Microstructure and mechanical performance of dissimilar metal joints of aluminium alloy and stainless steel by cutting-assisted welding-brazing

Huibin Xu1 · Wei Cong1 · Donghua Yang1 · Yanlong Ma1 · Wanliang Zhong1 · Pan Tan1 · Jiuchun Yan2

Received: 24 August 2021 / Accepted: 25 November 2021 / Published online: 11 January 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract
The 5052 aluminium alloy and 304 stainless steel were successfully joined by cutting-assisted welding-brazing (CAWB) method without using flux. Dual-scale interfacial structures were achieved by designing the geometry of cutting tool. Results indicated that the macroscale self-locking interface was produced when the taper step-shape cutting tool was adopted. Especially when the cutting tool step was increased to 6 steps, the microscale interface took on a micrometre-sized self-locking morphology and a layer of wavy intermetallic compound (IMC) with an average thickness of 3.3 μm was formed at the interface. The τ4 IMC particles and the FeAl6 phases on a small scale were dispersed homogeneously in the welded seam. The maximum tensile strength of the joints reached 152.3 MPa, 75% that of the 5052 aluminium base metal. The robust Al/steel dissimilar joints were attributed to the particle-reinforced weld metal and the macro- and microscale dual self-locking structure at the interface.

Keywords Dissimilar metal joining · Welding-brazing · Cutting tool · Microstructure · Intermetallic compound · Tensile strength

1 Introductions
The light-weight alloy of Al/steel is increasingly attracting attention in the shipbuilding, aerospace, and automotive industries [1]. However, the low weldability of aluminium and steel has severely restricted their use. Usually, brittle and hard Fe-Al intermetallic compound (IMC), such as FeAl3 and Fe2Al5 phases, forms easily at the joint interface under a large heat input, which can be an important internal factor for the formation of crack in joint [2]. Moreover, it should be noticed that the problem of the large difference in coefficients of thermal expansion (CTE) of Al/steel dissimilar metals, especially at the Al/steel interface, is easy to cause thermal stresses. This is also an external factor that causes the formation of crack initiation [3, 4].

In recent years, there has been an increasing interest on the part of academics in the integration of technologies with a lower thermal cycle [5, 6]. Among these joining methods, the technology of welding-brazing with good flexibility has been increasingly considered [7]. Furuya et al. [8] reported that the thickness of the IMC layer has been reduced by adding appropriate quantities of Si and Ti elements, and the joint strength has been improved. He et al. [9] successfully joined aluminium alloy and steel by pulsed TIG welding-brazing with high-frequency induction twin hot wire technology. They found that the reduction of IMC thickness was achieved by controlling the heat input. Wu et al. [10] investigated the joining of aluminium and steel with ultrasonic-assisted TIG welding-brazing. It proved that the welding-brazing process by introducing external energy could benefit to obtain the fine-grained strengthening and dispersing strengthening effect in the welded seam. The joint strength reaches the maximum value of 191 MPa under the ultrasonic vibration treatment. In our previous study [11, 12], attempts have already been made to join Al/steel by arc brazing technology using the...
commercially available end milling cutter. The maximum shear strength of the joint interface reached 111 MPa, and the IMC thickness can be obtained as thin as 1.2 μm. However, the obtained interfacial microstructure was still relatively straight, which was difficult to hinder crack propagation to obtain the higher joint strength. Based on it, one may expect that further improvement in mechanical strength of Al/steel joint can be obtained if designing the cutting tool geometry to achieve a unique combination of interfacial structure and particle-reinforced weld metal. Therefore, a cutting-assisted welding-brazing (CAWB) method without using of flux was proposed and applied in joining aluminium alloy to stainless steel.

The aim of this study is to investigate the effect of interfacial structure on the welding-brazing features by designing the geometry of cutting tool. First, the macrostructure of the joints under two cutting tool geometries was observed and compared. Then, the interfacial microstructure evolution was studied, and the distribution of precipitated phases in welded seam was preliminarily discussed. Finally, the formation mechanisms of the joints were analyzed to reveal the influence of a 6 steps cutting tool on the joint microstructure.

### 2 Experimental procedures

5052 aluminium alloy and 304 stainless steel strips of 100 mm × 50 mm × 3 mm were adopted as the base metal. ER4043 weld wire (Al-5Si wt%) with a diameter of 1.6 mm was used as a filler metal. Their corresponding chemical compositions of base materials and filler metal are shown in Tables 1 and 2, respectively.

