Interfacial quality prediction model for Al/steel sheets during friction stir–assisted double-sided incremental forming with synchronous bonding

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Abstract
The widely investigated Al/steel laminated structures are challenged with subsequent plastic deformation due to the prone generation of interfacial brittle intermetallic compound layer. To overcome this drawback, a recently proposed thermomechanical forming technology as friction stir–assisted double-sided incremental plastic forming with synchronous solid-state interfacial bonding is utilized to fabricate Al/steel laminated structures. Typical interfacial bonding-forming performances produced by a series of experiments classified as sound bonding, de-bonding, over-thinning, penetration and crack are individually assessed. Local working peak temperature and maximum forming force in loading area are recorded and evaluated during stable bonding-forming stage. Considering the heat-force coupling effect, a pressure-strain-temperature–based prediction model is modified to assess interfacial quality, which is conformed to experimental results. This work can help obtain proper process window to successfully fabricate Al/steel laminated parts and shall also inspire to build guidance of related thermomechanical joining-with-forming processes to achieve high interfacial performance.

Keywords Dissimilar Al/steel bonding · Friction stir · Double-sided incremental forming · Process quality prediction · Interfacial performance

1 Introduction
The demands of lightweight laminated structures are emerging in shipping, maritime, and kitchenware industries because of their comprehensive performance in high relative strength, vibration absorption and corrosion resistance. In practical applications, various steel to aluminum alloy laminated sheets are receiving more attentions attributed to their wide applicability and cost-effectiveness. Traditionally, the aluminum alloy is bonded to steel by a few mechanical approaches, like self-piercing riveting and clinching processes [1, 2]. Nevertheless, these mechanical methods are often limited by the thickness of metallic sheets and the ductility [3]. In recent years, some joining processes, including current or friction resistance spot joining, cold metal transfer welding, and friction stir welding (FSW) [4–6] have been investigated to join the two dissimilar materials by importing heat input. Among these methods, FSW originally devised as a solid-state bonding process exhibits flexible applicability for joining dissimilar metals. Boccarusso et al. [7] analyzed force and microstructure evolution on the friction stir lap welding process of dissimilar AA6082/MgAZ31 sheets, through which the dissimilar joint was successfully obtained with fine metallurgical bonding free of micro crack and penetration. Chung et al. [8] investigated the interfacial performance of the joint of dissimilar steels F82H/SUS304, which revealed that the sheets are simply mixed without diffusion. More derived processes were also developed based on FSW. Sapanathan et al. [9] recently developed a friction melt bonding process, by which DP980 and AA6061-T6 layers were bonded and Fe-Al intermetallic compound (IMC) layer formed. Reza-E-Rabby et al. [10, 11] established another newly developed process as friction stir dovetailing to join dissimilar materials, which can
simultaneously produce interfacial metallurgical bonding mixed with mechanical occlusion of Al/steel sheets.

Nevertheless, over thick interfacial IMCs with typical components and morphology may also be induced by friction stir related process, which can cause deteriorated physicochemical properties due to the existence of Al-rich phase, interfacial voids and hook effect [12–14]. In this case, the subsequent plastic deformation ability of prepared Al-steel laminates is very limited. Recently, some effective dissimilar bonding methods were developed to obtain large deformation of whole part under special requirements. Huang and Yanagimoto [15] proposed a thermally assisted joining technology via local plastic deformation that combines mechanical anchoring and fast diffusion bonding features to achieve high production performance, which is an alternative solution for joining or assembling Al/steel laminated parts. Good joining performance is obtained attributed to the thin interdiffusion layer and microanchoring effect. This work also proved that the locally distributed plastic strain is positive to interfacial bonding. Li et al. [16] developed a process window for a novel friction stir assisted thermomechanical forming process to fabricate Al/steel solid-state bonded parts with synchronous incremental plastic deformation. The effects of forming parameters on part profile, interfacial morphology and thickness distribution are discussed. Proper parameters combination is also derived as a guideline for the related process.

To find out the interfacial joining states, Govindaraj et al. [17] studied the bond strength of cold roll bonded aluminum sheets and established an applied fit model to the experimental outcomes. Donati and Tomesani [18] proposed analytical methods for evaluating the quality of seam welding in aluminum alloy extruded profiles. However, bonding quality prediction still needs further investigations for other thermomechanical dissimilar bonding processes. Therefore, a prediction criterion model for assessing bonding states is particularly worth exploring to help confirm interfacial process quality for the technologies combining bonding and plastic deformation.

