Chapter 9
Design and Development of Robust Fixture to Perform Friction Stir Welding/Processing on Conventional Vertical Milling Machine

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Introduction

Friction stir welding and processing (FSW/P) is a solid-state process that coalesces metal below its melting point under extreme strain applied by the high strength non-consumable rotating tool [1]. The relative motion between the rotating tool and workpiece produces very high undesirable forces, like axial force, welding/processing force, and torque force during processing [2–4]. Figure 9.1 shows the schematic diagram of various forces acting during FSW/P. It is very crucial for the work plate to be rigidly fixed while processing. A very slight displacement in the work plate can create an adverse effect on the qualities of the material. The issue is during the plunging stage of friction stir welding (FSW), a rotating tool applies lateral force on a workpiece abutted joint that increases the gap between the workpiece interfaces. This separating force between two work plates is only observed in FSW but not in friction stir processing (FSP) as it has a single work plate. However, very high torque and axial force are noted at the initial stage of tool–workpiece interaction. Also, the loose-fitting of a workpiece in the fixture is associated with safety concerns, while FSW/P, a minor casualty, may lead to tragic accidents.

The FSW/P process can be described in three stages: (a) plunging stage, (b) dwelling stage, and (c) translational stage. After the plunging stage, peak forces on the tool stabilize with the generation of heat and increases the flowability of material [5]. Therefore, the fixture has to resist more severe stresses during the plunging stage than dwelling and translation stages. Thus, while designing FSW/P fixture,

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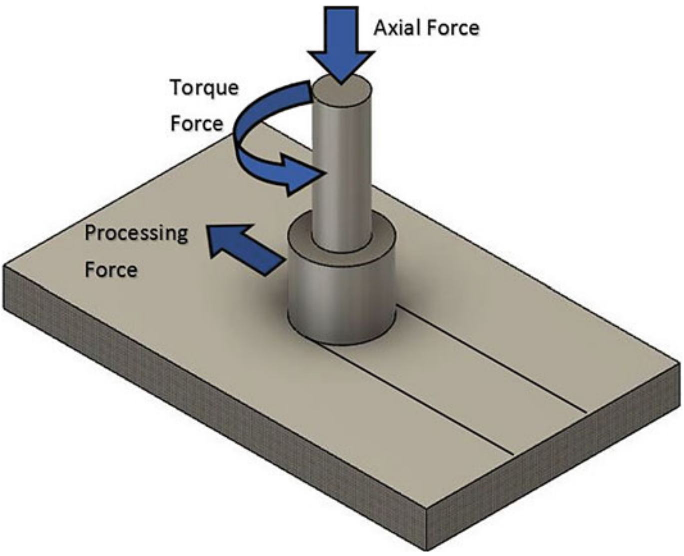

Fig. 9.1 Various forces acting during FSP

peak forces generated during the plunging stage must be considered. The success of FSW/P is directly or indirectly dependent on the design of the fixture, clamping device, and material used. Nowadays, companies are specially manufacturing the FSW/P type of machine that has an inbuilt accessory of fixture and clamping devices [6–8]. But such kind of machines requires a very high cost of investments. Thus, it is necessary to construct an economical fixture for the FSW/P in a universal vertical milling machine design in such a way that it withstands high forces and hold the workpiece rigidly. Moreover, it is possible to modify a conventional vertical milling machine for FSW/P through a suitable design fixture and clamping device [9–12].