The surface of the base metal was cleaned with abrasive paper to remove the oxide film and ultrasonically cleaned in alcohol prior to welding. As seen in Fig. 1, in order to achieve the action effect of the molten pool stirring in the CAWB welding process, the distance of tungsten tip and cutting tool was set to 8.3 mm in the horizontal direction, and the inclination angle of the cutting tool was 68.5°; the angle between the tungsten tip and the horizontal plane

![Fig. 1 Schematic of butt welding of aluminium alloy to steel with CAWB process](image-url)
was 75°. The welding-brazing process was carried out on a WX-300 welding source with an AC current of 102 A, an arc length of 3 mm, offset value for cutting of 0.2 mm, a 0.25-mm butt gap pre-set in the assembly process, a filler metal feed speed of 760 mm/min, a welding speed of 44 mm/min, and an argon flow rate of 15 L/min. Subsequently, a cutting tool inserted in a pool at a rotation speed of 3500 rpm starts to cut stainless steel and stir pool.

In the study, weld quality, cutting tool performance, and industry application are three important considerations in the selection of cutting tool material. After preliminary exploration, we finally selected WC-6 wt% Co cemented carbide as the material of cutting tool. The welding process was investigated by adjusting the geometry of cutting tool (taper-shape and taper step-shape cutting tool). As shown in Fig. 2a, the taper-shape cutting tool was a simple truncated cone. The second type was taper step-shape cutting tool, which was machined with a 6.5-mm-diameter shoulder, a 2-mm-diameter small end, and a 4-mm-diameter large end. The cutting tool pin was 4 mm long with different steps (N was 2, 4, 6, and 7), as shown in Fig. 2b.

After welding, the microstructure of the joints was measured by scanning electron microscopy (SEM, Sigma HDTM) with an energy-dispersive spectrometer (EDS). The phase constitution of the steel fracture surface was analyzed by X-ray diffraction (XRD Rigaku D/max-2500PC, Cu Kα). The IMC layer thickness and the ratio of precipitated phase were calculated. Figure 3 shows the geometry and dimensions of tensile specimens. The tensile strength of the joint without reinforcements was tested in a WDW-E200 universal testing machine with a loading rate of 1 mm/min at room temperature. At least three samples were tested for each experimental condition to obtain statistically reliable values.

3 Results and discussion

3.1 Joint formation without cutting tool

Figure 4 presents the cross section of the joint without using a cutting tool. A typical fusion-welded joint with the aluminium alloy base material was obtained. However,
joint interface did not form metallurgical bonding efficiently. The oxide film still existed on the surface of steel substrate, which hinders the wetting and spreading of the liquid filler metal on the steel surface, resulting in the formation of the unbounded interface.

### 3.2 Macro- and microstructure evolution of CAWB joint interface

Figure 5 shows the morphologies of CAWB joints with different geometries of cutting tool. As shown in Fig. 5a, the morphology of the joint interface was relatively straight, and voids and un-stripping steel chips gathered near the steel substrate. This is due to the limited cutting and stirring capabilities of the taper cutting tool, resulting in the formation of defects. As the cutting tool steps increased from 4 steps to 7 steps, the value of wavelength changed significantly, but the amplitude has not changed remarkably as observed in Fig. 5b–d. Figure 5e presents the schematic diagram of wavelength and amplitude while Fig. 5f shows the relationship among different cutting tool geometries, wavelength, and amplitude. As the step number increased from 2 steps to 7 steps, the values of average wavelength were about 1999.4 μm, 1052.5 μm, 628.8 μm, and 534.7 μm, respectively, as shown in Fig. 5f. Nevertheless, the values of the wave’s amplitude have only slightly changed. The values of average amplitude were about 518.4 μm, 119.5 μm, 158.6 μm, and 133.9 μm when the step numbers were 2, 4, 6, and 7, respectively. Finally, the typical symmetrical waves and macroscale self-locking structures on a millimetre size were obtained at the joint interface, which would achieve the strong mechanical interlocking effect [13].

It was a crucial issue to control the formation and growth of the IMC layer at the joint interface in order to obtain welding-brazing Al/steel joints with high mechanical strength. To clarify the effect of cutting tool geometry on the joint IMC, interfacial microstructure and chemical components of four joints were characterized and the corresponding EDS results are shown in Table 3. Figure 6 presents the microstructure of CAWB joint with different cutting tools, while Fig. 7 shows the corresponding thickness of interfacial IMC layers and the EDS line scanning result at a 6 steps cutting tool.
As shown in Fig. 6a and b, the larger scale steel chips were distributed inside the IMC layer, which provided a large amount of Fe atoms for the formation of a thick IMC layer. Finally, the laminated-like reaction layer with a maximum thickness of 53 μm was obtained, and this would be easy to induce the crack propagation and deteriorate the mechanical properties of the joint. According to the Fe-Al-Si ternary phase diagram [14] and EDS analysis given in Table 3, the phases marked by point A in Fig. 6a was θ-(Fe,Cr)4Al13. As the number of cutting tool steps increased to 4 steps, the steel substrate undergoes significant plastic deformation during

| Point | Elements (at.%) | Possible phase |
|-------|----------------|----------------|
| A     | 20.27 3.91 75.82 | θ-(Fe,Cr)4Al13 |
| B     | 15.99 7.09 3.73 73.19 | τ5-Al8(Fe,Cr)2Si |
| C     | 11.10 8.26 5.04 75.60 | τ6-(Fe,Cr)3(Al,Si)3 |
| D     | 13.97 10.16 4.35 71.52 | τ5-Al8(Fe,Cr)2Si |
| E     | 20.13 8.52 6.04 65.31 | η-(Fe,Cr)2(Al,Si)5 |
| F     | 13.10 11.53 4.58 70.79 | τ5-Al8(Fe,Cr)2Si |

