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ORIGINAL ARTICLE

Using TRIZ methods in friction stir welding design

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Abstract Welding is an extremely important joining method in the manufacturing process. For the last few years, the friction stir welding (FSW) method has significantly increased the quality of a weld. However, FSW has a slightly short research and application progress. The related applied experiences are not prevalent. Therefore, FSW has a lack of reference information on related welding applied design, such as fixture, joining, and integrated design. This article intends to combine innovative design methods in the application of FSW design. Additionally, this article establishes the applied design mode of FSW through case analysis to assist engineers or design personnel who are not familiar with the FSW process. This will help to decrease trial and error or failure risks in the welding process of fixture design. Encountered welding difficulties are thus solved after being guided by the theory of inventive problem solving (TRIZ) design method. By combining traditional TRIZ design methods, this article also refers to other TRIZ methods proposed by some scholars because work will often encounter various engineering challenges. This article hopes to provide welding design personnel with innovative design ideas under research and for practical application.

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Keywords FSW · TRIZ · Fixture design · Innovative

Abbreviations

FSW	Friction stir welding
TRIZ	Theory of inventive problem solving (in Russian)
TWI	The Welding Institute
SEIP	Single engineering inventive principle
FRP	Fiber-reinforced plastic
FSSW	Friction stir spot welding
GTAW	Gas tungsten arc welding

1 Introduction

In the manufacturing field, welding is an extremely important method of metal material shaping. To achieve material bonding and necessary strength in the conventional arc welding process, the operational temperature must reach melting point (as temperature change will easily produce drastic distortion because of thermal expansion and cooling shrinkage to affect manufacturing precision). It is therefore necessary to decrease the influence of distortion by using the correct material selection, welding method, weld design, fixture design, and temperature control.

Ever since the Industrial Revolution, steel became the main applied material. Following the energy crisis and the awakening of environmental consciousness, lightweight, energy saving, recyclable and reusable features of manufacturing, and the use of a metal product became important concerns. Aluminum alloy is corrosion-resistant, lightweight, and recyclable. Therefore, aluminum alloy has gradually replaced steel [1, 2]. But aluminum has a high

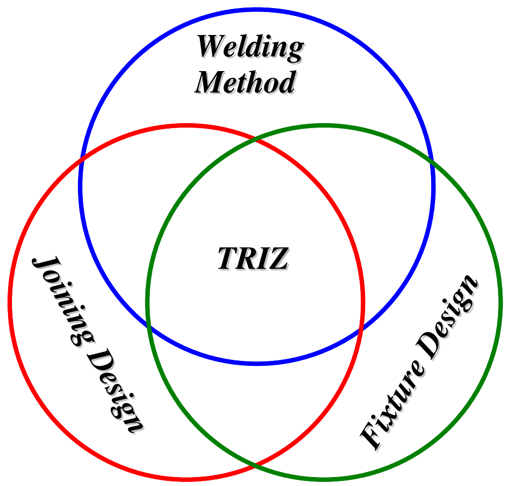

Fig. 1 Welding design connection

thermal conductivity which makes traditional electric arc welding highly difficult. Distortion and strength decrease produced by high temperature result in a technical bottleneck to mass application [3].

Friction stir welding (FSW) was invented by The Welding Institute (TWI) in 1991 [4, 5]. It is different from traditional electric arc welding. FSW conducts material extrusion and stirring to achieve a welding effect by means of welding tool rotation which generates heat by friction. FSW is the best welding method for a high thermal conductivity, like aluminum alloy, and it is stronger than traditional electric arc welding [6].

In previous electric arc welding applications, the welding process and fixture design usually rely on abundant experience to conduct the effective welding design. The most related information indicates that the design of a welding fixture is controlled and protected by patent rights.

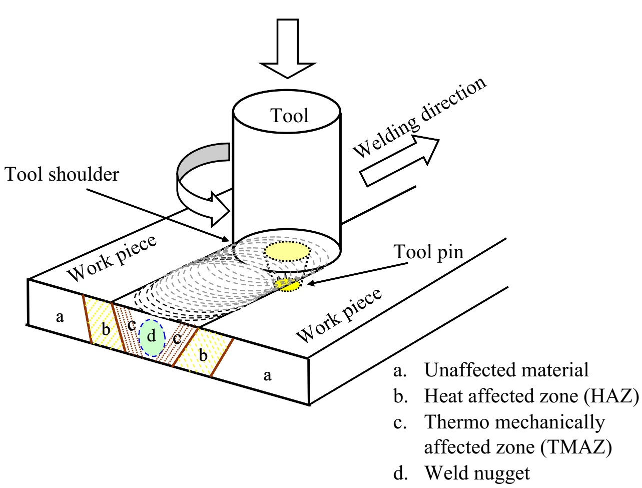

Fig. 2 FSW principle diagram [5]

Table 1 TRIZ 39 engineering features

Number	Features
1	Weight of moving object
2	Weight of non-moving object
3	Length of moving object
4	Length of non-moving object
5	Area of moving object
6	Area of non-moving object
7	Volume of moving object
8	Volume of non-moving object
9	Speed
10	Force
11	Tension, pressure
12	Shape
13	Stability of object
14	Strength
15	Durability of moving object
16	Durability of non-moving object
17	Temperature
18	Brightness
19	Energy spent by moving object
20	Energy spent by non-moving object
21	Power
22	Waste of energy
23	Waste of substance
24	Loss of information
25	Waste of time
26	Amount of substance
27	Reliability
28	Accuracy of measurement
29	Accuracy of manufacture
30	Harmful factors acting on object
31	Harmful side effects
32	Manufacturability
33	Convenience of use
34	Repairability
35	Adaptability
36	Complexity of device
37	Complexity of control
38	Level of automation
39	Productivity

Though FSW has been developed for more than 10 years to produce much related research and literature, they are only focused on material welding property [7–9], welding parameters analysis [10–14], and application [15–17]. There are no referenced discussions or literature about how to conduct welding and fixture design in the application [18–20]. Additionally, it is extremely difficult to find an experienced technical talent of FSW.

Table 2 TRIZ 40 inventive principles

Number	Rules
1	Segmentation
2	Taking out
3	Local quality
4	Asymmetry
5	Merging
6	Universality
7	Nested doll
8	Anti-weight
9	Preliminary anti-action
10	Preliminary action
11	Beforehand cushioning
12	Equipotentiality
13	The other way around
14	Curvature
15	Dynamization
16	Partial or excessive actions
17	Another dimension
18	Mechanical vibration
19	Periodic action
20	Continuity of useful action
21	Skipping
22	Blessing in disguise
23	Feedback
24	Intermediary
25	Self-service
26	Copying
27	Cheap short-living objects
28	Mechanics substitution
29	Pneumatics and hydraulics
30	Flexible shells and thin films
31	Porous materials
32	Color change
33	Homogeneity
34	Discarding and recovering
35	Parameter changes
36	Phase transitions
37	Thermal expansion
38	Strong oxidants
39	Inert atmosphere
40	Composite materials

As such, this article will introduce the theory of inventive problem solving (TRIZ) innovative design method [21, 22] to assist the design development of welding and fixture in the FSW process. Through case analysis, this article wishes to establish a systematic FSW applied design method. Common technical problems in the welding design include method selection and the joining and fixture design, shown in Fig. 1. This article connects method selection and design of joining and fixture through TRIZ to conduct analysis of encountered problems and to locate the solution.

