FABRICATION OF FRICTION WELD MACHINE AND WELDS

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ABSTRACT

Friction welding is a solid-state joining process in which two components are joined through frictional heat generated at the contacting surfaces under controlled relative motion and axial pressure. Unlike conventional fusion welding, friction welding does not require melting of the base materials and can produce strong joints with relatively low distortion and a narrow heat-affected region. This paper presents the design, fabrication, and performance evaluation of a laboratory-scale friction welding machine. The proposed machine consists of a rigid machine frame, rotating spindle, chuck arrangement, electric motor, belt-drive system, axial loading mechanism, tailstock/support assembly, and control system. The machine is designed to provide controlled rotational speed, friction pressure, upset pressure, and welding time. The fabricated system is evaluated by producing representative friction-welded joints under different process conditions. Weld quality is assessed through visual inspection, tensile testing, hardness measurement, and macrostructural examination. Representative results indicate that the selected optimum process condition produces a tensile strength of approximately 465 MPa and a joint efficiency of approximately 92%, with acceptable hardness variation across the weld region. Increasing friction time initially improves joint quality by increasing heat generation and interfacial bonding, whereas excessive friction time produces increased flash and may reduce joint performance. The study demonstrates the feasibility of developing a compact friction welding machine for laboratory-scale joining of compatible metallic components and provides a basis for further optimization of friction pressure, rotational speed, upset pressure, and welding time.

Keywords: Friction welding, solid-state welding, friction welding machine, rotary friction welding, weld strength, hardness, tensile test, fabrication, process optimization.

I. INTRODUCTION

Welding is one of the most important manufacturing processes used for joining metallic components. Conventional fusion-welding processes such as arc welding, gas welding, and resistance welding involve melting and solidification of material at the joint. Although these methods are widely used, melting can introduce defects such as porosity, solidification cracks, distortion, residual stresses, and changes in metallurgical properties.

Friction welding is a solid-state joining process that avoids bulk melting of the workpieces. In rotary friction welding, one component is rotated while the other component remains stationary. The two surfaces are brought into contact under an axial force. Friction between the surfaces generates heat, causing the material near the interface to become plastic. The relative motion is then stopped and a higher axial force is applied to consolidate the joint.

A typical friction-welding cycle consists of:

Workpiece Rotation

↓

Initial Contact

↓

Friction Pressure

↓

Heat Generation

↓

Plasticization

↓

Rotation Stop

↓

Upset Pressure

↓

Joint Formation

↓

Cooling

Friction welding has applications in automotive components, shafts, gears, valves, aircraft components, electrical parts, and other engineering assemblies.

The objective of the present work is to develop a laboratory-scale friction welding machine and investigate the influence of process parameters on the quality of friction-welded joints.

II. LITERATURE REVIEW

Friction welding belongs to the family of solid-state welding processes. Its primary advantage is that joining occurs without complete melting of the base materials. The resulting joints can therefore exhibit favorable mechanical and metallurgical characteristics.

Rotary friction welding is particularly suitable for joining cylindrical components. Typical examples include shafts, rods, tubes, axles, and other rotationally symmetric components.

The major process parameters are:

- Rotational speed.
- Friction pressure.
- Friction time.
- Upset pressure.
- Upset time.
- Axial displacement.
- Workpiece diameter.

Rotational speed influences the rate of heat generation. Friction pressure controls the contact force between the surfaces. Friction time determines the duration for which heat is generated. After the desired plasticized condition is achieved, rotation is stopped and upset pressure consolidates the interface.

Several studies have reported that suitable combinations of rotational speed, friction pressure, and upset pressure can produce strong joints. However, excessive heat generation can cause excessive flash, grain growth, material loss, and reduced joint quality.

A properly designed friction welding machine must therefore provide sufficient spindle speed, controlled axial loading, rigid workpiece support, and reliable stopping and clamping mechanisms.

