ}$ C. This indicates that FSW of brass was accomplished in its true spirit in terms of its basic theme, i.e., solid state welding technique. Moreover, evaporation of zinc will never be observed at 598  $^{\circ}$ C, requiring the boiling point of Zn, i.e., at 907  $^{\circ}$ C. Therefore, porosity at the HAZ owing to zinc evaporation was never found even in the single experiment, as shown in Figures 15–18. Conclusively, there exists a good agreement between the numerical and empirical weld temperatures.

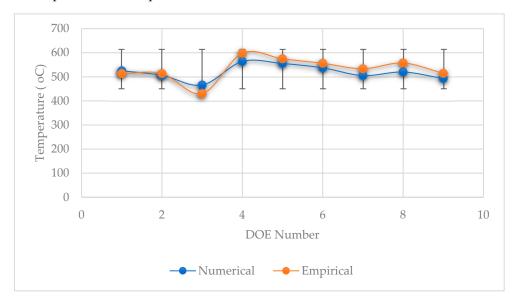


Figure 12. Empirical validation of numerical results for maximum temperature.

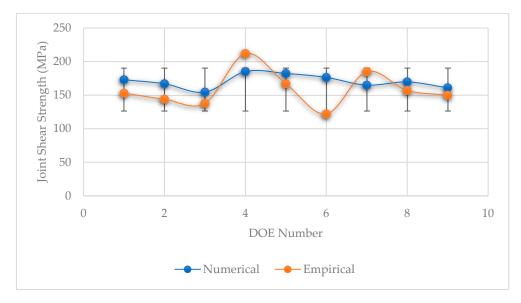


Figure 13. Comparison of empirical and numerical weld strength.

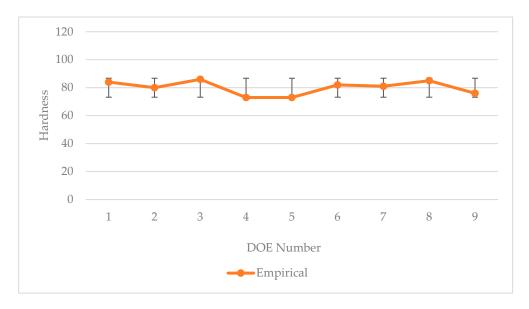


Figure 14. Hardness obtained from experiments.

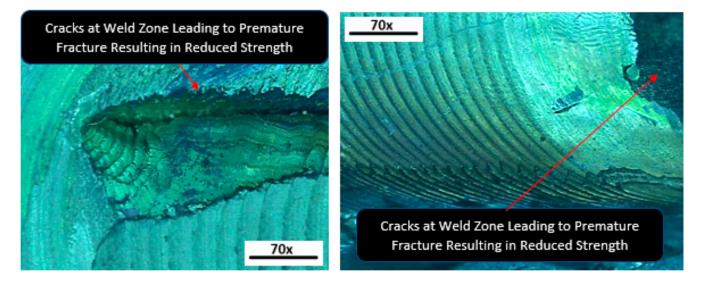


Figure 15. Cracks in the weld zone.

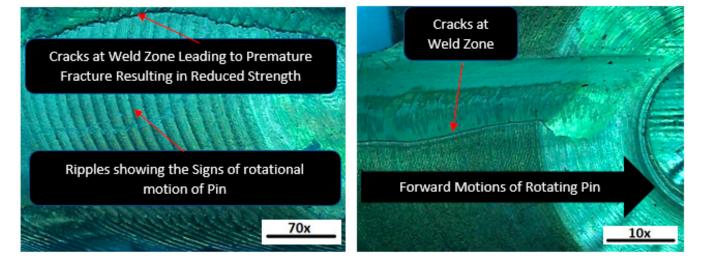


Figure 16. Cracks left over the passage of pin.

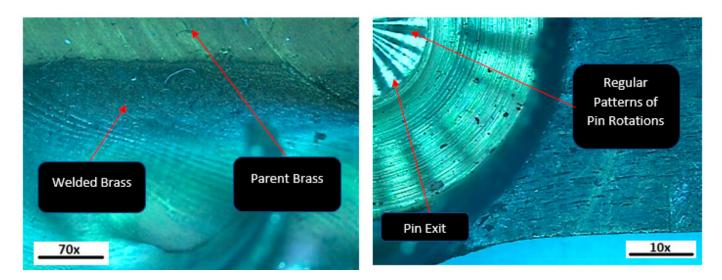


Figure 17. General features seen in all welded samples.