2 Research methodology

2.1 Friction stir welding principle

Through heat sources, such as arc, plasma, and laser, traditional welding method usually melts material to conduct the joining. Working temperature is therefore higher than the metal's melting point. Additional joining produces material changes and large thermal distortion. The required working skills and proficiency are high.

FSW was invented by TWI in 1991 and patented as a new welding technique. Different from the general welding method, FSW uses a spinning non-consumable tool to increase temperature and soften the material by friction. Its principle is shown in Fig. 2:

The non-consumable tool must have a shoulder and a pin. The tool is fastened at the end of a mandrel mechanism that can provide rotation. During FSW process, the workpiece must be fixed. Then, the tool rotates to move downward to shoulder and produce friction on the surface of the workpiece. Heat produced by friction at the tool shoulder facilitates the temperature increase at the welding part of the material and reaches the plastic state. The pin enters the material and rotates concurrently with the shoulder to stir the plastic material. The shoulder presses the plastic material downward for compaction. The stirring tool moves forward along the weld direction and completes the welding process. This can be divided into heating→stirring→pressing→cooling.

Heat produced by friction in the process will gradually stabilize, following the temperature increase and softness of the material (because the material softens and the friction coefficient decreases). The highest working temperature reaches 70–80% of the material's melting point and the material remains in the solid state during the welding process. FSW is a low-temperature and solid-state joining method. This welding process does not need any additional filler. FSW uses mechanic friction so that the workpiece sustains the work force from stirring tool. The workpiece must have a proper fixture to fully bring the FSW feature into play.

Since the temperature is low in this welding process, distortion becomes small after the weld so protective gas and filler are not needed. Additionally, FSW does not produce strong arc light, metal fumes, and spatter. And since FSW does not need to increase material temperature above the melting point, this saves considerable energy

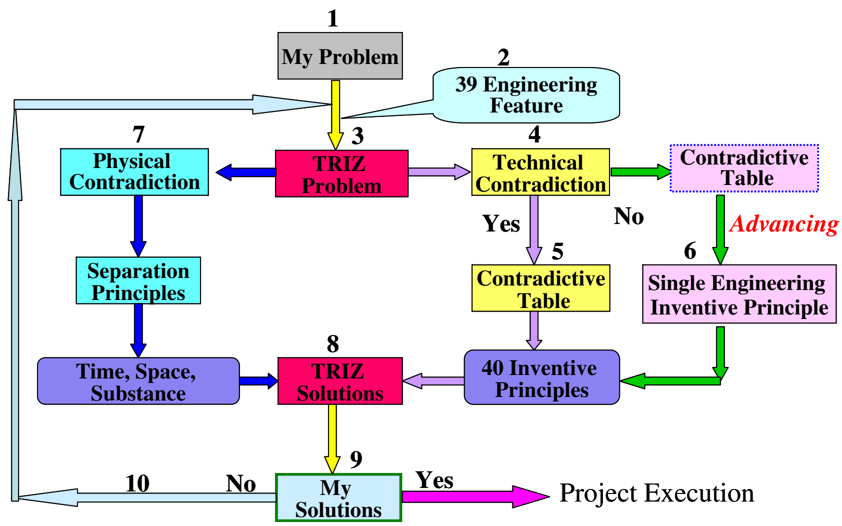

Fig. 3 TRIZ resolving flowchart

consumption. The design requirements of the welding fixture and jig are quite different from the traditional welding method. The FSW method has had great success throughout the industry.

2.2 The TRIZ innovative design method

The TRIZ method was developed in the former Soviet Union by G. Altshuller who had analyzed over 400,000 patents [21, 22]. In solving engineering problems, the engineers usually encounter the system's contradiction, i.e., when a system improves one certain engineering feature, another engineering feature worsens. As soon as the engineer encounters the contradiction, he usually adopts a compromise for handling and does not really solve the problem.

Altshuller thought that problems encountered in the invention could be overcome by the scientific method. Inventions inevitably encounter problems and contradictions, then leap from compromising dilemma. As a result, Atshuller studied worldwide famous patents to eliminate the contradiction method—TRIZ through the integration of interdisciplinary technology. During the problem solving process, TRIZ applies some tools, including separation principle, substance-field analysis, 76 standard solutions, and ARIZ. Among which, the most famous and practical one is the contradictive matrix table that compiles frequently encountered technical contradictions. They are featured into 39 engineering parameters (shown as Table 1) and 40 inventive principles (shown as Table 2) to establish a contradictive matrix and provide solutions for technical contradiction [23–25].

First of all, technical personnel propose the encountered technical problem or conflict. The designer then introduces TRIZ and transfers it into a TRIZ problem. TRIZ tools are used to obtain the general solution of that TRIZ problem and finally transfer that general solution to a solution applicable in engineering technology. The process is shown in Fig. 3.

The TRIZ problem solving process can be divided into the following steps:

Step 1: Confirm and clarify the encountered technical problem and difficulty that needs to be solved.

Step 2: The technical problem goes through TRIZ's 39 engineering parameters and becomes a TRIZ problem.

Step 3: Confirm whether technical contradiction or physics contradiction exists in the TRIZ engineering problem.

Physics contradiction—improving and worsening engineering parameter is the same parameter, i.e., self-conflict, go to step 7;

Technical conflict—different conflict exist or a single improving/worsening engineering parameter.

Step 4: Different parameter technical contradictions exist, then directly enter TRIZ contradictive matrix to locate the corresponding principle. If a single improving or worsening parameter can be located only, or no conflict existed among parameters, go to step 6.

Step 5: Through a TRIZ contradictive matrix (improving parameter is set as *Y*-axis, while worsening parameter is set as *X*-axis), conflict problem can obtain inventive suggested principle, go to step 8.

If a corresponding position is an empty matrix, then go to step 6.