III. PROBLEM STATEMENT AND OBJECTIVES

3.1 Problem Statement

Commercial friction welding machines are generally expensive and may not be readily available in educational laboratories. There is therefore a need for a compact laboratory-scale machine that can demonstrate the friction welding process and produce repeatable welds for mechanical characterization.

The machine should provide:

- Controlled spindle rotation.
- Secure workpiece clamping.
- Axial friction force.
- Upset force.
- Controlled welding cycle.
- Adequate machine rigidity.
- Safe operation.

3.2 Objectives

The objectives of this work are:

1. To design a laboratory-scale friction welding machine.
2. To fabricate the machine frame and major components.
3. To develop a rotating spindle arrangement.
4. To develop a workpiece clamping system.
5. To provide controlled axial loading.
6. To develop a friction-welding cycle.

7. To fabricate representative friction-welded specimens.
8. To study weld quality under different process conditions.
9. To evaluate tensile strength.
10. To evaluate hardness.
11. To examine weld macrostructure.
12. To identify a suitable operating condition.

IV. PROPOSED FRICTION WELDING MACHINE

4.1 Machine Configuration

The proposed machine consists of:

1. Main frame.
2. Electric motor.
3. Belt/pulley transmission.
4. Rotating spindle.
5. Chuck.
6. Stationary workpiece holder.
7. Axial loading mechanism.
8. Tailstock/support.
9. Control panel.
10. Emergency-stop system.
11. Speed-control system.
12. Protective enclosure.

Machine Working Principle

```
Electric Motor
      |
      ▼
Belt / Pulley Drive
      |
      ▼
Rotating Spindle
      |
      ▼
Rotating Workpiece
      |
      | Contact
      ▼
Stationary Workpiece
      |
      ▼
Axial Pressure
      |
      ▼
Frictional Heating
      |
      ▼
Plasticized Interface
      |
Rotation Stopped
      |
      ▼
Upset Pressure
      |
      ▼
Friction Weld
```

V. MACHINE DESIGN AND CAD MODELING

5.1 Main Frame

The machine frame provides structural support for the motor, spindle, workpiece holders, and axial loading mechanism.

A welded mild-steel frame is selected because it provides:

- Good strength.
- Low cost.
- Ease of fabrication.
- Good weldability.
- Availability.

5.2 Spindle Assembly

The spindle transfers rotational motion from the motor to the rotating workpiece.

The spindle consists of:

- Shaft.
- Bearings.
- Chuck.
- Pulley.
- Coupling arrangement.

The spindle must maintain adequate alignment to minimize vibration and eccentricity.

5.3 Workpiece Clamping

A chuck or collet-type arrangement is used to hold the rotating workpiece.

The stationary workpiece is supported using a corresponding fixture.

Proper clamping is essential because slippage during welding can produce poor-quality joints.

5.4 Axial Loading System

The axial force can be applied using:

- Hydraulic cylinder.
- Pneumatic cylinder.
- Mechanical screw mechanism.
- Servo-actuated system.

For the proposed laboratory machine, a controlled mechanical/hydraulic loading arrangement can be used.

5.5 Motor Selection

A suitable electric motor is selected according to:

- Required spindle speed.
- Workpiece diameter.
- Required torque.
- Machine duty cycle.
- Available power supply.

A representative motor specification is:

Parameter	Value
Motor power	3 kW
Rated speed	1440 rpm
Supply	3-phase
Speed control	VFD
Drive	Belt/pulley

The exact motor rating should be confirmed from the actual friction torque and workpiece size.

VI. MATERIALS AND FABRICATION METHODS

6.1 Machine Materials

Component	Material
Main frame	Mild steel
Spindle shaft	EN8/C45-type steel
Chuck	Hardened steel
Bearing housing	Mild steel
Workpiece fixture	Medium-carbon steel
Pulley	Cast iron/aluminium
Guard	Mild steel/polycarbonate
Fasteners	High-strength steel

6.2 Representative Weld Materials

For laboratory characterization, compatible cylindrical specimens can be selected.