In this work, experimental campaigns of friction stir–assisted double-sided incremental forming (DSIF) with synchronous pin-less solid-state bonding of DC05 and AA5052 sheets are carried out. The interfacial bonding and through thickness deformation performances of the formed parts are evaluated by analyzing the thermomechanical effects of peak temperature and axial loading force. Moreover, a pressure-strain-temperature–based interfacial bonding prediction model is modified and validated, which can be successfully used to assess interfacial quality.

## 2 Experimental campaigns

### 2.1 Materials and experimental procedures

To achieve the proposed friction stir–assisted DSIF with synchronous bonding (FS-DSIF&SB) concept, prepared dissimilar sheets are processing in a DSIF platform as illustrated in Fig. 1a. Two horizontal forming tools are driven by servo motors connected to CNC system. The forming process mainly contains setting and processing stages:

#### Step I: setting stage

1.0-mm thick AA5052-H32 as outer sheet and 0.8-mm thick mild steel DC05 as inner sheet are cut in 180 mm × 180 mm. The physical and chemical materials properties of as-received AA5052 and DC05 sheets are included in Tables 1, and 2. The contact surfaces of the two dissimilar sheets are carefully polished by electric brush to expose the fresh matrix. Then, all surfaces are rinsed with alcohol to remove debris and oil stains. The outer side as AA5052-H32 sheet is evenly sprayed with high temperature resistant black paint and graphite-based lubricant for temperature infrared sensor temperature detection and ST—AA5052 contact friction reduction. Infrared camera (ThermoIMAGER 160) is used to capture the temperature history through the process, especially the working peak temperature in localized loading zone.

After calibrating initial loading position of tools, pretreated base sheets are firmly clamped by fixtures with the same rolling direction in working space. Corresponding NC toolpath codes are built into CNC system to achieve designed shape of part.

#### Step II: processing stage

As displayed in Fig. 1b, the rotational pin-less master tool (MT) feeds at a fixed rate as 720 mm/min for process stability. The slave tool (ST) moves coordinately to provide sufficient back support for MT. The radius of the flat-end and the fillet arc of tools are both 5 mm. Material of KG7-cemented carbide is used for the tools to ensure red hardness. A squeeze factor 0.9 and the thickness distribution control solution are utilized to adjust the loading force for tools.

As shown in Fig. 1c, the high-speed rotational rod-shaped rigid MT generates adequate friction stir–induced heat on the contact area conducted to sheets to complete the dissimilar thermomechanical bonding. Thus, effect of material flow can be mainly reflected by different rotation speed of MT. Meanwhile, the incremental plastic
deformation of localized loading material is realized by pre-designed spiral toolpath as shown in Fig. 1d. Ruled by the coupling effects of friction-induced heat and loading force, interfacial solid-state bonding is eventually achieved with incremental plastic deformation for the whole part.

In this step, the process parameters can be adjusted according to specific materials and forming conditions to control frictional heat input. Additionally, different forming performance modes may appear due to the complex thermomechanical effects through the process.

As a joining-with-forming technology combined with the features of DSIF and FSW processes, three determined parameters as step down (S, mm), wall angle (α, °), rotational speed (R, RPM) shall be investigated in evaluating interfacial bonding states. A series of experiments with

**Table 1** Nominal chemical composition of as-received materials sheets (in wt.%)  

| Materials | C  | P  | S  | Mg  | Si  | Fe  | Mn  | Cr   | Others | Al  |
|-----------|----|----|----|-----|-----|-----|-----|------|--------|-----|
| AA5052    | –  | –  | –  | 2.2–2.8 | 0.25 | 0.4 | 0.1 | 0.15–0.35 | 0.35 | Bal |
| DC05      | 0.06 | 0.02 | 0.02 | – | 0.02 | Bal | 0.35 | – | – | 0.01 |

**Table 2** Mechanical properties of as-received materials

| Materials | Density (g/cm³) | Young’s modulus (GPa) | Yield strength (MPa) | Melting temperature (°C) | Elongation at break (%) |
|-----------|-----------------|----------------------|---------------------|------------------------|------------------------|
| AA5052    | 2.7             | 69                   | 175                 | 607                    | 15                     |
| DC05      | 7.85            | 200                  | 136                 | 1500                   | 33.9                   |
different parameters combinations are carried out to fabricate laminated conical parts as listed in Table 3.

