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Conversion and automation of an idle lathe into a rotary friction welding experimental system

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ABSTRACT

This paper presents the conversion of an idle lathe into a continuous drive rotary friction welding (RFW) system. Bed structure, headstock, tailstock and cross slide of the lathe were used and the required attachments were designed, manufactured and mounted appropriately. An electric motor with a magnetic brake and a hydraulic piston were utilized for continuous drive and compression units, respectively. Automation controls were implemented to manage rotational speed, friction and forging pressure, and processing time. The effectiveness of the developed system was evaluated by attempting to weld solid and pipe specimens made of similar and dissimilar materials. The tests confirmed the success of the welding process. Difficulties in welding of dissimilar materials were overcome by increasing the rotational speed, friction pressure and process time, and by applying forging pressure acting after the drive unit has stoped.

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1. INTRODUCTION

Rotary friction welding (RFW) is an effective solid-state joining technique where two parts are welded together through friction and pressure at their surfaces [1, 2]. In this method, two pieces are brought into contact under high pressure, and then one of the parts rotates at high speed in its axis while the other is kept stationary, increasing friction at the interface and generating heat. The resultant heat causes a temperature increase and applied pressure provides plastic deformation and interpenetration of the softening materials, and thus parts are welded. Throughout the friction welding process, the rotating component also controls the friction between the surface of the parts, ensuring the even distribution of the generated heat [3].

Rotary friction welding offers distinct advantages, particularly in cases where the other welding methods face challenges, such as the joining of cylindrical components. This method effectively addresses the complexities encountered in welding cylindrical parts, particularly the challenges related to adjusting concentricity between two cylinders and achieving uniform application of the welding bath. In addition, while differences in physical and chemical properties of dissimilar materials can inhibit successful welding using other methods, friction welding, as mechanical joining technique, enables the welding of dissimilar materials. Due to such advantages, friction welding finds a wide range of applications across industries and is widely preferred especially for joining cylindrical parts. Besides outstanding mechanical properties, friction welding delivers rapid and efficient manufacturing processes, effectively meeting industrial requirements [4, 5].

Due to the aforementioned advantages of the technique and the industrial demand for the systems that can implement that process, the development of friction welding systems has been the subject of many studies. Nicholas reviewed friction welding processes and the systems used for specific purposes [6]. Details of continuous drive and stored energy systems that can be used as drive mechanisms were explained. Alves et al. used a commercial friction welding machine offering a fixed rotational speed to weld dissimilar materials of aluminum and stainless steel [7]. For this reason, the effects of variable rotational speeds were not examined in the experiments. Yohanes et al. aimed to add the flywheel to a rotary friction welding machine [8]. They investigated the effects of three different thicknesses of flywheels on the tensile strength of the joints in the experiments. Stutz et al. explained the differences between inertia friction welding and direct drive

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friction welding systems and adapted a friction stir welding system into a rotary friction welding machine to perform direct drive friction welding experiments [9]. Welding of molybdenum materials was successfully achieved on the adapted system. Xie et al. carried out experiments on a commercial friction welding machine, without applying forging pressure, under the maximum constant friction pressure of 80 MPa and maximum constant rotational speed of 2000 rpm provided by the system [10]. The maximum tensile strength of welded parts was obtained at a process duration of 4 s. Banerjee et al. studied a commercial MTI-built inertia friction welding machine and investigated the effects of inertia on the strength of welded parts [11]. Zhang et al. used high-frequency induction heating equipment with a commercial friction welding machine to simultaneously heat dissimilar materials to the same level during welding [12]. Qin et al. used an HWI-GXH inertia friction welding machine and mounted a circular mold on the outer surface of the welded part to control the flash generation provided by considerable deformation [13].

As mentioned above, in most friction welding test studies, it is seen that the systems used were developed from scratch for this purpose or high-cost industrial systems were preferred. Few studies have been carried out where existing equipment has been converted to a friction welding system. Shah et al. converted a lathe into a friction welding system by creating and integrating the necessary attachments[14]. A pneumatic system was preferred as the compression method which may not be effective at a low rotational speed of spindle for welding materials that require high friction pressure, such as steel. Sasmito et al. modified a lathe machine into a rotary friction welding system [15, 16]. The developed system can apply forging pressure up to 85 MPa. The effects of different rotational speeds on microstructure and strength were possible to investigate with the developed system. Benkherbache et al. performed rotary friction welding tests using a parallel lathe and investigated the effects of rotational speed on the mechanical properties of the welded parts [17]. It is noted that no changes have been made to provide pressure on the lathe and the friction load is applied through the tailstock. It is considered that the friction pressure, which is the dominant mechanism of friction welding, cannot be precisely adjusted in this way.