Step 6: Set parameter is introduced into single engineering inventive principle (SEIP) method [26] to obtain

Table 3 SEIP solutions of improving engineering feature

Feature	Rules	Level times			
		A >10 times	B 8–9 times	C 6–7 times	D 4–5times
1	Weight of M	35		18,28,26,27,31,34	02,03,10,29,01,08,19,36,40
2	Weight of non-M	35,10,19,28	01	02,15,18,26	13,22,29
3	Length of M	01,29	15,35,04	08,10,17,24	28
4	Length of non-M		35	28,14	01,26,03,10,15
5	Area of M		02,15	13,26,30,04	10,14,17,29,32,01,18,19,28
6	Area of non-M		18,	02,35	16,30,40,04,36,39
7	Volume of M		35,01	10,29,04,15,34	06,07,13,26,40
8	Volume of non-M	35		02	10,14,34
9	Speed	28	35,13	10,19,34,38	02,18,01,08,15
10	Force	35,10,18,37	36,01	15,19,28	03,13,21
11	Tension/pressure	35,10,36	37	02	14,03,19
12	Shape	10	01,14,15	32,34,35	02,04,29,40,13,22,26
13	Stability of object	35	02,39	27,40	01,13,15,18,32,10,28,30
14	Strength	03,35,10,40	15	27,28,14	26,01,29
15	Durability of M	19,35	03,10	27	02,28
16	Durability of non-M			10,35	01,16
17	Temperature	35,19	02	03,22	16,17,18,32,39,10,27,30,36
18	Brightness	19,32	01	15,26,35	02,06,13,16
19	Energy spent by M	35	19	18,28,02,15	12,06,24
20	Energy spent by non-M				19,35
21	Power	35,19,02,10		38,26,34	06,17,16,28,32
22	Waste of energy		07,35	02	06,18,19,38,10
23	Waste of substance	10,35,18,28	31	24,02,27	03,39,40,06,29,34
24	Loss of information		10		26,35,22
25	Waste of time	10,35,18,28		04,05,32,34	20,24,26,29
26	Amount of substance	35,03,29	18	10,14	27,28,40,02,15,31
27	Reliability	35,11,10	03,28,40	27	01,02,08,13,21,24,32
28	Accuracy of measurement	32,28,06	26	03,10,13,24,35	34,01,02
29	Accuracy of manufacture	32	28,10	02,18,26	35,02
30	Harmful factors acting on object	22,35,02	01,33	18,19,24,28,39	27,40,10,13,37
31	Harmful side effects	22,35,02	01,39	18	40,15,17,19,21,24
32	Manufacturability	01	13,27,35,28		15,16,24,12,26
33	Convenience of use	01,13	02	12,28,32,34,15,25,35	16,17
34	Repair ability	01,10,02	11,35	13,15,25	16,32,27,28
35	Adaptability	35,01,15		16,29	13,02,06
36	Complexity of device	13	01,28,26	02,10,19,24,29,35	15,17,27,34
37	Complexity of control	28	35	16,26,27,01,02,19	03,13,15,24,29,39
38	Level of automation	35,13	28	26,01,02	10,18,27,32
39	Productivity	10,35,28	01	18	02,26,38,24,34,37

inventive suggested principles (shown as Tables 3 and 4), go to step 8.

Step 7: TRIZ separation principle is used to obtain suggested principle through separation of time, space, and substance.

Step 8: Obtained TRIZ suggested principle conducts proper selection to obtain TRIZ solution.

Step 9: TRIZ solution transfers to inventive design reference for solving an actual engineering problem to produce a final solution.

Table 4 SEIP solutions of worsening engineering feature

Feature	Rules	Level times			
		A >10 times	B 8–9 times	C 6–7 times	D 4–5times
1	Weight of M		35	08,15,28,02,26,40	06,10,18,28,29,01,13,19,31,36,37,38
2	Weight of non-M	35	27,26,28	01,10,06,13,19	18,02,22
3	Length of M	01	15,29,14,17,28	04,13,19,35,10	02,09,16,26
4	Length of non-M			10,14,26	01,28,35,07,16
5	Area of M	17	15	13,26,10,29	01,19,34,02,03,04,14,30,32
6	Area of non-M			35,16,18,40	02,10,17,39,30
7	Volume of M		35,02,10	29,15	06,07,13,01,04,14,34,40
8	Volume of non-M	35	02	18	
9	Speed	35,28	13	34,10,12	08,04,38
10	Force	35,10,36	28	02,19,18,37	15,03,16,21,26,40
11	Tension/pressure	35,10	37,36		02,03,14,18,19,01,40
12	Shape	01,35	29,10,14,15	13,04,34,40	38,32,02
13	Stability of object	35,39	01,02	13,18,30,40	03,32,17,22
14	Strength	28,03,35	10,14,40	15,09,27	18,02,26,32
15	Durability of M	35	03,19	10,27,28,06	02,18,25
16	Durability of non-M		16	35	10,01,40
17	Temperature	35,19	02	10,03,39	18,21,22,26,27,28,32,38
18	Brightness	19,32,01,13		15	02,24,06,17,26,35
19	Energy spent by M	35,19		06	01,02,24,32,10,13,18,27,28,38
20	Energy spent by non-M			01	35
21	Power	35,19,10	02,18	32,06	27,31,38
22	Waste of energy	35,02	19,15	10	06,07,13,14,18,28,32
23	Waste of substance	10,35,28	18	02,05,24,27,31,39	03,13,29,34,40
24	Loss of information	10		24	35,22,26
25	Waste of time	10,28,35,18		32,04,34	20,26,29
26	Amount of substance	35,03	18,29	10	06,19,24,30,31
27	Reliability	10,11,35,40	27	01,03,28	13,02,08,19,24,29
28	Accuracy of measurement	28,32,26	03	10,01,24,34	02,13
29	Accuracy of manufacture	32	10,28	18,26,35	02,01,03,24,25
30	Harmful factors acting on object	22,35,02,01		28,33,18,19,27	24,40,10,37
31	Harmful side effects	35,02,22,39		18,01	21,40,17,24
32	Manufacturability	01,35	28	26,27	13,10,29
33	Convenience of use	01	28,35	02,32,13,15,26	12,27,16,25,34
34	Repair ability	01,10,02		11,13,27,35	16,28,32,15
35	Adaptability	15,01,35		02,29	13,16
36	Complexity of device	01,26	10,28	35,13,29	02,19,15,24,27,34
37	Complexity of control	35	27	26,28,02,18	03,15,19,29,01,10,25,32
38	Level of automation	35	02	26,34,01,28	10,24,18
39	Productivity	35,10,28		01	14,15,29,34,37,02,03,17,26

Step 10: When obtained suggested principle cannot satisfy final demand, engineering parameter can be redefined to go through steps 1 to 9 once again and obtain new suggested inventive principle, go back to step 3.

Use of TRIZ contradictive matrix is shown in Table 5: when "#21-Power" is selected as an improving feature and "#9-Speed" as a worsening feature, respectively. The corresponding matrix obtains suggested inventive principles as 2, 15, and 35.