### 2.2 Exemplary investigation of process

From the experimental measured results of typical test ⑤ $S_{0.25-\alpha 55-R3200}$ with designed forming height 35 mm as shown in Fig. 2, axial force and working temperature can reach relatively stable range after initial rapid rise. Maximum temperature of localized loading area can reach about 420 °C at forming height 5 mm (~30% of total forming time) with the dynamic equilibrium of heat generation and dissipation. This temperature is the peak value of the whole part in real time. At the initial forming stage, Z-axial force history of MT is in a similar trend with working temperature, which is also consistent with the features of conventional Al/steel FSW related processes [19, 20]. However, the maximum MT Z-axial force is only about 1 kN and MT Z-axial force at stable forming stage is basically lower than 800 N. It is quite much smaller than 3–5 kN usually induced in conventional Al/steel FSW process [19, 20]. Notably, the recorded working temperature and axial force are smoothed from the highest points and intermediate steady values as stated in our previous work [21]. From Fig. 2, visible galling in steel side of part is caused by strong friction stir and tangential movement of the downward moving MT. Unwanted cutting chips may be produced when the rotational feeding MT firmly contacts with the DC05 surface. These chips are removed with heat air gun in time to protect inner surface quality of the part to avoid further galling. This undesirable appearance may also bring roughness and crack to steel outer side [21].

The most concern in this work is the interfacial bonding states of laminated parts after the process. Typical forming appearance modes are illustrated in Fig. 3, which can be distinguished as follows: successfully bonded (e.g., ⑤ $S_{0.25-\alpha 55-R3200}$), de-bonded (e.g., ⑥ $S_{0.25-\alpha 45-R3200}$), penetration (e.g., ④ $S_{0.25-\alpha 62.5-R3200}$), excessive thinning (e.g., ② $S_{0.35-\alpha 60-R3600}$) and crack (e.g., ⑨ $S_{0.15-\alpha 60-R3600}$).

The bottom row of displayed pictures are the macro peeling test results to demonstrate rationality of typical classification. The reasons of inducing different interfacial bonding states shall be attributed to the main factors during the process: plastic strain, pressure, temperature and materials.

![Fig. 2](image)

Fig. 2  History of MT Z-force and maximum temperature during process

| Test no | Step down S (mm) | Wall angle α (°) | Rotational speed R (RPM) |
|---------|------------------|-----------------|--------------------------|
| ①      | 0.25             | 55              | 2600                     |
| ②      | 0.35             | 60              | 3600                     |
| ③      | 0.10             | 55              | 3200                     |
| ④      | 0.25             | 62.5            | 3200                     |
| ⑤      | 0.25             | 55              | 3200                     |
| ⑥      | 0.25             | 45              | 3200                     |
| ⑦      | 0.40             | 55              | 3200                     |
| ⑧      | 0.35             | 50              | 2800                     |
| ⑨      | 0.15             | 60              | 3600                     |
| ⑩      | 0.25             | 47.5            | 2800                     |
| ⑪      | 0.35             | 60              | 2800                     |
| ⑫      | 0.15             | 60              | 2800                     |
| ⑬      | 0.35             | 50              | 3600                     |
| ⑭      | 0.15             | 55              | 3800                     |
| ⑮      | 0.15             | 50              | 2000                     |
| ⑯      | 0.15             | 50              | 2000                     |
| ⑰      | 0.15             | 47.5            | 3200                     |
| ⑱      | 0.15             | 45              | 1500                     |

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properties. In the following section, the interfacial quality assessment and prediction method for obtaining desirable sound state appearance mode as shown in Fig. 3a is introduced by evaluating above individual and interactive factors.

3 Analytical model for predicting interfacial process quality

3.1 Dissimilar sheets deformation in current loading area

The magnitude and distribution of loading forces conducted by rigid forming tools are the main driving sources for materials plastic deformation and interfacial bonding. Thus, it is significant to take an insight of localized loading mode to understand the materials response.

Fig. 3 Illustration and actual process appearance and interfacial peeling behavior of 5 typical types of forming modes

Fig. 4 Illustration of deformation mode by stress components in loading area of FS-DSIF&SB process
Study of deformation mechanism in DSIF process [22] reveals that ST mainly provides back pressure support for AA5052 layer. Therefore, at the compressive zone, the back support of ST and effects of stretching-bending [23, 24] are dominated along the through-thickness direction. The shearing stress \( \tau_{0s} \) is resolved through the frictional force induced by MT. Taking a small element into account in through thickness direction of sheet at the contact area as displayed in Fig. 4, the stress components \( \tau_{0s}, \sigma_r, \sigma_\theta, \) and \( \sigma_\phi \) in interfacial position can be derived [21], which are main driven sources of materials sliding and bonding. More details on the thermomechanical deformation mechanism and derived interfacial stresses can be referred to our previous work [21].