Parida et al. [13] developed a fixture and clamping system that securely holds the workpiece. It also eliminates the formation of a gap between the joint and reduces job switching time with a cost-effective strain gauge-based force measuring dynamometer. Richter-Trummer et al. [14] studied the effect of different clamping forces on the distortion and residual stress developed in the abutted FSW joint. It was observed that lower distortion and a more uniform residual stress distribution is produced through the thickness due to higher clamping forces. Ramnath et al. [15] designed and analyzed three FSW fixture materials, that is, cast iron (C45), die steel (D4), and tool steel and hard alloy (H20) by ANSYS software. The outcome of this analysis deduced that C45 steel material is also successfully used as a fixture material in place of D4 and H20 materials. Further, it noticed that the design of a wedge shape at the corner of the fixture reduces the stress concentration. Ahmed and Saha [16] developed and proposed an FSW fixture for joining a thin sheet of aluminum alloy by using a lever-type clamping system and asbestos as a cover plate to reduce heat loss. The feasibility of the fixture is successfully established by FSW of 0.5 mm thin AA 6061-T6 sheets at five different tool travel speeds. Fratini et al. [17] have specially designed an inbuilt cooling system in a backplate of FSW fixture and choice of materials to overcome the shortcomings of welding of titanium alloy sheets. In this present work, a fixture and the clamping system is designed and developed to overcome the problem of fixture rigidity that securely holds a workpiece and fixture to the milling bed during processing. It also reduces the job shifting time and easy installation on conventional vertical milling machine bed. The unavailability of an expensive company made FSW/P machine motivated to design and develop a fixture that modifies traditional vertical milling machines into the FSW/P machine.

Design and Development of a Fixture

The adequately developed fixture has shown high efficiency in carrying out FSW/P operations in the conventional vertical milling machine. While designing FSW/P fixture, the following are the points that should be considered: (a) Backplate should be reasonably thick relative to the thickness of the work plates to be processed or welded. (b) The chosen material should have a low thermal conductivity that maintains a sufficiently high temperature to promote the work material plasticization and flow. (c) It is necessary to clamp from the top so that work plates should not lift from their position during processing. (d) The longitudinal and transverse movement of the work plate should be restricted. (e) In the case of FSW, for smooth welding, its joint should be kept intact to reduce the gap between the plates. The fixture has four main components: fixture plate, locating device, clamping device, and the support plate.

Component of a Fixture

Fixture plate. It is the core part of the fixture with a size 320 × 280 mm and a thickness of 22 mm under which is a rectangular recess of size 280 × 100 mm with a depth of 8 mm to facilitate the setting of a workpiece. The corner point of this recess has a circular blind hole of diameter 8 mm that helps in proper accommodation and proper alignment of a rectangular workpiece. Sliding slot recess in the X and Y directions are also provided to locate the workpiece in their position (see Fig. 9.2).

Locating device. It is a device that correctly positions and restricts the movement of a workpiece in a lateral and longitudinal direction. It helps in the accommodation of workpiece if any little variation in shape and size.

Sliding plate in X direction: It accommodates the workpiece if there is any variation in length. The half circular-cut gives run out of space for the FSP tool at the end stage of the process. The slotted hole helps in X direction movement and can be tightened

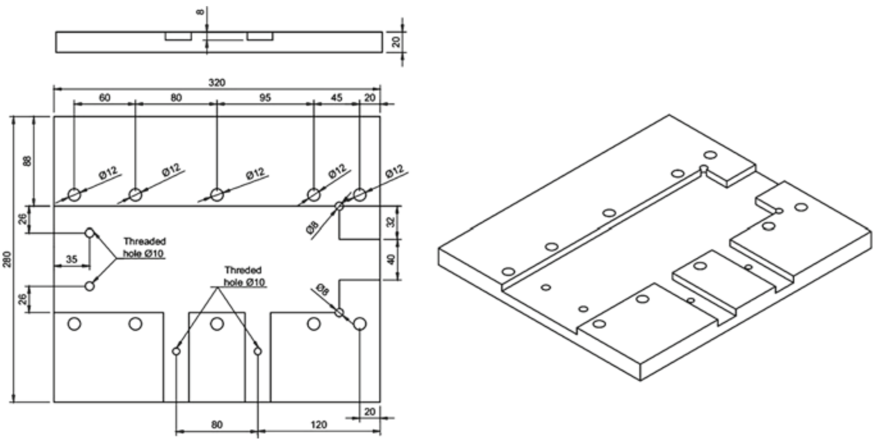

Fig. 9.2 Fixture plate with recess for the accommodation of workpiece (all dimensions in mm)

in that position using the Allen bolt. The dimension of the sliding plate is shown in Fig. 9.3a.