This study, different from most of the existing works available in the literature, aims to develop a cost-effective friction welding machine that can meet a wide range of experimental requirements by using the bed structure, headstock, tailstock, and cross slide of a currently idle lathe. The developed system allows the welding of both similar and dissimilar materials. With an automation system, hydraulic unit, and direct drive mechanism, it offers a wide range of rotational speed, friction, and forging pressure. Additionally, welding time can be precisely adjusted. The developed system has been tested for welding of similar and dissimilar materials and successful joints are obtained.

2. DESIGN OF ROTARY FRICTION WELDING SYSTEM

In the initial phase of the design study, a three-dimensional model of the lathe machine that is available in our workshop was established. Utilizing that design, compression unit (A), drive unit (B), and automation unit (C) were designed using SolidWorks software. In this design, a hydraulic piston is placed on the tailstock and an electric motor is placed on the drive shaft of the spindle directly with a coupling as shown in Figure 1.

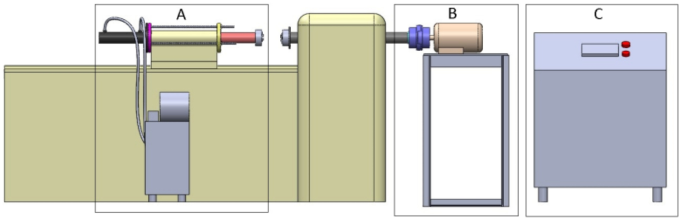


Fig. 1. Schematic of the friction welding system, (A) Compression unit, (B) Drive unit, (C) Automation unit.

2.1. Design of Compression Unit

A literature review was initially conducted regarding the required magnitude of the compressive force to design the compression unit. Based on the findings, it was concluded that a force of 20 kN could be sufficient to perform the desired tests. Due to the high compression force requirement, it has been decided that using a hydraulic unit would be more appropriate. Then, the diameter of the hydraulic cylinder was determined as 63 mm to achieve the desired compression load and to operate the hydraulic system efficiently. The maximum pressure of the hydraulic unit was selected as 50 bar.

Infinitely threaded attachments were preferred to reduce the impact of the reaction forces generated during the application of compression force in hydraulic cylinder. Figure 2 shows the schematic representation of the compression unit. In the design of the compression unit, the tailstock of the lathe machine was utilized to ensure concentricity. The piston was connected to the tailstock using flanges (A&C). The cylinder of the piston is shown in green colour in Figure 2 and technical drawings of the flanges are given in Figure 3 and Figure 4.

To link the cylinder to the chuck and enable the piston's axial movement through the tailstock, a component named connecting adapter (B) was designed as illustrated in Figure 5. This component also restricts the backward movement of the specimen due to compression during the welding process.

To minimize the shear stress and vibrations that arise due to frictional forces during the operation, a chuck fixing rod was manufactured from solid steel as shown in Figure 6. This part was embedded into the cylinder of the tailstock.

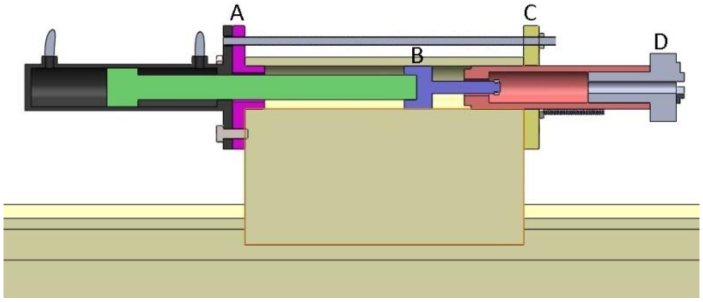


Fig. 2. Cross-sectional view of the compression unit.

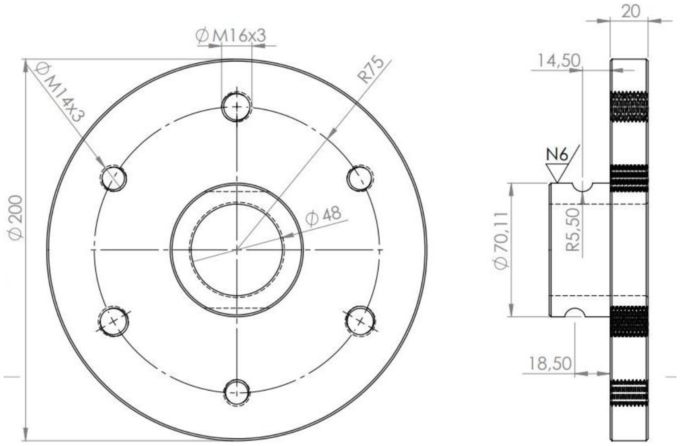


Fig. 3. Technical drawing of the left flange (A).