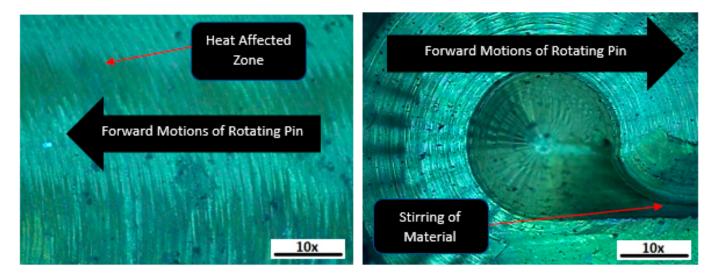


Figure 18. The most common features in all the welded samples.

From Figure 13, it can be deduced that if the revolutionary pitch is kept smaller then a FSW weld may be achieved with maximum joint strength of 228 MPa, as in the case of DOE4. On the other hand, the DOE3 having the highest revolutionary pitch, i.e., 40 revolutions per mm, imparts lower weld strength of 138 MPa among the whole DOE numbers. Therefore, the DOE4 and DOE3 resulted in the maximum and minimum weld strength as well as weld temperature, respectively, with their inverse relationship with the revolutionary pitch. Hence, it can be experimentally and numerically said that the DOE4 delivers the best combination of weld factor levels that may further be declared as the optimal factor levels as far as the optimal weld temperature and weld strength are concerned.

However, the hardness was found to be the lowest for DOE4 which, at first glance, negates the statement of optimal factor levels for DOE4, as shown in Figure 14. In fact, this needs to be discussed in detail supporting the DOE4 for its optimal output. The lowest empirical value of hardness existing at DOE4 was 73 HR. Likewise, the maximum weld hardness was found for DOE 3, i.e., 86 HR. Hence, it can be inferred that there exists an inverse relationship between weld hardness and both weld temperature and weld strength. As DOE4 and DOE3 are associated with the lowest and highest revolutionary pitches, the revolutionary pitch has a direct relationship with weld hardness. So, this reveals that the lower weld hardness value for DOE4 may be deemed as the best.

A likely explanation of the excellence of the lowest value of weld hardness at DOE4 is that the highest weld hardness value is not appreciated since it increases the brittleness of the joint, while welding brass, copper, and zinc may form intermetallic compounds at the HAZ which are generally brittle in nature. Therefore, low weld hardness is usually desired, which is amazingly found again for DOE4 and high weld hardness is surprisingly found at DOE3. This validates the optimal combination of weld factors indirectly, which are actually available in the DOE4, imparting also the optimal weld hardness at the weld zone, as it delivered the optimal weld strength and optimal weld temperature.

As a result, there exists a strong relationship between weld temperature, weld strength, and weld hardness at DOE4, which means 1450 rpm and 60 mm/min can be strongly recommended as optimal weld factor levels. In fact, DOE4 is that combination of welding factors imparting numerically and empirically the best weld strength, the maximum weld temperature, and the minimum weld hardness. As maximum weld strength and temperature with minimum weld hardness are the excellent characteristics of the weld bead, an optimally solid bond could possibly be guaranteed at DOE4.

Additionally, maximum joint strength was empirically found to be 228 MPa for DOE4, which is 83.00% of the ultimate tensile strength (UTS). The welding efficiency of the joint in terms of approaching the base metal UTS was satisfactory, which is more than 80.00%. This efficiency may further be enhanced in future numerical and experimental studies considering various other weld factors, e.g., tilt angle of the tool, changes in the shape of the pin, and changing the levels of those weld factors that were currently used in this research.

Finally, the lowest weld strength was found for DOE6. The reason for this low strength is the higher hardness value for DOE6, which made the friction stir bond harder. As hardness gives rise to brittleness, the HAZ for DOE6 was more brittle, reducing the bond strength when testing in shear.