As materials undergo incremental plastic deformation and fast atoms diffusion, the complex material behaviors can be macroscopically characterized as sheet thinning and interfacial bonding. The thickness variation of laminated sheet is an important indicator of load bearing. During conventional incremental sheet forming process, wall thickness distribution is usually regarded to follow cosine law which may be also extended to the laminated sheet. However, it is not suitable for DSIF process due to the requirement of adequate contact squeeze by ST [16, 22]. In order to control thickness distribution of dissimilar sheets to prevent losing contact between ST and AA5052 sheet, combined thickness of the two metallic sheets can be estimated by introducing fitting coefficients [21], which is modified according to a thickness distribution prediction model in DSIF [25].

\[
t_{e} = t' + t'' = t_{0} (1 - [(1 + ah^2 + bh)(1 - \cos \alpha)]) \quad (1)
\]

where \( t_{e} \) is the final thickness of the laminated sheet and \( t_{0} \) is the original total thickness of the two sheets. \( a \) and \( b \) are the fitting parameters and set as \(-0.00013\) and \(-0.0482\), respectively. A squeeze factor combined with the fitting parameters can be used to adjust support force for this process [21]. \( h \) is the position in current forming height. Superscripts \( i \) and \( o \) represent the inner (DC05) and outer (AA5052) sheets, respectively. During this thermomechanical process, thinning amounts on inner and outer layers are assumed as even and equally proportional. Therefore, combined thickness depends on the wall angle \( \alpha \) if forming height \( h \) is determined. The actual fabricated Al/steel laminated part with thickness distribution with designed forming height 20 mm is displayed as Fig. 5, which also confirms the evenly thinning deformation mode.

Localized loading area of conical parts in ISF-related process is commonly recognized as plane strain condition, i.e., \( \epsilon_0 = 0 \) [26]. Based on the assumption of plastic volume conservation, \( \epsilon_0 + \epsilon_t + \epsilon_\phi = 0 \). Then, the total equivalent plastic strain for the localized loading area can be calculated via the strain component \( \epsilon_r \).

\[
\epsilon_r = \sqrt{\frac{2}{3}} \epsilon_0 \epsilon_0 = \sqrt{\frac{2}{3}} (\epsilon_t^2 + \epsilon_\phi^2) = -\frac{2}{\sqrt{3}} \epsilon_t = -\frac{2}{\sqrt{3}} \ln \frac{t_{e}}{t_{0}}
\]

(2)

### 3.2 Working temperature prediction

In addition to mechanical deformation, the working temperature of loading area as another important detection indicator can be approximately treated as the peak temperature during the thermomechanical incremental forming process. Referring to previous study in FSW-related processes [27], the peak temperature model can be written in a form of

\[
\frac{T_{\text{peak}}}{T_{\text{melting}}} = k \left( \frac{R^2}{3 h} \right)^\beta
\]

Where \( T_{\text{melting}} \) is the melting temperature of AA5052, and fitting parameters \( \beta, \kappa \) vary between \( 0.04–0.06, 0.65–0.75 \) [27], respectively. To properly describe the heat response in FS-DSIF&SB process, our previous simulation work [28] has revealed that increased ratio of step down and wall angle (i.e. \( S/\alpha \)) has a positive role on elevating peak temperature of loading area within the preset parameters range. According to the similar thermomechanical condition, the peak temperature model in FSW-related process can be modified as Eq. (3) to establish relationship for base material and process parameters including step down \( S \), wall angle \( \alpha \), feed rate \( v \) and rotation speed \( R \) in the proposed FS-DSIF&SB process.

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**Fig. 5** Fabricated Al/steel laminated part with thickness distribution of test ② S0.25-α55-R3200. a Well-bonded in stable forming-bonding stage. b wall thickness distribution

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where $\beta$, $\kappa$, $\gamma$ are fitting parameters for the model. Due to the pin-less tool configuration, lower limits of parameters are taken to suppress the influence of process parameters. By coding in MATLAB, $\beta = \gamma = 0.04$ and $\kappa = 0.75$ are suitable to fit measured experimental results.