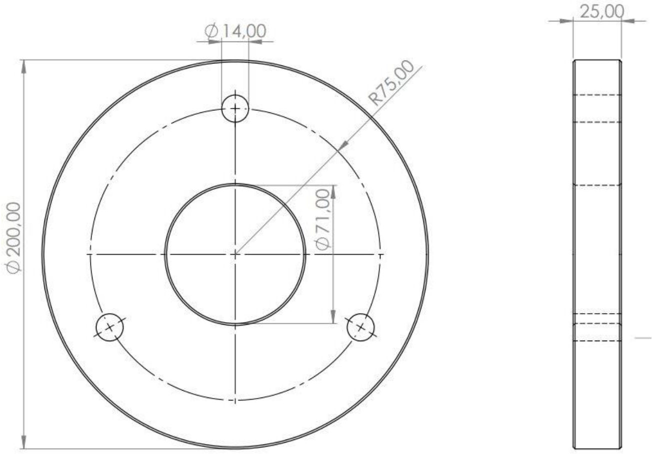


Fig. 4. Technical drawing of the right flange (C).

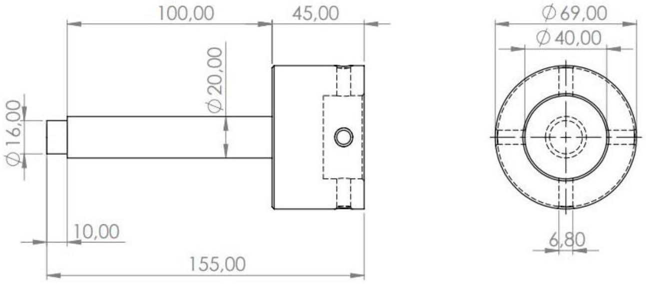


Fig. 5. Technical drawing of the connecting adapter.

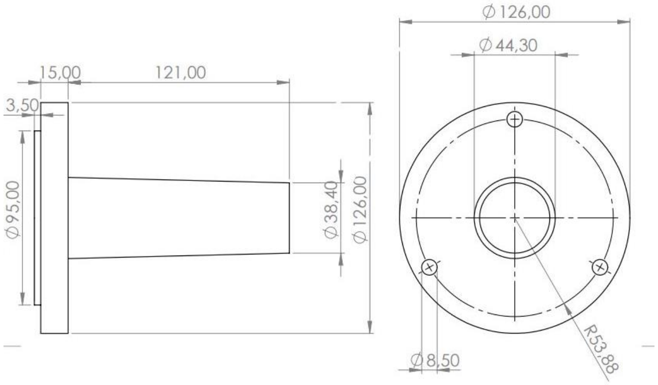


Fig. 6. Technical drawing of chuck fixing shaft.

2.2. Design of Drive Unit

In the drive unit, an inverter-controlled electric motor with a maximum rotational speed of 3000 rpm was selected due to high-speed requirements. During the welding process, it is expected that the motor will encounter high torque values. Therefore, a 7.5 kW motor was chosen to meet this demand. Also, when the welding process reaches the desired stage, the motor needs to provide a sudden stop, therefore, a motor with a brake system was chosen.

The motor was attached to the spindle with a direct drive configuration to avoid specific losses and delays associated with the belt-driven motion system. This mounting method also eliminates any delays in stopping the spindle when the brake is activated. A coupling connecting shaft, shown in Figure 7, was produced to achieve the connection. To prevent the backward movement of the specimen due to compression during the welding process, a stepped cylindrical block is placed at the center of the interface between the spindle and intermediate flange connected to the drive shaft.