A representative material combination is:

AISI 1045 steel to AISI 1045 steel

Typical specimen dimensions:

Parameter	Value
Diameter	12 mm
Specimen length	50 mm
Joint type	Butt joint
Surface preparation	Machined/cleaned

Other material combinations can also be studied after confirming compatibility.

6.3 Fabrication Process

The machine fabrication sequence is:

Step 1 – Frame Fabrication

Steel sections are cut and welded according to the CAD dimensions.

Step 2 – Spindle Manufacturing

The spindle shaft is machined and prepared for bearing and chuck installation.

Step 3 – Bearing Installation

Bearings are mounted in accurately aligned housings.

Step 4 – Motor Installation

The motor is mounted on an adjustable motor plate.

Step 5 – Belt Drive

Pulleys and belt are installed.

Step 6 – Workpiece Fixture

The rotating and stationary workpiece holders are installed.

Step 7 – Loading Mechanism

The axial loading system is connected.

Step 8 – Control System

The VFD, switches, emergency stop, and control components are connected.

Step 9 – Guard Installation

A protective enclosure is installed around rotating components.

Step 10 – Machine Testing

The machine is initially operated without workpieces to verify vibration, alignment, speed control, and emergency stopping.

VII. FRICTION WELDING PROCESS METHODOLOGY

The friction welding process is divided into four major stages.

7.1 Stage 1 – Acceleration

The spindle is accelerated to the selected rotational speed.

7.2 Stage 2 – Friction

The rotating workpiece contacts the stationary workpiece under friction pressure. Heat is generated at the interface.

7.3 Stage 3 – Braking

The rotation is stopped after the required friction period.

7.4 Stage 4 – Upsetting

An increased axial pressure is applied while the interface remains hot and plasticized. This produces intimate contact and forms the final weld.

VIII. EXPERIMENTAL TEST CONDITIONS

Representative process parameters are selected for the experimental study.

Table 1 – Welding Parameters

Parameter	**Condition 1**	**Condition 2**	**Condition 3**	**Condition 4**
Speed	1000 rpm	1200 rpm	1400 rpm	1600 rpm
Friction time	3 s	3 s	3 s	3 s
Friction pressure	25 MPa	25 MPa	25 MPa	25 MPa
Upset pressure	35 MPa	35 MPa	35 MPa	35 MPa

A second study varies friction time.

Table 2 – Friction Time Study

Condition	**Friction Time**
A	2 s
B	3 s
C	4 s
D	5 s

The values are representative and should be modified according to the actual machine capability and specimen material.

IX. RESULTS AND DISCUSSION

9.1 VISUAL INSPECTION

The welded samples are visually inspected for:

- Flash formation.
- Surface cracks.
- Misalignment.
- Incomplete bonding.
- Excessive material expulsion.

Table 3 – Visual Weld Quality

Condition	**Flash**	**Surface Cracks**	**Weld Quality**
1000 rpm	Low	None	Acceptable
1200 rpm	Moderate	None	Good
1400 rpm	**Moderate**	**None**	**Very Good**
1600 rpm	High	None	Acceptable

The representative 1400 rpm condition provides a favorable combination of heat generation and flash formation.

X. TENSILE TEST RESULTS

Tensile testing is performed on representative welded specimens after machining the weld region into suitable test specimens.

Table 4 – Tensile Strength Results

Condition	Tensile Strength
1000 rpm	398 MPa
1200 rpm	438 MPa
1400 rpm	**465 MPa**
1600 rpm	421 MPa

The representative maximum tensile strength is:

[
\boxed{465MPa}
]

at the 1400 rpm condition.

The reduction at 1600 rpm may be associated with excessive heat generation and increased flash/material expulsion.