### 4. Microscopic Examination of Friction Stir Welding Zone (FSWZ)

Welded and fractured samples were analyzed at the friction stir welding zone (FSWZ) after the samples were welded and tested under shear loading. The friction stir welding zone is that area under investigation where all the vital thermal and mechanical gradients in terms of maximum temperature and the highest strengths are highly likely. Therefore, microscopic examination of FSWZ was thought to reveal crucial phenomena while friction stir welding of brass. Microscopic examination of this research was performed using both the coordinate measuring machine (CMM) and a scanning electron microscope (SEM). In CMM, there were available three magnification levels employed and placed as 70×,  $30\times$ , and  $10\times$  in each microscopic image;  $70\times$  means the features' dimensions have been magnified up to 70 times and so on using  $30 \times$  and  $10 \times$ . Exciting and fascinating features were revealed in this microscopic investigation including their effects on the little errors found between numerical and empirical studies. Cracks in the weld zone are shown microscopically in Figures 15 and 16, causing few variation points of the welding strength to occur, as shown in Figure 13, when these welded samples passed through the tensile tester. Effects of frictional heating and FSW factors on microscopic features may be seen in Figures 17 and 18, including pin exit location, ripples due to pin forward movement, marks of uniform stirring of brass material, and the borderline between parent and welded brass. This validates further the causes of a few errors in results between both thermal and mechanical studies, i.e., numerical and empirical, which will be discussed in detail. In addition, the regular circles (see Figure 16) had the same diameter as that of the tool pin, as shown in Figure 8.

As far as yellow brass 405-20 is concerned, this is an alpha brass with 20–36% zinc by weight in copper. Few alloying elements (e.g., tin and lead, as shown in Table 1) may be added in the copper-zinc (Cu-Zn) brass alloy, resulting in acquiring the desired brass characteristics, such as machinability, color, corrosion resistance, etc. Major brass behavior in terms of strength and ductility largely depends on the addition of Zn in Cu. For example,

when Zn percentage is added in Cu up to 50%, tensile strength increases with a substantial reduction in ductility due to an abrupt rise in the hardness value [38]. This reduction in ductility and increment in brittleness is clearly evident from the findings of Figure 14 for weld hardness.

Yellow brass 405-20 has 63% of Cu and 34.7% of Zn, which is why it has a yellow color. The yellow brass under investigation is considered to be the better percentage combination of Cu and Zn, imparting the best strength and ductility. There is another advantage of the valuable alloying addition of Zn in the copper, which basically lowers the cost of the resulting brass material. Of course, the color of brass strongly depends on the percentage blend of both Cu and Zn. For instance, if the percentage of Zn is reduced to a range between 5 and 20%; the color of brass is changed to red with substantial changes in its various properties and its processing requirements [38].

Alpha brasses have a face-centered cubic (f.c.c.) crystal structure since copper is f.c.c. As yellow alpha brass has already better strength with higher ductility, it is suited to various cold working processes. This is due to the reason that yellow alpha brasses are subjected to pitting corrosion, which is known as dezincification [38]. Friction stir welding is a cold working process due to the presence of frictional heating during the welding of materials. FSW welds the brass and other materials while stirring and heating materials at a temperature below their melting points. Zn is found to be evaporated when brasses are welded by conventional joining techniques, which melt the materials to be welded. The melting point of Zn is 419.5 °C and the boiling point of Zn is 907 °C. Critical and microscopic examinations including SEM are usually required after FSW of brass alloy to look closely at the heat-affected zone for any dezincification and uneven joint fracture patterns. Moreover, two other phases of brass alloys may also be encountered, which are known as beta and alpha-plus-beta phases, when the Zn percentage in copper exceeds 36%. Beta phases have body-centered cubic (b.c.c.) crystal structures [38]. Additionally, others phases of brass are also possible based on increasing the percentage weight of Zn in Cu, including beta dashed, gamma, epsilon, and hetta brasses [39]. Since the yellow brass under investigation has less than 36% Zn in copper, these other phases are not discussed further due to their absence in the joint.

As described earlier, the minimum weld temperature found while FSW of brass was 430.39 °C, which is greater than the melting point of Zn, though it is lower than the boiling point of Zn. Dezincification is associated with the evaporation of Zn during FSW, which is likely to occur at a weld temperature greater than the boiling point of Zn. The maximum temperature found was only 598 °C during the numerical and empirical studies, implying that dezincification was not possible in the current research during FSW of brass even in a single DOE and especially in DOE4.

However, the melting of Zn occurs in all the DOEs, suggesting that little dislocations of Zn or few micro-level pits/cracks initiators may be found during FSW of brass, as can be seen in Figure 15. Likewise, more continuous cracks may be found due to melting of Zn at the weld zone, as shown in Figure 16.

Another problematic phenomenon occurred during the cold processing of brass is called season cracking/stress corrosion. This stress corrosion is also called intergranular corrosion and happens due to the residual stresses after the cold working of brass. Cold processed brass is usually annealed to remove these residual stresses, ultimately removing the likelihood of intergranular corrosion. This phenomenon is also found to occur at a faster rate in ammonia atmospheres [38]. Since FSW involves preparing the samples in cold conditions, the cracks in Figures 15 and 16 are thought to be the result of these residual stresses during FSW of brass in the absence of necessary annealing required for prepared samples. Moreover, variation in the joint strengths in the DOEs may also be caused by these residual stresses as a result of cold working during brass sample preparation.