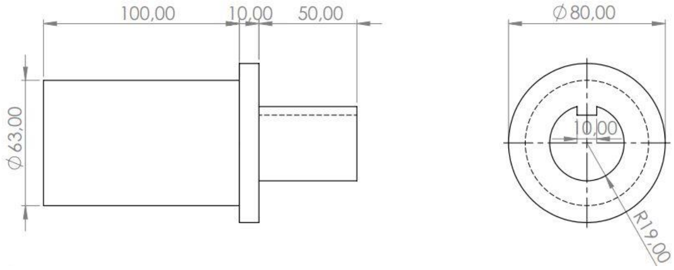
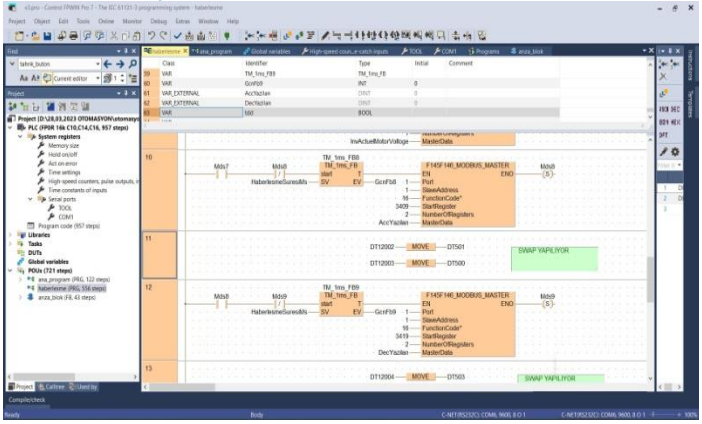


Fig. 7. Technical drawing of coupling connecting shaft.

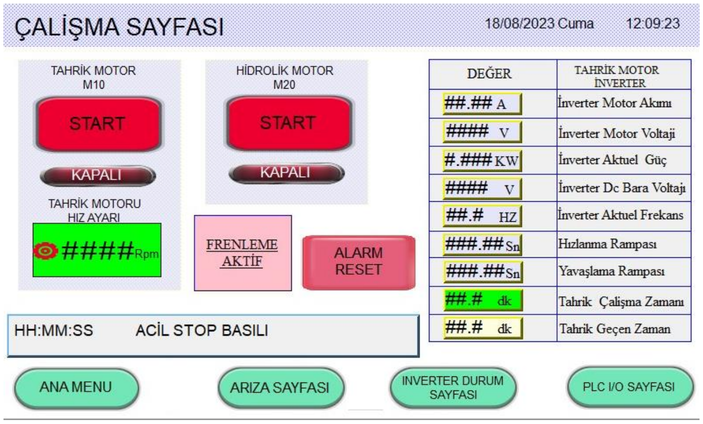
2.3. Automation System (PLC)

The programmable logic control (PLC) program FPWIN Pro7 was used to create the automation system as shown in Figure 8. This system simultaneously controls the process parameters such as hydraulic unit pressure, rotational speed of the motor, processing, and magnetic braking time. It also displays motor power, current, and voltage values reached during the operation. It is possible to adjust the time taken for motor start-up and shutdown, as well as the braking time. Since the motor is linked to an inverter, it can activate motor protection during instances of excessive loading, ensuring operational safety. The control panel is shown in Figure 9.



	Class	Identifier	Type	Initial	Comment
59	VAR	TM_1ms_FB9	TM_1ms_FB		
60	VAR	GcnFb9	INT	0	
61	VAR_EXTERNAL	AccYazilan	DINT	0	
62	VAR_EXTERNAL	DecYazilan	DINT	0	
63	VAR	tdd	BOOL		

Fig. 8. FPWIN Pro7 PLC program interface.



DEĞER	TAHRİK MOTOR İNVERTER
##.## A	İnverter Motor Akımı
##### V	İnverter Motor Voltaji
#.### KW	İnverter Aktuel Güç
##### V	İnverter Dc Bara Voltajı
##.# HZ	İnverter Aktuel Frekans
###.## Sn	Hızlanma Rampası
###.## Sn	Yavaşlama Rampası
##.# dk	Tahrik Çalişma Zamanı
##.# dk	Tahrik Geçen Zaman

Fig. 9. User interface of PLC unit.

3. ASSEMBLY PROCESS

In the assembly process, the auxiliary components were initially produced. After the quality checks, all the parts were assembled by taking into concentricity between the chucks as shown in Figure 10. To prevent any reaction forces on the tailstock due to the high level of compression force, the lathe's carriage was positioned behind the tailstock. The PLC control unit was positioned next to the motor. A hydraulic lever was also used to control the forward and backward movement of the piston.

Fig. 10. Developed rotary friction welding system.