Table 5 The usage of TRIZ contradictive matrix

Improving Feature \ Worsening Feature		…	#9	#10	…
		…	speed	Force	…
…	…	--	--	--	--
#21	Power	--	**2** - Taking Out **15**- Dynamization **35**- Parameter Changes	2,26, 35,36	--
#22	Waste of energy	--	16,35,38	36,38	--
…	…	--	--	--	--

Table 6 TRIZ solutions of feature #20 relative to feature #27

Improving \ Worsening	#27 Reliability
#20 Energy spent by non-moving object	10 Preliminary Action 23 Feedback 36 Phase Transitions

Fig. 4 ARC welding

Fig. 5 FSW welding

Fig. 6 Grooved for ARC welding

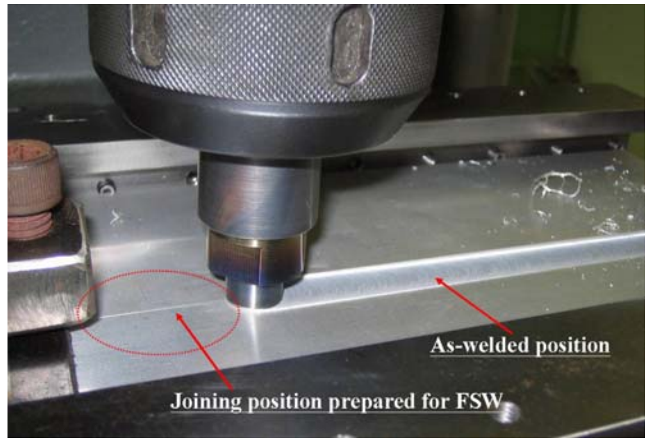

Fig. 7 Prepared surfaces for FSW

Since TRIZ theory originates from invention in different technical fields and integrates physics, chemical, and engineering sciences, the theory is beyond field limitation and can be fully applied in other industries. TRIZ is therefore widely applied as a technical tool for engineering conflict and inventive R&D. In the preliminary stage and application of new technology, TRIZ can fully bring its effect into fully play, especially when there is a lack of reference data and insufficient experience.

The advantages of TRIZ are that it can transfer system contradiction and conflict into a useful factor and be compiled into an effective method to solve the problem to facilitate research and for design personnel to rapidly solve the problem.

3 Design examples analysis

3.1 Example 1—selection of welding method

Welding requires heating to reach melting status to join. If input heat is insufficient, incompatibility or incomplete fusion will be produced. However, if input heat is too high, the heat-affected zone becomes too large to affect joining quality. This effect becomes significant in aluminum alloy material which has high thermal conductivity rate. Input heat improvement and control is an important engineering parameter in welding and can be regard as "#20-Energy spent by a non-moving object" in the TRIZ engineering feature. In the meantime, welding does not want a negative effect and can regard TRIZ worsening parameter "#27-Reliability." When we refer these two parameters to TRIZ contradiction table, we can locate inventive suggested principles, as shown in Table 6.

Choosing inventive principle "#36-Phase transitions" relates to temperature. Traditional electric arc welding requires weld temperature to reach material melting point. Then, the welding area will form a liquid fusion to complete welding. This is shown in Fig. 4. If FSW is adopted and uses aluminum alloy as an example, the highest operational temperature is about 550°C. The welding area still retains a solid state shown in Fig. 5. Taking aluminum alloy 6061T6 as an example, the material's physical state changes and welding strength increases from 60% of base metal to 78% [12]. FSW uses only one sixth of the energy as compared to electric arc method [27, 28]. Therefore, FSW is the suitable choice.

3.2 Example 2—welding method selection

Manufacturing wants to decrease welding locations to the minimum to reduce the influence of distortion and improve welding quality. If electric arc welding is adopted, grooving

Table 7 TRIZ solutions of feature #23 relative to feature #32

Improving \ Worsening	#32-Manufacturability
#23-Waste of substance	15 Dynamization 33 Homogeneity 34 Discarding and Recovering

Table 8 TRIZ solutions of feature #33 relative to feature #14

Improving \ Worsening	#14-Strength
#33- Convenience of use	3 Local Quality 28 Mechanics Substitution 32 Colour Change 40 Composite Materials

must be done to the welding position of the workpiece, as shown in Fig. 6. Welding consumable is melted to fill in to truly achieve the full joining and dilution. This welding process must remove material at the welding location and filler, flux, and protective inert gas are involved. To ensure joining strength, welding consumable and base metal must adopt different materials [4]. The function of the flux and protective inert gas is to enhance alloy composition and prevent oxidation of melting metal. The above welding process indicates a double waste to use a material (remove then fill in) that will increase the manufacturing cost.

TRIZ is therefore introduced. In the welding process, improving parameter and worsening parameter can be regarded as "#23-Waste of substance" and "#32-Manufacturability," respectively. TRIZ hopes to reduce material waste required by the welding process. The corresponding suggested principles are shown in Table 7:

In terms of #33-homogeneity, the feasible method is that penetration welding is directly conducted to the welding position without grooving. Thus, additional filler is not needed and the process is simple. However, this method is usually applicable in a thin workpiece. If penetration welding has to be done to a thick plate, FSW or expensive electron beam welding must be adopted.

If "#15-Dynamics" is considered, friction spinning and concurrent stirring of FSW do not need additional filler. This feasible welding method is shown in Fig. 7.

If considered factors in the welding processes are different, such as complicated profile, large variety, and small quantity, and so on, the welding process is expected not to affect the welding strength quality and can be rapidly and conveniently done. Through TRIZ, improving parameter and worsening parameter can be set as "#33-Convenience of use" and "#14-Strength" separately. The corresponding principles are shown in Table 8:

Among corresponding principles, feasible suggestion is "#40-Composite materials." Welding process can change into:

1. Different materials are used to conduct joining, such as adhesive bonding, brazing, and soldering.
2. To groove weld and fill in welding consumable.

3.3 Example 3—the development of the missile launch tube

Missiles are an important item in ammunition and are equipped with a specific tube for launching and transport. Previous tube material includes fiber-reinforced plastic (FRP) and steel. Though FRP is lightweight for easy transport and is easily made, FRP is easily burned and damaged after launching and cannot be used for recycling. Additionally, FRP cannot be recycled and does not conform to environmental requirements. However, steel is heavy and is not good for mobile transportation. In consideration of environmental protection and practical utility, aluminum alloy is adopted to conduct the development and manufacturing of the tube. Since the tube is slim, long, and has a hollow structure, internal size becomes the important manufacturing focus as the internal part must facilitate the smooth passing of the missile. The manufacturing method includes machining, hot extrusion, and assembly welding. However, the manufacturing method is limited by the

Table 9 TRIZ solutions of feature #23 relative to feature #8

Improving \ Worsening	#8- Volume of non-moving object
#33- Convenience of use	None suggestions

Table 10 SEIP solutions of improving feature #8

Appeared no.	Innovative rules
>10 times	35 Parameter change
6–7 times	2 Taking out

function of the manufacturing equipment and cannot be conducted by machining and hot extrusion. Only the assembly welding method can be used. Traditional electric arc welding inevitably causes extreme distortion. FSW is therefore the only feasible method.

The internal box size must be maintained within a certain tolerance, and the internal parts cannot conduct treatment after assembly welding. Proper fixture must be designed to maintain precise internal size after FSW. Fixture can provide necessary clamping, positioning, and size control. The TRIZ method is introduced to conduct the design of necessary fixture and provide direction and suggestions.