Moreover, micrographs from the scanning electron microscope (SEM) revealed the presence of negligible pores, the uneven granular structure of brass, FSW tool marks, and crack marks after tensile testing, as shown in Figure 19 for DOE4. Pores indicate

Appl. Sci. 2023, 13, 2433 20 of 23

slight evidence of evaporation of zinc whereas uneven granular structures indicate poor dynamic recrystallization. Together, all these revelations strongly contribute towards a slight reduction in the joint strength, which is why the overall strength was found to be lower than that of the parent brass material. These are also the cause of little errors between numerical and empirical results.

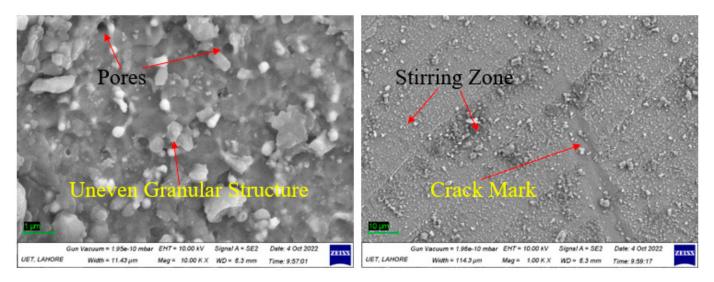


Figure 19. SEM micrographs of welded specimen for DOE4.

## 5. Conclusions

In this work, novel brass 405-20 was friction stir welded using two weld factors, namely rotational speed and traverse speed. Both empirical and numerical studies were conducted using brass 405-20 for the first time. Full factorial design of experiments (DOEs) was implemented for both numerical and empirical research works. Three response parameters were focused on, namely thermal distribution at HAZ, joint strength, and joint hardness at the HAZ. Two numerical FEA studies were performed, transient thermal analysis (FEA\_A) and static structural analysis (FEA\_B). Thermal outputs of FEA\_A were input to the FEA\_B to find the shear stress at the joint resulting in numerical values of joint strength. Moreover, weld temperature was numerically confirmed using FEA\_A. Empirical values of weld strength and weld temperatures were also found to validate the numerical results. Weld hardness was only studied experimentally due to its direct involvement in the healthy discussion on finding optimal weld factor levels, which were found for DOE4. The main findings during the current numerical and empirical investigational settings include a good agreement of numerical studies with the empirical work. Optimal FSW factor levels were found to be 1450 rpm and 60 mm/min for DOE4 in full factorial settings. The maximum temperature was found to be 598 °C, which is well below the melting point of brass. So, successful friction stir welding of brass was validated in terms of its basic definition of solid-state welding. This temperature was found for DOE4. Maximum joint strength was found to be 228 MPa, again at DOE4, which is 83.00% of base brass strength. Microscopic examination revealed crucial clues as to the reasons for lower weld strength as compared to that of the parent brass material strength. Weld hardness was found to be the lowest for DOE4, i.e., 73 HR, validating further that DOE4 carries an optimal combination of both rotational speed and traverse speed for FSW of brass 405-20.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13042433/s1, Figure S1: Coupling Thermal Transient Analysis (FEA\_A) with Static Structural Analysis (FEA\_B), Figure S2: Electric Saw Equipment for cutting sides of testing strips; Figure S3: A sample Cut by Electric Saw Equipment; Figure S4: Customized FSW using CNC Machining Centre; Figure S5: Thermal Imager; Figure S6: An example of Thermal Image

Appl. Sci. 2023, 13, 2433 21 of 23

from Testo 868 Imager; Figure S7: Hounsfield Tensometer for measuring Friction Stir Weld Strength (FSWS); Figure S8: Rockwell Hardness Tester.

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#### **Abbreviations**

ANN Artificial Neural Network

ASTM American Society for Testing and Materials

CFD Computational Fluid Dynamics
CNC Computer Numerically Controlled
CS Cold Spot in the Thermal Image

DOE Design of Experiments
FEA Finite Element Analysis
FSW Friction Stir Welding
FSWFs Friction Stir Welding Factors

HAZ Heat Affected Zone

HS Hot Spot in the Thermal Image

HSS High Speed Tool Steel UTS Ultimate Tensile Strength

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Appl. Sci. 2023, 13, 2433 23 of 23

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