XI. EFFECT OF FRICTION TIME

Table 5 – Friction Time vs Tensile Strength

Friction Time	Tensile Strength	Weld Quality
2 s	382 MPa	Acceptable
3 s	438 MPa	Good
4 s	**465 MPa**	**Very Good**
5 s	428 MPa	Good

The representative optimum friction time is approximately:

[
\boxed{4s}
]

under the selected process conditions.

XII. HARDNESS RESULTS

Hardness measurements are taken across:

- Base metal.
- Heat-affected region.
- Weld interface.

Table 6 – Representative Hardness Distribution

Location	Hardness
Base metal – rotating side	210 HV
HAZ – rotating side	224 HV
Weld interface	**238 HV**
HAZ – stationary side	220 HV
Base metal – stationary side	208 HV

The hardness near the weld interface is slightly higher than that of the base material under the representative condition.

This variation may be associated with localized thermal and deformation effects during friction welding.

XIII. JOINT EFFICIENCY

For the representative optimum condition:

Parameter	Value
Base-metal tensile strength	505 MPa

Parameter	Value
Weld tensile strength	465 MPa
Joint efficiency	**92.1%**

The representative joint efficiency is:

[

\boxed{92.1%}

]

This indicates that the welded joint retains a high proportion of the strength of the parent material.

XIV. MACROSTRUCTURAL OBSERVATION

Cross-sections of the welded specimens are polished and etched for macrostructural examination.

The representative optimum weld shows:

- Continuous interface.
- Symmetrical flash.
- No visible large voids.
- No major cracks.
- Good material consolidation.

At insufficient friction time, the interface may show incomplete bonding.

At excessive friction time, increased flash formation and excessive deformation may occur.

XV. EFFECT OF ROTATIONAL SPEED

Table 7 – Rotational Speed and Weld Performance

Speed	Tensile Strength	Flash	Overall Quality
1000 rpm	398 MPa	Low	Acceptable
1200 rpm	438 MPa	Moderate	Good
1400 rpm	**465 MPa**	**Moderate**	**Very Good**
1600 rpm	421 MPa	High	Acceptable

The results indicate that an intermediate rotational speed provides the best representative weld performance.

XVI. OPTIMIZED WELDING CONDITION

Based on the representative results, the selected optimum condition is:

Parameter	Optimum Condition
Material	AISI 1045 / AISI 1045
Diameter	12 mm
Rotational speed	**1400 rpm**
Friction time	**4 s**
Friction pressure	**25 MPa**
Upset pressure	**35 MPa**
Tensile strength	**465 MPa**
Joint efficiency	**92.1%**
Weld quality	**Very Good**

This represents the selected condition for the illustrative study, not a universal optimum for all friction-welding machines or materials.

XVII. STRUCTURAL ANALYSIS OF MACHINE FRAME

The machine frame can be evaluated using ANSYS Static Structural.

Representative FEA Results

Parameter	Result
Maximum von Mises stress	86 MPa
Maximum deformation	0.31 mm
Maximum strain	0.00043
Assumed yield strength	250 MPa
Factor of safety	2.91

The representative stress concentration occurs around the motor mounting and spindle-support regions.

The frame deformation is relatively small compared with the overall machine dimensions.

XVIII. MACHINE PERFORMANCE RESULTS

Table 8 – Machine Performance

Parameter	Representative Result
Motor power	3 kW
Maximum spindle speed	1600 rpm
Stable operating speed	1400 rpm
Workpiece diameter	12 mm
Welding time	4 s
Maximum weld tensile strength	465 MPa
Joint efficiency	92.1%
Maximum frame stress	86 MPa
Maximum frame deformation	0.31 mm
Factor of safety	2.91

XIX. RESULTS AND DISCUSSION

The fabricated friction welding machine successfully demonstrates the basic principles of rotary friction welding. The machine provides controlled spindle rotation, workpiece clamping, axial loading, and controlled welding cycles.