Precise control of internal box size can be regarded as TRIZ improving parameter "#8-Volume of non-moving object." Additionally, manufacturing must consider convenience of use that fixture cannot be dismantled due to as-welded shrinkage and stress distortion. Worsening parameter is therefore selected as "#33-Convenience of use." After referring to TRIZ contradictive table, this is an empty matrix so that TRIZ does not provide any suggested principle as shown in Table 9.

As a result, we refer to the SEIP method that is derived from TRIZ contradictive table. When there is an empty matrix or no contradiction has existed, those principles appearing most frequently in the contradictive matrix are used as suggested principles. Engineering parameter "#8-Volume of non-moving object" among improving feature table is compiled into statistics; part of the frequency of the appearances of these parameter's corresponding principles are listed as the Table 10.

As for the engineering parameter "#33-Convenience of use," if worsening inventive principle is referred, part

Table 11 Prior inventive principles of SEIP for worsening #33

Appeared no.	Innovative rules
>10 times	1 Segmentation
8–9 times	28 Mechanics Substitution
	35 Parameter changes
6–7 times	2 Taking out
	32 Color change
	13 The other way around
	15 Dynamization
	26 Copying

Table 12 Prior inventive principles of SEIP for improving #29

Appeared no.	Innovative rules
>10 times	32 Color change
8–9 times	28 Mechanics substitution
	10 Preliminary action
6–7 times	2 Taking out
	18 Mechanical vibration
	26 Copying

of the frequency of appearances of these parameters corresponding principles is listed in Table 11.

If "#29-Accuracy of manufacture" is taken into consideration for improving, part of the frequency of appearances of these parameters corresponding principles is listed in Table 12.

To summarize, multiple engineering inventive principle "2-Taking out" has been appearing many times and is used as a common suggested principle.

From the actual profile, internal support of a welding product really needs the withdrawing method after the welding process. However, how to withdraw internal support is a problem. Since as-welded material is equipped with expansion when heated and shrinkage when cooling, it could tightly restrain internal support and cannot withdraw it. Inventive principles "1-Segmentation", "15-Dynamization," and "10-Beforehand cushioning" can be chosen to propose design ideas. Inventive principle "1-Segmentation" can conduct a separate design to internal support. Inventive principle "15-Dynamization" can give an idea to design proper relative motion among components.

Additionally, inventive principle "10-Beforehand cushioning" can propose an idea to leave shrinkage volume [12] after FSW when workpiece conducts pre-machining. Actual application is shown in Fig. 8.

3.4 Example 4—aluminum heater and copper backing plate

Target backing plates are used for sputtering target loading and cooling in the film coating process of optoelectronics and liquid crystal display (LCD) industries. The target material is tightly adhered to the target backing plate which is made of pure copper. High temperatures produced in the film coating process are controlled by a water cooling system inside the plate. The manufacturing process will dig out a water path in the copper plate and then seal weld the gating cover to the backing plate. It can withstand water pressures up to 6 kg/cm^2. This weld requires tight joining with the target to actually achieve a cooling effect. Since surface flatness after treatment becomes extremely important for seal welding, huge welding distortion cannot achieve the flatness requirement.

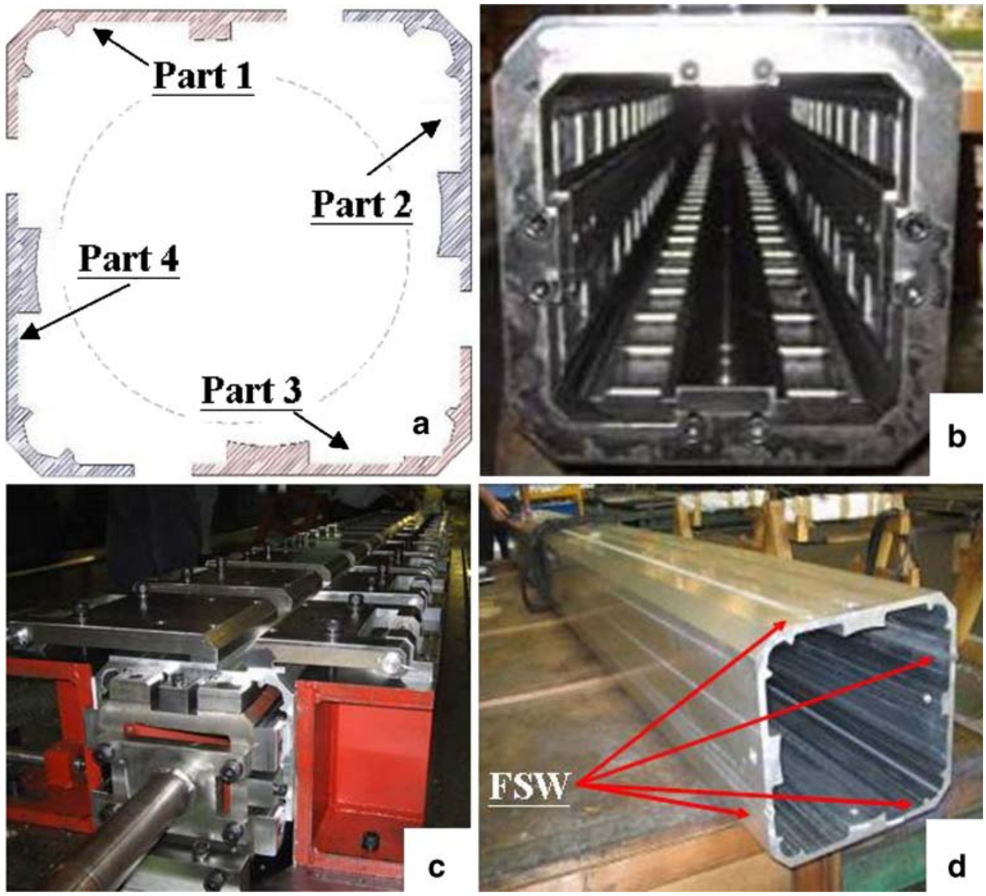

Fig 8 Fixture and manufacturing for launch box: **a** Segmentation design for parts, **b** dynamic sliding fixture, **c** fixture assembly and FSW, **d** as-welded finished product

In the LCD manufacturing array process, the heater of the chemical vapor deposition plasma equipment is an aluminum component for product heating. After the component within a thick aluminum plate has a specific groove, it then installs the heating coil and conducts a seal weld with cover. Except for the sealing requirement, the coil must closely make contact within the aluminum plate to truly conduct thermal conductivity and heating purpose.

The aluminum heater and the target backing plate have a common point where the welding track is a 2D curve. The sealing and high thermal conductivity material (especially the target backing plate) is made of pure copper. The thermal conductivity rate of copper is higher than that of aluminum. Therefore, it is hard to do a large area by traditional electric arc welding. The existing method is electronic beam welding; yet, costs are considerably high.

The FSW process accompanies an extremely high extrusion. When the water path or coil cover is not well fixed, FSW will cause distortion and warpage to break away from the original position. Additionally, the number of back and forth welds are intensive. If every part has to be fixed and does not affect the weld marching track, it is not easy to conduct design and assembly of fixture.