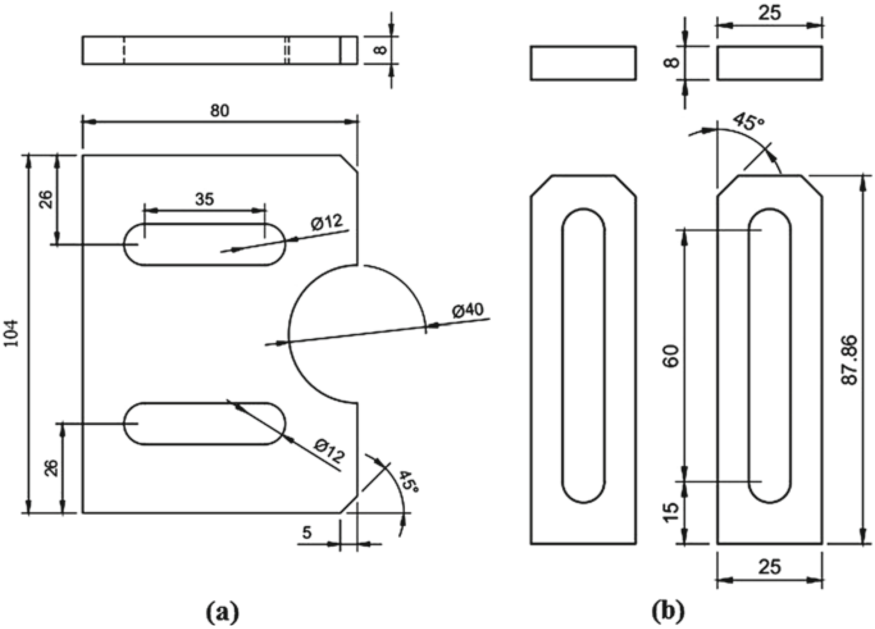

Fig. 9.3 Sliding plate to constraint workpiece movement in **a** X direction and **b** Y direction (all dimensions in mm)

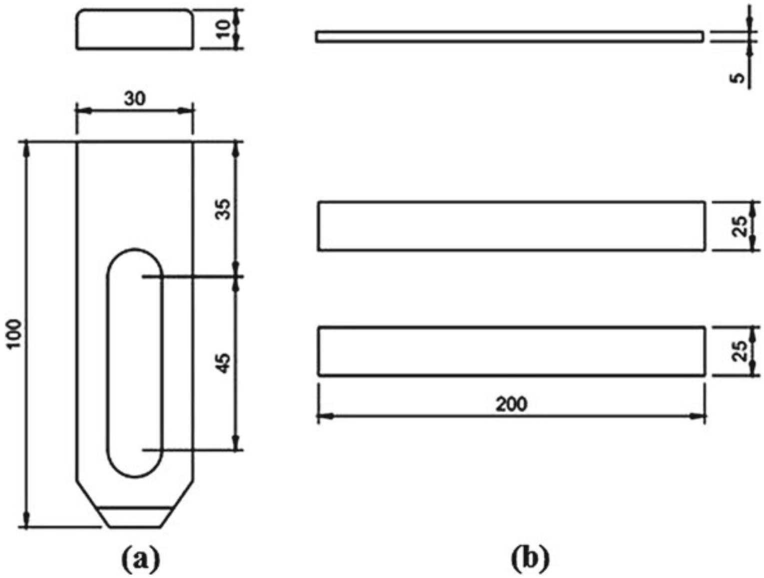

Fig. 9.4 **a** Clamping device and **b** the support plate (all dimensions in mm)

Sliding plate in Y direction: It accommodates the workpiece if there is any variation in width. The slotted hole helps in movement in Y direction and can be tightened in that position using the Allen bolt (see Fig. 9.3b).

Clamping device. The purpose of clamping is to hold the workpiece accurately in the fixture and to ensure that the work should not be displaced under processing forces. The clamping device design should be such that the operating time is as minimum as possible. Thus, tightening of Allen bolt in clamping quickly and directly fixed to the T-slot nut in vertical milling machine bed, which further ensures the rigidity of the workpiece with fixture. The shape and size of the clamp are shown in Fig. 9.4a.

Support plate. It uniformly distributes the clamping forces on a workpiece. It kept between the workpiece and the clamp, made up of the same material as that of the fixture. Thus, it restricts the upward movement of a workpiece, and results in negligible distortion during and after the processing work material. The dimension of the support plate is shown in Fig. 9.4b.