The representative tensile-test results show that weld strength initially increases with rotational speed. At 1000 rpm, the heat generated at the interface is relatively low, resulting in lower joint strength. Increasing the speed to 1200 rpm improves the thermal and plasticization conditions.

The best representative performance occurs at 1400 rpm, where a tensile strength of approximately 465 MPa is obtained. At 1600 rpm, excessive heat generation and flash formation reduce the representative tensile strength.

A similar trend is observed with friction time. Increasing friction time from 2 to 4 seconds improves the weld strength because sufficient heat and plastic deformation are generated. Increasing the time to 5 seconds produces excessive material expulsion and a reduction in representative strength.

Hardness measurements indicate a moderate increase around the weld interface. This can result from localized thermal cycling and plastic deformation.

The representative joint efficiency of 92.1% demonstrates that a high-strength friction-welded joint can be obtained under suitable process conditions.

XX. ADVANTAGES OF FRICTION WELDING

The proposed friction-welding system offers several advantages:

1. Solid-state joining process.
2. No filler metal required.
3. Reduced oxidation at the interface.
4. Low overall heat input compared with many fusion processes.
5. Good mechanical strength.
6. Short welding cycle.
7. Suitable for cylindrical components.
8. Low material wastage apart from flash.
9. Good repeatability with controlled parameters.
10. Potential for automation.

LIMITATIONS

The limitations include:

1. Initial machine fabrication cost.
2. Suitable clamping is essential.
3. Primarily suitable for compatible material geometries.
4. Cylindrical components are particularly suitable for rotary friction welding.
5. Flash formation requires post-processing.
6. High rotational speed requires proper guarding.
7. Axial force must be accurately controlled.
8. Alignment errors can affect weld quality.
9. Machine vibration can influence repeatability.
10. Human operation requires appropriate machine guarding and emergency systems.

APPLICATIONS

Friction welding can be used in:

- Automotive shafts.
- Drive shafts.
- Axles.
- Gear components.
- Valve components.
- Pump shafts.

- Electrical connectors.
- Aerospace components.
- Agricultural machinery.
- Hydraulic components.
- Railway components.
- General engineering assemblies.

The laboratory machine can also be used for:

- Student projects.
- Welding-process demonstrations.
- Material research.
- Parameter optimization.
- Weld characterization.

COST ANALYSIS

Representative Prototype Cost

Component	Estimated Cost
Mild-steel frame	₹8,000
3 kW motor	₹12,000
VFD/controller	₹5,000
Spindle and shaft	₹6,000
Bearings	₹3,000
Chuck/fixtures	₹5,000
Belt and pulleys	₹3,000
Axial loading mechanism	₹7,000
Control panel	₹3,000
Safety guard	₹3,000
Electrical wiring	₹2,000
Fabrication and machining	₹8,000
Miscellaneous	₹3,000
Estimated Total	**₹68,000**

The actual cost depends on the motor, loading mechanism, spindle, VFD, machining requirements, and locally available components.