Fixture design hopes to operate under simple components application and does affect convenience of use. As a result, this problem is set as improving parameter "#26-Amount of substance" meanwhile worsening parameter is

Table 13 TRIZ solutions of feature #26 relative to feature #33

Improving \ Worsening	#33-Convenience of use
#26-Amount of substance	10 Preliminary Action 25 Self-Service 29 Pneumatics and Hydraulics 35 Parameter Changes

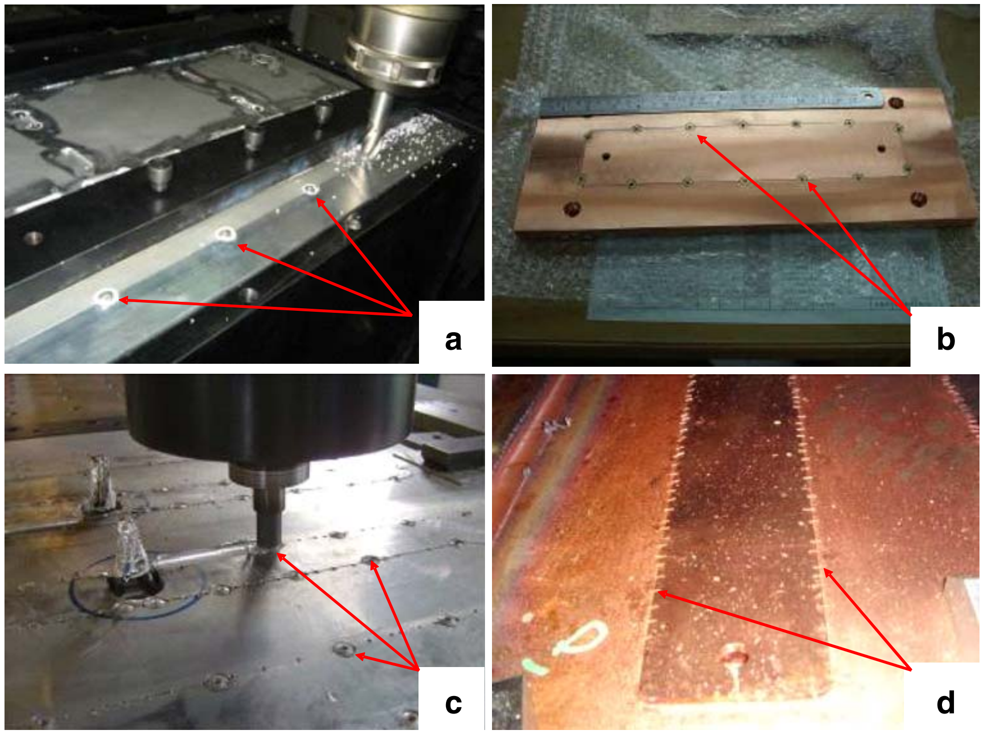

Fig. 9 Pre-fixed modes: **a** False welding, **b** fasten by screw, **c** FSSW, **d** hammering

"#33-Convenience of use." To refer to the contradictive table, the suggested principles are as shown in Table 13.

Inventive principle "10-Preliminary action" and "25-Self-service" have high feasibility in this problem. The electric arc welding processes usually conduct false welding to do partial surface welding on different components for decreasing movement before the formal welding assembly. If assembly position is correct, then formal welding is conducted. If position is not right, the surface false welding position is removed and then the components will separate.

With TRIZ suggested principles and a combination of previous experiences, cover and body can conduct partial connection. Feasible method includes: (1) arc weld con-

Fig. 10 Cu backing plate

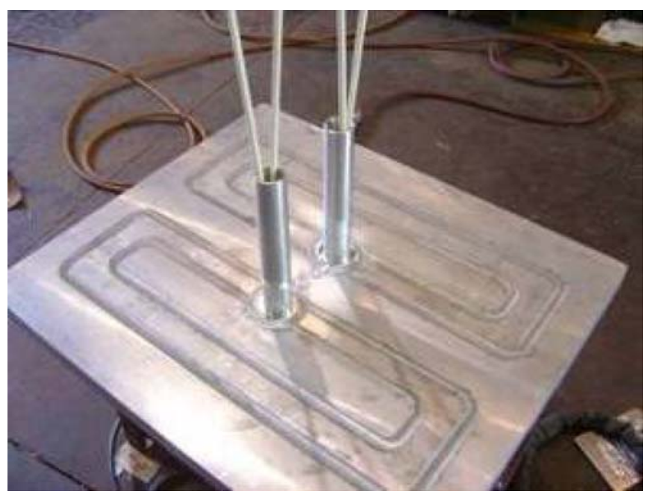

Fig. 11 Al heater

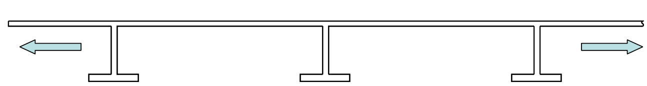

Fig. 12 Desk cross-sections

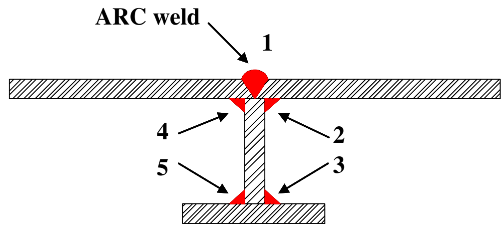

Fig. 13 ARC welding design

ducts false welding; (2) fastens by the same material screw; (3) friction stir spot welding (FSSW); and (4) hammering method causes the distortion of welding position, as shown in Fig. 9.

Among which, the first method does not have sufficient pre-heating as aluminum and copper have high thermal conductivity and false welding only does partial welding on the surface. Sometimes, the temperature gap is too huge to produce cracking so that the effect is not good.

The second method requires additional step for drilling, threading, and making a specific screw; the third method, tool of FSW, can conduct FSSW at weld track with additional auxiliary. Finally, using the fourth method, hammering distortion, will cause poor fixation between cover and body.

Among which, the third method does not require additional resource and completely conforms the suggested TRIZ principles "#10-Preliminary action" and "#25-Self-service". Application illustrations are shown in Figs. 10 and 11.

The third method does not require the design of an additional fixture within the workpiece; simple fixation and press at the edge of workpiece will serve the function. This design conforms to the TRIZ rule of ideality.

3.5 Example 5—aluminum deck structure on ships

Ships in the past were usually all made of steel. Its overall weight was quite heavy which would require huge oil consumption. To cope with soaring oil prices, increase of transportation speed and decrease of time and cost, aluminum alloys are replacing steel to make vessel structural parts. Especially the deck above the water line is adopting aluminum alloy to decrease vessel weight. Generally speaking, a vessel deck has a huge area and requires plate expansion by welding and rib enhancement to achieve the desired strength.