The complete diagram of the fixture and its various parts is shown in Fig. 9.5. The fixture and all its parts are fabricated at M/s. Keytex Machines (Surat, India) within acceptable dimensional tolerance after finalizing the drawing. The final fabricated FSW/P fixture is easily installed on the milling machine bed T-slot with the help of ten Allen screws of size M12 $\times$ 1.25. However, the provision of four extreme holes (at the start and the end of processing) rigidly holds the fixture with milling bed even after relaxing the clamping bolt (see Fig. 9.6). For the sliding plates, two Allen

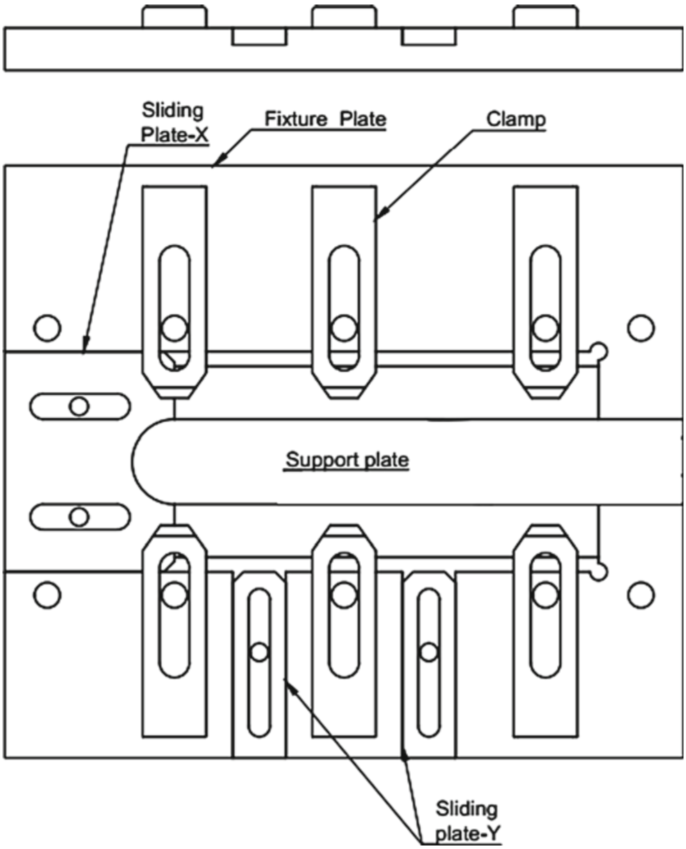

Fig. 9.5 The complete diagram of the fixture and its parts

screws of size M10 × 1.25 are used. Table 9.1 shows the bill of material of designed and fabricated FSW/P fixture.

Heat Treatment of the Fixture Plate

Surface hardening is a process that has a sort of techniques like carburizing, nitriding, carbonitriding, and so on through which wear resistance of component is improved without affecting the ductility of an interior part that gives toughness [18]. The combination of surface hardness for wear resistance and toughness to internal part for impact resistance is useful in applications like gear teeth, cam, shaft, bearing, tools, dies, and automotive clutch plates. The material used for manufacturing fixture is medium carbon steel (C45 steel). It is also designated according to ASTM A29 grades AISI 1045 steel. The chemical composition and material properties are shown