The predicted peak temperature of the loading area can provide an intuitive estimation on interfacial bonding thermal field. As a direct result of heat response, it also works as an internal variable affecting flow stress, which will be substituted into the calculation formula of modified interfacial quality prediction criterion. The prediction error between the predicted peak temperature and measured result is defined as,

$$\text{Err} = \frac{100\%}{|T_{\text{Me}} - T_{\text{Es}}|}$$

As shown in Fig. 6, the error marked on each column between measurement and prediction is rather acceptable (the largest relative error is 10.15%, the smallest relative error is 0.32% and the mean relative error is 3.05%), which proves that the modified peak temperature model is proper for FS-DSIF&SB process. Although temperature distribution is different between inner and outer sheets due to their difference in specific heat capacity and thermal resistance in interfacial heat conduction. However, as for a specific metallic thin sheet (AA5052 or DC05, less than 1.0-mm thick), the difference on temperature distribution through the sheet thickness can be ignored. Therefore, the temperature of AA5052 side at the dissimilar interface is approximately equal to that on AA5052-ST side measured by the infrared thermometer. Among the measured results as shown in Fig. 2, the working peak temperature of each test is much lower than melting point of AA5052 sheet ($\sim 600^\circ\text{C}$). Therefore, dissimilar AA5052/DC05 sheets are in solid-state bonding and deformation during the process.

3.3 Criterion for predicting bonding quality under thermomechanical effect

Referring to previous study on predicting seam welding quality [18], the ratio of interfacial pressure to equivalent stress of base material is an important factor to judge bonding condition. This pressure–time-flow principle is in an integrated form as follows,

$$K = \int \frac{P}{L} dl \geq K_c$$

where $K_c$ is the critical value and $l$ is the welding length. However, as stated on the published solid-state bonding investigation [3], the induced plastic strain via the whole process is also confirmed to highly contribute to atoms interaction and interfacial anchor morphology, which proves the significance of plastic strain on mechanical and metallurgical bonding mechanisms. Moreover, thermal effect shall be considered in a bonding process. Here, a ‘$Q$’ criterion is derived as an independent dimensionless target to predict current bonding state. By integrating the plastic strain with the ratio of interfacial normal pressure $P$ to temperature-dependent equivalent stress $\tilde{\sigma}_o$ of the soft outer base material AA5052.

$$Q = \int \frac{P}{\tilde{\sigma}_o} d\tilde{\varepsilon}_p$$

Corresponding to the elevated temperature condition in loading area, equivalent stress $\tilde{\sigma}_o$ of AA5052 is treated as dependent on current working temperature [21].
The interfacing pressure \( P \) illustrated in Fig. 4 can also be calculated from the combination of forming parameters as stated in our previous work [21]. Therefore, by submitting specific forming parameters into Eq. (6) under simplified proportional loading condition, the bonding quality prediction criterion can be written as,

\[
\sigma_s = 178 \times \left[ 1 - \left( \frac{T - 25}{607} \right)^{0.9} \right] \tag{7}
\]

The interfacing pressure \( P \) can also be calculated from the combination of forming parameters as stated in our previous work [21]. Therefore, by submitting specific forming parameters into Eq. (6) under simplified proportional loading condition, the bonding quality prediction criterion can be written as,

\[
Q = \frac{(2\sqrt{3} + \mu \frac{\sqrt{3}}{2} \beta)}{2\mu - \frac{\sqrt{3}}{2}} \frac{2h}{t_o} \left[ 1 - \frac{(1 + \alpha + b)(1 - \cos \alpha)}{1/2} \right] \tag{8}
\]

A parameter integrated criterion model is thus modified to predict the interfacing states which can be used to check the input process parameters before conducting the FS-DSIF&SB technology. A critical value \( Q_c \) which can reflect the interfacing quality shall be set. Only when the calculated \( Q \) exceeds the critical threshold value, the interfacing quality of the fabricated part is acceptable. Hence, the critical determination criterion can be obtained as \( Q \geq Q_c \).

### 3.4 Application and validation of ‘Q’ interfacing quality prediction model

To express the types of appearance modes as displayed in Fig. 3, thermomechanical effects of process parameters are required to be further investigated based on the ‘Q’ interfacing quality criterion. The aim of process quality prediction can be achieved then by submitting the parameters combination into the ‘Q’ criterion. Here, the interfacing appearance state of each test is analytically evaluated according to the experimental setup listed in Table 3 to directly reveal the influences of forming parameters and induced heat-force conditions in stable bonding-forming stage. The \( Q \) value of each test is obtained from Eq. (7) and then plotted in Fig. 7 (solid dots and squares).