4. EXPERIMENTAL STUDY

The expectation from the prepared welding system is to perform welding of both solid specimens and pipes made of similar or dissimilar materials. Therefore, to test the performance of the system, samples made from plain carbon steel and Al 7075 material with varying diameters were prepared. Initially, steel samples with a diameter of 14 mm were welded, followed by the welding of Al samples with a diameter of 20 mm. Subsequently, a joint was created between a 14 mm diameter steel sample and an aluminum sample. Finally, steel pipes with an external diameter of 20 mm and a wall thickness of 2 mm were welded. Forging pressure was not applied in the preliminary experiments. The rotational speed applied friction pressure, and duration of the welding process in the experiments are presented in Table 1. The values given in the table present the process parameters of preliminary tests without a comprehensive experimental design. In preliminary tests, it was observed that the successful welding time was quite long compared to those of studies in the literature due to the low rotational speed of the spindle and the lack of forging pressure.

Table 1. Process parameters of preliminary tests.

Material	*Diameter (mm)*	*Revolution (rpm)*	*Pressure (bar)*	*Time (s)*
St-St (solid)	14	800	10	58
Al-Al (solid)	20	800	15	33
St-Al (solid)	20	800	15	72
St-St (pipe)	24	800	10	45

The fixing conditions of the steel samples and the connection between the chucks are shown in Figure 11. Under the same fixing conditions, all the samples were welded successfully as shown in Figure 12. To test material adhesion at the part interfaces and whether the welds were successful, the upsetting regions of the welded parts were deeply machined by turning process and the joint interfaces were visually inspected by dye penetration. Also, welded pipes were sliced along the longitudinal direction, and inner upsets inside the pipes were inspected. Machined welded joint and inner upset of the pipe joint are shown in Figure 13. It has been observed that the part interfaces completely disappear in similar materials while the interfaces remain in the form of lines in the welding of dissimilar materials. Based on this, it is concluded that similar materials offer better weldability capabilities in rotary friction welding while there is difficulty in welding dissimilar materials. To overcome this problem, a parametric study is being carried out in which different welding parameters are taken into account, as process parameters will directly affect the adhesion at part interfaces. Experiments show that increasing the rotational speed, friction pressure and processing time significantly improves the adhesion at the interface of dissimilar materials. Additionally, besides the friction pressure, a high level of forging pressure applied after the system stops has been very effective in the success of welding dissimilar materials. Studies are continued to determine the optimum process parameters according to the different types of materials.

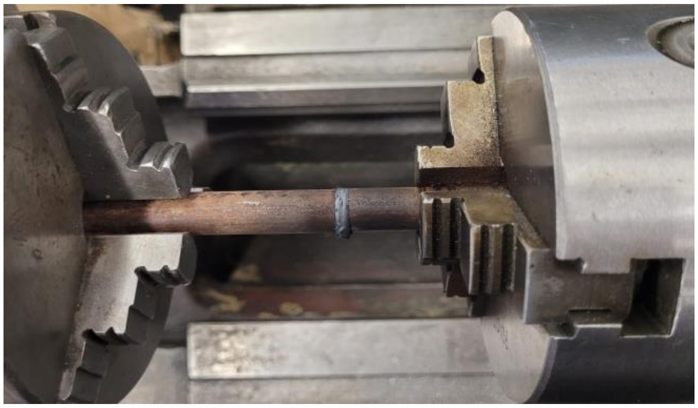


Fig. 11. Fixing condition of steel samples.

Fig. 12. Welded samples; (a) steel to steel, (b) Al to Al, (c) steel to Al, (d) steel pipes.

Fig. 13. Cut section of the welded steel pipes.

5. CONCLUSION

In this paper, the conversion of an idle lathe machine into a friction welding experimental setup was presented, in detail. Firstly, a three-dimensional model of the lathe was created in a computer environment and all required attachments that will provide adaptation have been designed and manufactured. The components of the pressure and drive units and their capacities were devised based on the literature survey. The bed structure of the lathe was used to balance the high tangential and axial forces occurring during the welding process. The compression unit was mounted on the tailstock for axial concentricity. Direct drive of the spindle was intended to eliminate flexing problems and provide reduced vibration at high rotational speeds and sudden braking. Thanks to the automation of the system, it was possible to alter welding parameters such as rotation speed, friction pressure, forging pressure and welding time in a wide range and to simultaneously monitor values such as power and current. Consequently, the system was configured to allow comprehensive experimental studies on friction welding.

The success of the developed system has been examined by performing a series of preliminary experiments using steel and aluminum samples. It has been observed that steel bars and pipes could be easily welded with this method. Difficulties in welding dissimilar materials have been overcome by increasing the rotational speed, friction pressure and process time, and by applying forging pressure. Studies are continued to determine the optimum process parameters according to the different types of materials.

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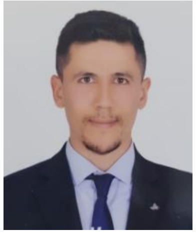

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