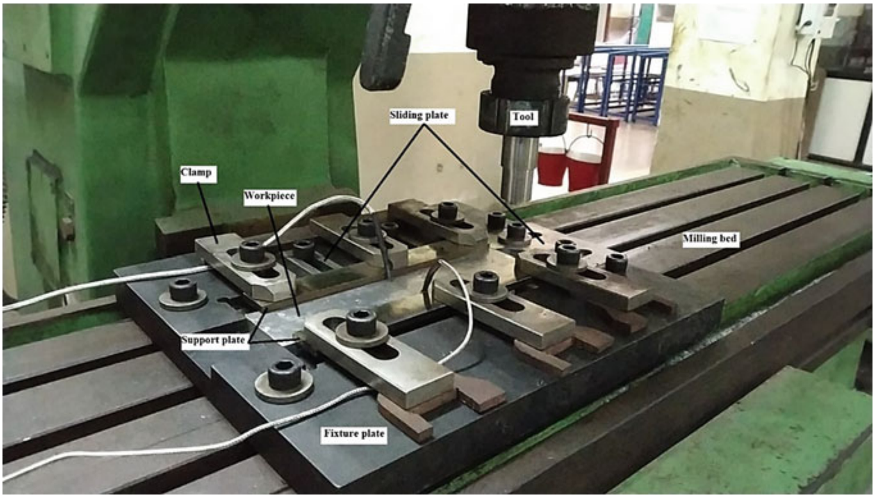

Fig. 9.6 Final fabricated fixture installed on the vertical milling machine bed

Table 9.1 Bill of material

Item No.	Parts	Size (mm)	Material	Quantity
1	Workpiece	200 × 100 × 8	Aluminum alloy	1
2	Fixture/baseplate	320 × 280 × 22	C45 (surface hardened)	1
3	Sliding plate (X direction)	104 × 80 × 8	C45	1
4	Sliding plate (Y direction)	100 × 30 × 10	C45	2
5	Support plate	200 × 25 × 5	C45	2
6	Allen screw	M12 × 1.25	Carbon steel	10
7	Allen screw	M10 × 1.25	Carbon steel	4
8	T-slot nut	–	C45	10

in Tables 9.2 and 9.3, respectively. Its hardness increased by heating it in the furnace between 820 and 950 °C with coke (at austenite with its high solubility of carbon) hold until temperature is uniform throughout the section. So, at this temperature, carbon diffused into the surface and provided a hardness of more than 55 HRC. Thus, this method improves the resistance to surface indentation, fatigue, and wear. Figure 9.6 shows the fixture plate appears black after surface hardening due to carbon diffusion during the hardening process.

Table 9.2 Chemical composition of C45 steel

Element	C	Fe	Mn	P	S
Content (wt %)	0.42–0.50	98.51–98.98	0.60–0.90	≤0.040	≤0.050

Table 9.3 Physical and mechanical properties

Properties	Density	Young's modulus	Poisson's ratio	Yield strength	Ultimate tensile strength
Values	7.87 g/cc	200 GPa	0.33	310 MPa	565 MPa

Testing of Fixture

Finite Element Analysis (FEA) of the Fixture Plate

The mechanism of force action in FSW/P is similar to that of face milling cutting operation. For FEA under static conditions, three maximum forces, such as axial force, transverse/processing force, and torque force generated during the plunging stage are considered. The boundary conditions applied are similar to actual situations. During FSP, the fixture/base plate is fixed to the milling machine bed with a T-slot nut and Allen screws. Therefore, the boundary conditions for the fixture plate is kept fixed in all three directions. All interfaces between the workpiece and fixture plate are kept in sliding contact. The vertical upward movement of a workpiece is restricted due to the clamping device. The results are calculated based on the assumption of linear response to the stress.

Steps of FEA analysis. Following are the steps for the FEA of designed and developed FSW/P fixture:

1. Selection of "Study static stress" from various simulation applications.
2. Selection of fixture material (i.e., AISI 1045) and workpiece material (i.e., AA 6061).
3. Meshing is the most crucial part of the simulation process, where intricate geometries are segregated into simple elements that can be used as discrete local approximations of the larger component. The meshing influences the accuracy, convergence, and speed of the simulation. The smaller the mesh size, the higher the accuracy, but it increases the time to solve. The mesh element type used is a solid tetrahedral with 24,750 elements with 41,802 nodes (see Fig. 9.7).
4. Apply boundary conditions for the FSP fixture model.
5. Application of loads such as vertically downward force due to the FSP tool, torque force generated due to the rotating moment of a tool and horizontal force due to processing speed. Based on the Trimble et al. [4] observation of force measurement during friction stir welding Al alloy, the maximum forces during the plunging stage were taken into consideration for stress analysis. The considered load for static stress analysis is 20 kN for a vertically downward force, 2 kN for a horizontal force, and 60 Nm for a torque force.