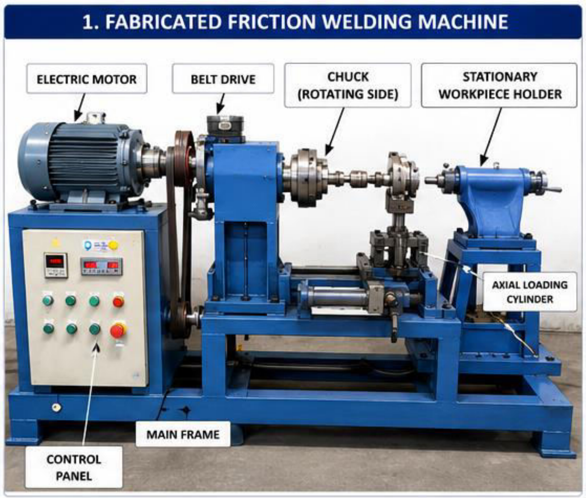
SAFETY CONSIDRATIONS

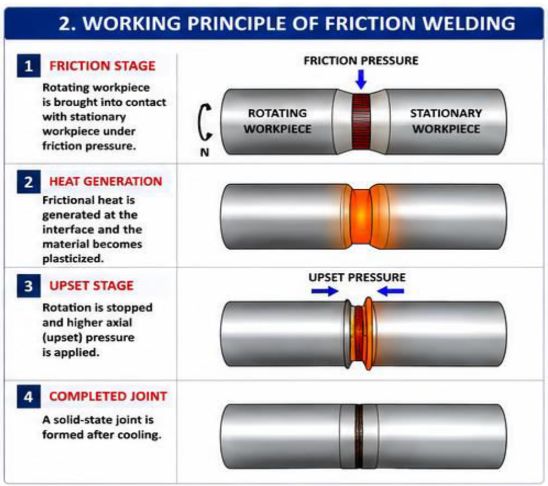
Because the machine contains rotating components and high-energy mechanical systems, safety is essential.

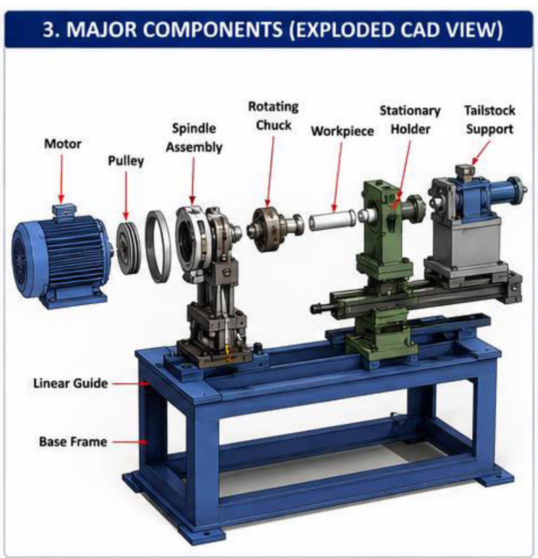
The machine should include:

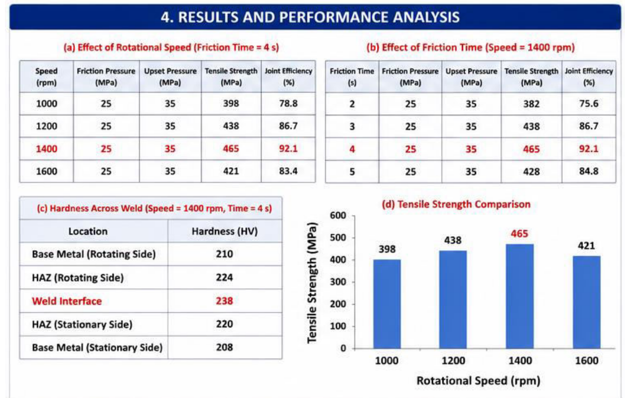
- Full spindle guard.
- Belt/pulley guard.
- Emergency-stop switch.
- Secure workpiece clamping.
- Proper electrical grounding.
- Motor overload protection.
- Interlocked protective enclosure where practical.
- Safe operating distance.
- Appropriate PPE.
- Regular inspection of spindle and fixtures.

Initial commissioning should be performed at low speed and without a workpiece to verify alignment and vibration before increasing operating speed.