Previously, the gas tungsten arc welding (GTAW) method was used for plate joining. It requires many welds and has a huge as-welded distortion to affect quality and function of assembly. Taking Fig. 12 as an example, four plates are assembled; yet, every unit must conduct welding at five locations, as shown in Fig. 13. Additionally, too many welds require fillers that increase weight and waste material cost and technical personnel. When FSW is introduced, distortion and bonding strength can be improved. Plus, the required number of welds can be reduced.

Since the formation of a large area deck inevitably goes through a welding process, a proper welding design change may facilitate a simple, convenient, and reliable manufacturing process.

When the TRIZ design method is introduced, distortion improvement can be regarded as TRIZ improving parameters "#12-Shape" and "#29-Accuracy of manufacture." We also hope to improve distortion, not require additional enhance-

Table 14 TRIZ solutions of feature #12 & 29 relative to feature #14 & 23

Improving \ Worsening	#14-Strength	#23-Waste of substance
#12-Shape	10 Preliminary Action 14 Curvature 30 Curvature 40 Composite Materials	3 Local Quality 5 Merging 29Pneumatics and Hydraulics 35 Parameter Changes
#29-Accuracy of manufacture	3 Local Quality 27 Cheap Short-Living Objects	10 Preliminary Action 24 Intermediary 31 Porous Materials 35 Parameter Changes

Table 15 TRIZ solutions of feature #14 relative to feature #32

Improving \ Worsening	#32-Manufacturability
#14-Strength	3 Local Quality 10 Preliminary Action 11 Beforehand Cushioning 32 Colour Change

ment, or cause strength reduction. The corresponding worsening parameters can be regarded as“#14-Strength” and“#23-Waste of substance.” Contradictive table can obtain suggested principles as shown in Table 14:

If “#14-Strength” lists as improving parameter and does not want “#32-Manufacturability” to become worse, the obtained suggested principles are shown in Table 15.

Based on Table 15, “3-Local quality” and “10-Preliminary action” have high priority and appearance times.

Inventive principle “10-Preliminary action” can conduct a preset of rib enhancement by aluminum extrusion method to form I beam. Inventive principle “3-Local quality” can conduct partial assembly of three to one (two plates plus I beam with aluminum extrusion material) and decrease number of welds to one pass, as shown in Fig. 14.

After the introduction of FSW and the application of TRIZ, the design changes to increase production efficiency, reduce distortion, and not require post-treatment.

3.6 Example 6—FSW roller press

In the FSW process, we do not need additional fillers so that bonding of a workpiece will closely join and fix. When a workpiece is closely joined and fixed, the workpiece will not have distortion, warpage, or separation due to extrusion and thermal distortion in the stirring process. If the workpiece does not easily allow fixture or have an irregular surface, the FSW tool cannot maintain the relative welding depth with the workpiece to touch the bottom. So the shoulder does not conduct friction with the workpiece.

Therefore, the FSW process needs to maintain a constant welding depth. In the TRIZ engineering parameter, improving tool working depth can be regarded as “#3-Length of moving object.” Meanwhile, we do not want to press a workpiece due to height difference for it may separate. The worsening parameter is “#35-Adaptability.” Contradictive table can obtain suggested principles as shown in Table 16.

Among which, “1-Segmentation,” “14-Spheroidality curvature,” and “15-Dynamics” provide directions for improving design.

Additional fixed roller can be installed on main tool stirring mandrel of FSW to concurrently move along with main axis. When the tool conducts welding to a workpiece, this additional structure can press the workpiece at the same time. However, the FSW process is moving so a fixed roller can march forward along with the main axis. Corresponding to those suggested principles, design of the fixing end must be a cylinder roller and can be rotated, as shown in Fig. 15.

3.7 Example 7—development of aluminum alloy fuel tank

To increase cruising range, an aircraft adds an auxiliary fuel tank for carrying more fuel. To decrease fuel tank weight, a thin walled structure of 6061 aluminum alloy is adopted. Under design volume requirements, all joining positions on the fuel tank do not allow for leakage and the internal part must sustain a pressure test of 5 kg/cm^2. After machining, strict flatness is required. If as-welded distortion is too huge, it cannot achieve aviation design standard. The fuel tank design illustrated in Fig. 18 is made up of 27 parts. Thickness of main housing is 6 mm only, internal enhanced partition is 4 mm thick, and empty weight is 60 kg, as shown in Fig. 16.

The original design adopts GTAW to do the joining. Though the welding process is simple, the as-weld produces multi-direction distortion which exceeds preset machining volume, so it cannot achieve the required final

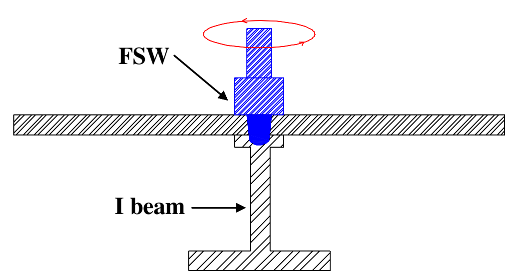

Fig. 14 TRIZ-FSW design

Table 16 TRIZ solutions of feature #3 relative to feature #35

Improving \ Worsening	#35-Adaptability
#3-Length of moving object	1 Segmentation 14 Curvature 15 Dynamization 16 Partial or Excessive Actions

dimension. The TRIZ design method is introduced for solving this problem.

In example 3.1, the FSW process is introduced; however, not all joining parts can be replaced by FSW. Based on manufacturing features, we locate the joining places that can apply the FSW process. After the joining places are located, we use example 3.2 for feedback to initial designed diagram. Then, we do design the changes and fill up the groove by arc welding to conform to aviation standards.

Welding places that can be replaced by FSW are distributed on five areas of a fuel tank: normal, backing, main plate, and two sides, as shown in Fig. 18. The size and joining part on each side are different and require having a different fixture design. If the five sides are individually made, FSW requires five kinds of fixture. Additionally, FSW needs positioning assembly fixture for the internal partition. The required fixture manufacturing cost will exceed the budget limit. As a result, TRIZ method is used to perform the fixture design.

First of all, the fixture must be applicable for welding at different positions, easily changed, easily manufactured, and can effectively conduct fixation. Also, the number of components should be decreased to reduce the manufacturing cost. Based on the TRIZ method, a fixture is used at different welding positions and can be regarded as improving parameter "#35-Adaptability"; meanwhile, we hope not to affect convenience of use. The worsening parameter is "#33-Convenience of use." The TRIZ contradictive table can obtain suggested principles as shown in Table 17.

Additionally, we hope to simplify the fixture manufacture corresponding to improving parameter "#32-Manufacturability" and produce a sufficient, stable holding effect corresponding to improving parameter "#13-Stability of object" at the same time decreasing fixture components to increase manufacturing cost, corresponding to the worsening parameter "#26-Amount of substance.". The TRIZ contradictive table can obtain suggested principles as shown in Table 18.

These suggestions indicate that "1-Segmentation" and "15-Dynamization" are common suggested principles. Furthermore, TRIZ sub-principles show that"1-Segmentation" would suggest that the object be divided into individual parts then made as an assembled object, and "15-Dynamization" also suggests dividing object into components and facilitating each component location, as needed.