Compared with the experimental results, a critical line as \( Q = 1.0 \) in Fig. 7 clearly divides the tests into two categories: successfully bonded and de-bonded. Hence, \( Q_c \) could be set as ‘1.0’. Moreover, if \( Q \) value exceeds 1.4, damage accumulation may deteriorate into failure in service. Therefore, the calculated \( Q \) value could help determine the deformed modes:

1. If \( Q < 1.0 \), the dissimilar sheets are not successfully bonded, as shown in Fig. 3b and Fig. 8a.
2. If \( 1.0 < Q < 1.4 \), the dissimilar sheets could be successfully bonded, as shown in Fig. 3a and Fig. 8b.
3. If \( Q > 1.4 \), the dissimilar sheets might be damaged, as shown in Figs. 3c-3e and Figs. 8c-8d.

The effects of process parameters on the dimensionless factor \( Q \) can be illustrated in Fig. 9. Under low-value parameters combination (e.g., ① \( S \leq 0.15 \text{ mm}, \alpha \leq 45^\circ \) and \( R \leq 2500 \text{ RPM} \), \( Q \) value is generally lower than ‘1.0’, indicating that it is almost impossible to achieve reliable interfacing bonding between dissimilar interfaces. Obviously, the \( Q \) value increases with the increase of the parameters, indicating that the higher possibility for obtaining sound bonding with deformation joint. However, excessive high-value parameters combination (e.g., ② \( S \geq 0.35 \text{ mm}, \alpha \geq 55^\circ \) and \( R \geq 3600 \text{ RPM} \) will result in relatively high \( Q \) value, which may bring about the risk of cracking and excessive thinning. According to Fig. 9, wall angle is the most influential parameter due to greater plastic deformation, which makes the closer contact between the localized loading material and rigid tools, thereby improving the friction stir effect.

![Fig. 7 Prediction model for assessing interfacing states by evaluating Q value](image)
Fig. 8  Performance of fabricated parts with different forming parameters. a Un-bonded \( \ominus \) S0.15-\( \alpha \)45-R2500, b \( \ominus \) well-bonded S0.25-\( \alpha \)55-R3200, c excessive thinning \( \oplus \)S0.35-\( \alpha \)60-R3600, d penetration \( \ominus \) S0.25-\( \alpha \)62.5-R3200

Fig. 9  Process interfacial quality predicted by \( Q \) response surfaces dependent on forming parameters in FS-DSIF&SB
The guidance for selecting process parameters combination is consistent with the above discussion on the experimental results.

4 Conclusions

In the present work, a newly established thermomechanical process is utilized to fabricate dissimilar laminated structures with designed shape. Interfacial quality prediction method is investigated to help better understand the plastic deformation and solid-state interfacial bonding behavior. The main points are summarized as follows:

1. Separated aluminum alloy AA5052 and steel DC05 sheets are successfully fabricated to truncated conical laminated parts by the pin-less FS-DSIF&SB process.
2. As a heat-force coupling process, peak temperature and axial force are in the same trend. The maximum Z-axis loading force is lower than 1 kN and the peak temperature through fabricating parts will not exceed 500°C. A modified empirical model based on forming parameters can accurately predict the peak temperature in localized loading area.
3. A series of 20 tests by the thermomechanical process are conducted to validate the feasibility of the deformation with synchronous solid-state bonding concept. Among the tests, 5 typical types of bonding quality variation through the cross-section view are classified as sound bonding, de-bonding, over-thinning, penetration and crack.
4. A 'Q' interfacial quality prediction model is modified based on pressure-strain-temperature relationship. This criterion method provides a threshold value \( Q_c \) as 1.0 to determine interfacial bonding states in FS-DSIF&SB process. This analytical method can also be extended to assess other similar thermomechanical joining-with-forming processes.
5. Based on the analytical 'Q' criterion, a proper forming parameters window for Al/steel sheets in FS-DSIF&SB is established within step down \( S \) as 0.15–0.35 mm, wall angle \( \alpha \) as 47.5–60° and rotation speed \( R \) as 2800–3200 RPM.

For the future work, the effect of each process parameter on surface roughness and microstructure evolution shall be investigated, especially the characterizations on interfacial phase change of IMC layer.

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Declarations

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Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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