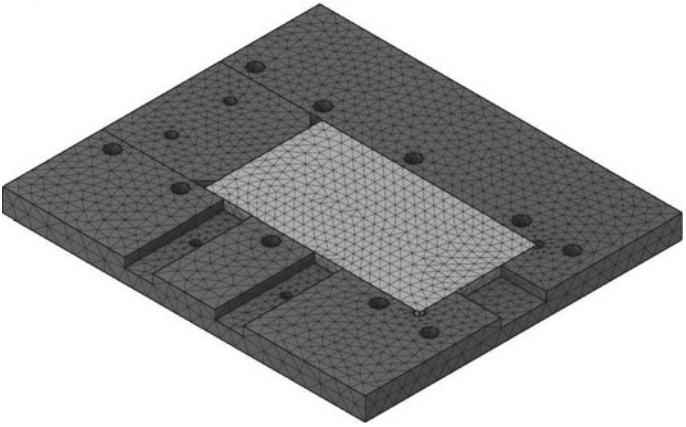

Fig. 9.7 The meshing of the fixture model

6. Solving the fixture model once it verifies the feasibility of the proposed model and its constraint.

FEA result. Von-Mises stress plot obtained after solving the fixture model, as shown in Fig. 9.8. When all three combined loads applied, the maximum Von-Mises stress was 7.248 MPa, which is lower than the yield strength of fixture material. Therefore, no failure is possible as the factor of safety is 15. The list of the result generated in terms of factor of safety, stress, displacement, reaction force, strain, and the contact pressure is shown in Table 9.4.

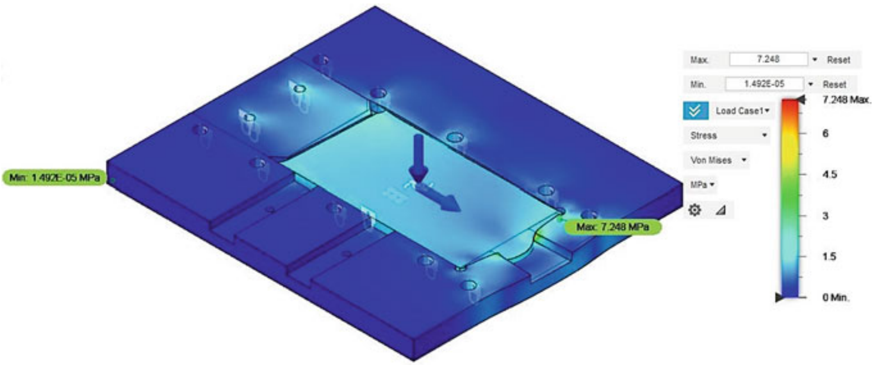

Fig. 9.8 Fixture model stress analysis

Table 9.4 Result summary with its minimum and maximum values

Name	Minimum	Maximum
Safety factor		
Safety factor	15	15
Stress		
Von Mises	1.492×10^{-05} MPa	7.248 MPa
Displacement		
Total	0 mm	0.001298 mm
Reaction force		
Total	0 N	45.69 N
Strain		
Equivalent	1.108×10^{-10}	6.23×10^{-05}
Contact pressure		
Total	0 MPa	8.044 MPa

Experimentation Through a Fixture

The fabricated FSW/P fixture is also experimentally validated on a traditional vertical milling machine of M/s. Batliboi company model number BFV-5 (see Fig. 9.6). The sample prepared with the help of the fixture has no defect, smooth surface finish, and have no distortion. During FSP, lesser vibration and no lateral and longitudinal displacement of the workpiece is observed as it is firmly held by fixture and clamping devices (see Fig. 9.9).

Fig. 9.9 Experiment setup

Conclusion

In this paper, the FSW/P fixture is designed and analyzed with the help of Autodesk Fusion 360 (Education License). Further, the robustness of the fixture and clamping device is validated with experimentation. From the result static stress analysis, it can be perceived that maximum stress generated is 7.248 MPa, the maximum displacement is 0.001298 mm, and the maximum reaction force is 45.69 N, which is within an acceptable tolerance. The stress concentration factor is observed negligibly on the fixture model, which ensures the rigidity of the fixture. The higher factor of safety imparts high failure strength, which is able to bear a higher load without failure. It is also experimentally validated that negligible vibration and no displacement in any direction is observed during FSP. The samples prepared were free from defects, and thus, the proposed fixture design is suitable for the FSW/P process.

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