Fig. 15 Dynamic fixed roller [29]

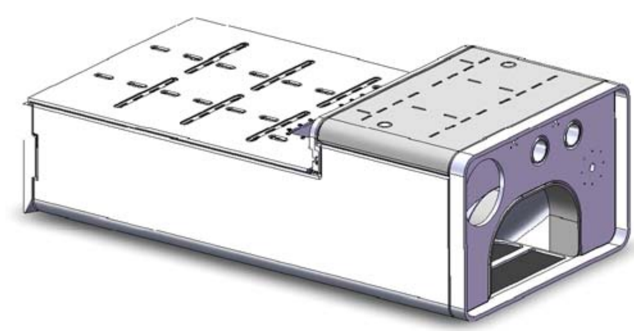

Fig. 16 Designed aluminum fuel tank

Table 17 TRIZ solutions of feature #35 relative to feature #33

Worsening / Improving	#33-Convenience of use
#35-Adaptability	1 Segmentation 15 Dynamization 16 Partial or Excessive Actions 34 Discarding and Recovering

The suggested inventive principles will design the fixture as a brick plate structure to fix and combine at the hole site. This method fully uses a different hole site on a component to conduct fixture and positioning assembly of different welding locations. This method can really achieve multiple changes and holding function. It can also be applicable in common application of FSW and GTAW. Figure 17 illustrates internal enforce assembly, while Fig. 18 indicates the sides of a fuel tank, including normal, backing, side, and main plate. Finally, Fig. 19 shows the finished product of FSW.

4 Conclusions

FSW gradually becomes an important method to form components in the manufacturing process. Though welding technologies such as material, welding quality, parameter comparison, microstructure, simulation analysis, and mechanical property have abundant studies, yet there is a lack of process design in the application of FSW. This article proposes to combine TRIZ and provide necessary concept design suggestions of the FSW process. Through verification and analysis of applied cases, this article obtains the following conclusions:

1. Through case analysis, the effective welding process control, the best welding parameter, appropriate process design, such as method selection, clamping method, and so on can precisely, rapidly, and effectively achieve the desired welding quality.
2. The welding process is different from general machining. It is a dynamic process (melting and solidification) and the material produces different changes along with the process. The design of the clamping method cannot have a basic principle of point, line, and surface as machining. The TRIZ innovative design is not limited by a fixed design model. It helps us develop new solutions to welding problems.
3. Under a different parameter combination, the TRIZ tool can acquire different innovative principles and provide a welding clamping design and concept to avoid much unnecessary trial and error work.
4. In terms of FSW cases, conflict problems (technical or physical) encountered in the process can be provided by the alternative thinking principles of TRIZ. Thus,

Table 18 TRIZ solutions of feature #32 & 13 relative to feature #26

Worsening / Improving	#26-Amount of substance
#32-Manufacturability	1 Segmentation 23 Feedback 24 Intermediary 35 Parameter Changes
#13-Stability of object	15 Dynamization 32 Colour Change 35 Parameter Changes

Fig. 17 Used for internal enforce assembly by GTAW welding

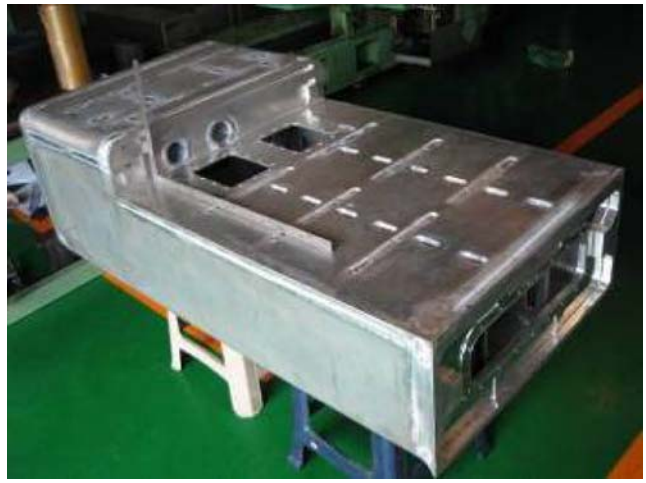

Fig. 19 As-welded tank

innovation replaces conventional compromise to avoid reduction of process quality.

5. In the TRIZ method, designer thinking is not limited by a single professional experience and the solution is equipped with innovation and diversification. Through the FSW applied cases, this article effectively combines TRIZ to conduct a welding process design that can remarkably reduce the reliance on professional technical personnel in the future welding process.
6. In the future, TRIZ cases applied in FSW will be accumulated to establish parameters and suggested design principles in the welding process to serve as references to subsequent designers and shorten R&D duration.
7. Through TRIZ design and FSW applied cases, this article hopes to explore TRIZ to design and process improvement of other machining and to establish parameters and suggested design principles of different fields.

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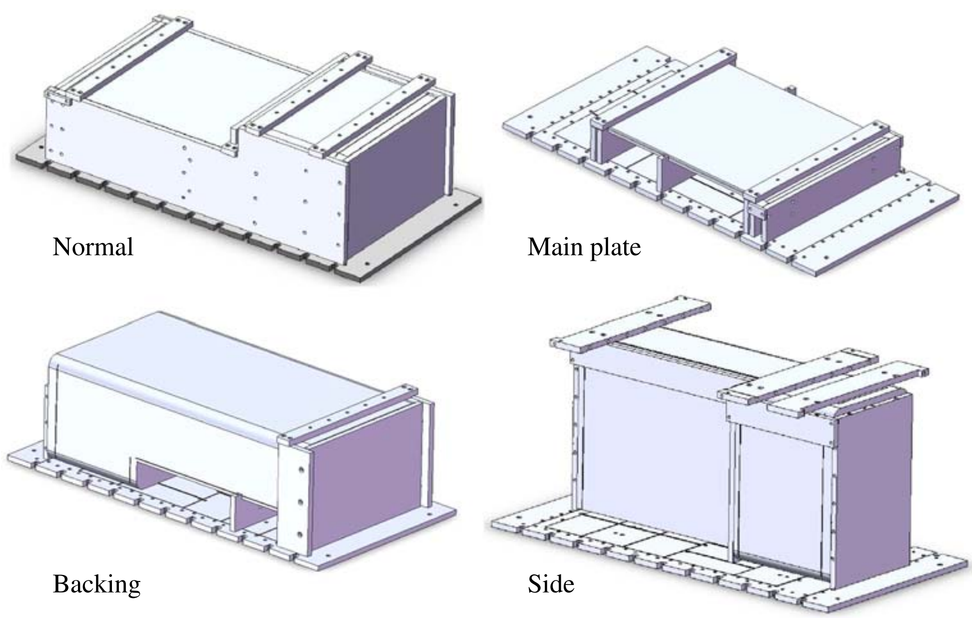

Fig. 18 Used for outer main enclosed assembly by FSW

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