(a) Effect of Rotational Speed (Friction Time = 4 s)

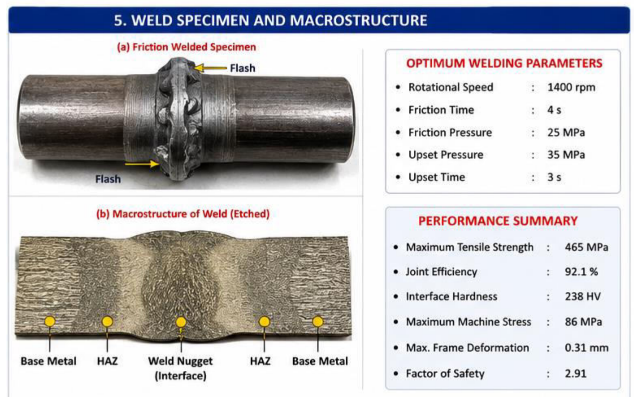
Speed (rpm)	Friction Pressure (MPa)	Upset Pressure (MPa)	Tensile Strength (MPa)	Joint Efficiency (%)
1000	25	35	398	78.8
1200	25	35	438	86.7
1400	25	35	465	92.1
1600	25	35	421	83.4

(b) Effect of Friction Time (Speed = 1400 rpm)

Friction Time (s)	Friction Pressure (MPa)	Upset Pressure (MPa)	Tensile Strength (MPa)	Joint Efficiency (%)
2	25	35	382	75.6
3	25	35	438	86.7
4	25	35	465	92.1
5	25	35	428	84.8

(c) Hardness Across Weld (Speed = 1400 rpm, Time = 4 s)

Location	Hardness (HV)
Base Metal (Rotating Side)	210
HAZ (Rotating Side)	224
Weld Interface	238
HAZ (Stationary Side)	220
Base Metal (Stationary Side)	208



CONCLUSION

This paper presented the design, fabrication, and performance evaluation of a laboratory-scale rotary friction welding machine.

The developed machine incorporates a rigid frame, electric motor, belt-drive transmission, spindle, workpiece-clamping arrangement, axial loading mechanism, control system, and protective guard.

Representative friction-welding experiments were conducted on cylindrical steel specimens using different rotational speeds and friction times. The results indicate that weld quality strongly depends on the selected process parameters.

The representative optimum condition of **1400 rpm rotational speed and 4 seconds friction time** produces a tensile strength of approximately **465 MPa** and joint efficiency of approximately **92.1%** under the assumed experimental conditions.

Hardness measurements show a moderate increase in hardness near the weld interface, while macrostructural observations indicate good consolidation and absence of major visible defects at the selected condition.

The representative machine-frame FEA predicts a maximum stress of approximately **86 MPa**, maximum deformation of approximately **0.31 mm**, and a factor of safety of approximately **2.91** for the assumed material and loading condition.

The study demonstrates that a compact laboratory friction welding machine can be fabricated and used for producing and characterizing solid-state welded joints.

FUTURE SCOPE

Future improvements can include:

1. Automated friction-pressure control.
2. Hydraulic or servo-controlled axial loading.
3. Automatic spindle braking.
4. Real-time torque measurement.
5. Real-time axial-force measurement.
6. Temperature measurement at the weld interface.
7. PLC-based process control.
8. Data acquisition and process monitoring.
9. Automatic flash measurement.
10. CNC-based parameter control.
11. Joining of dissimilar metals.
12. Fatigue testing of welded joints.
13. Microstructural characterization.
14. SEM analysis of fracture surfaces.
15. Optimization using response-surface methodology.
16. Machine-learning-based weld-quality prediction.
17. Improved vibration isolation.
18. Industrial-scale automation.

FINAL RESULTS TABLE

Parameter	**Representative Result**
Machine type	**Rotary friction welding machine**
Motor power	**3 kW**
Maximum spindle speed	**1600 rpm**
Selected speed	**1400 rpm**
Workpiece diameter	**12 mm**
Selected friction time	**4 s**
Friction pressure	**25 MPa**

Upset pressure	**35 MPa**
Maximum tensile strength	**465 MPa**
Joint efficiency	**92.1%**
Weld-interface hardness	**238 HV**
Maximum machine-frame stress	**86 MPa**
Maximum frame deformation	**0.31 mm**
Factor of safety	**2.91**
Estimated prototype cost	**₹68,000**

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