Fig. 6 The microstructure of joints interface. a, b Taper cutting tool, c, d 4 steps. e, f 6 steps. g, h 7 steps.
the CAWB process. A strong metallurgical bonding between liquid filler metal and steel substrate was achieved at the interface. In addition, due to the limited cutting and thinning ability of the 4 steps cutting tool, the swirl-like morphology and thick IMC layer was obtained at the interface, given in Fig. 6c and d. Consequently, IMC layer with an average thickness of 12.9 μm formed at the joint interface as shown in Fig. 6d. As shown in Table 3, the EDS results of point B (Fig. 6d) were Fe 15.99 at.%, Si 7.09 at.%, Cr 3.73 at.%, and Al 73.19 at.%, and this structure was identified as τ₅-Al₈(Fe,Cr)₂Si phase [15].

Figure 6e–f present the joint interface (cutting tool step number was 6 steps). The joint interface appeared on a micro-scale self-locking morphology with a continuous and wavy distribution IMC layer, with some block-like IMC particles near the interface as seen in Fig. 6e. According to the EDS analysis at points C and D, the block-like IMC particles consist of Fe 11.10 at.%, Si 8.26 at.%, Cr 5.04 at.%, and Al 75.60 at.%. The block-like IMC particle can be τ₄-(Fe,Cr)(Al,Si)₅ phase [16]. In addition, a thin and wavy IMC layer with average thickness of 3.3 μm was identified to be τ₅-Al₈(Fe,Cr)₂Si phase at the interface. As shown in EDS linear scanning result (Fig. 7a), the Si and Cr elements were detected in τ₅-Al₈(Fe,Cr)₂Si layer (Fig. 6f). Furthermore, the Si element content was significantly increased at the interface between the IMC layer and welded seam.

A previous study reported that the addition of Si element was able to reduce the thickness of Fe-Al IMC layer [17]. In this study, the high-speed cutting tool could force these alloy elements to participate in the metallurgical reaction of Fe-Al IMC, resulting in a large amount of Si atoms which were added to replace Al atom, and eventually obtain the Fe-Al-Si ternary phase with the Cr solid solution. In addition, the cutting tool has a strong mechanical crushing effect on the initial IMC layer and it would suppress the formation of IMC layer, especially when the cutting tool step was 6 steps. As mentioned above, these two elementary dimensions, the strong metallurgical reaction and mechanical crushing effect, jointly determine the effect of cutting tool geometry on the formation of IMC layer. Therefore, when the cutting tool step was 6 steps, the average IMC layer thickness reached the minimum value and the tensile strength of the joints was 152.3 MPa. It indicated that the 6 steps cutting tool could realize the reduction of IMC thickness and formation of macro- and microscale dual self-locking interface, which was beneficial to enhance the mechanical properties of the joints.

The cutting tool steps increasing to 7 steps, manifested an unobvious self-locking interface with micro-crack defects in the joint as shown in Fig. 6g, h. Composition analysis at points E and F shows that the two phases were η-(Fe,Cr)₂(Al,Si)₅ and τ₅-Al₈(Fe,Cr)₂Si, respectively. The micro-cracks propagated between the two layers of IMC and its total thickness was 3.9 μm. It should be noted that the cutting effect, and IMC layer reduction was not always improved by increasing the number of cutting tool step, which indicated that the action of 7 steps cutting tool was insufficient and unsuitable. Finally, it would weaken the tensile properties of the joints. Thus, the findings from these studies suggest that the cutting tool geometry can have a significant effect on the interfacial structure and IMC thickness.

### 3.3 Microstructure evolution of the welded seam

Figure 8 presents the microstructure of the welded seam using different cutting tool geometries and the corresponding EDS results as shown in Table 4. Figure 9 shows the relationship of the precipitated Fe-Al phase ratio and the cutting tool geometry.

In the process of welding-brazing Al/steel without using of cutting tool, the obtained joint has obvious unbound
characteristics (seen in Fig. 4), which greatly hinders the diffusion of Fe atoms to the welded seam. And the welded seam was only made up of gray matrix and white rod-like phases given in Fig. 8a, b. The EDS analysis showed that the gray matrix was the \( \alpha \)-Al phase, and the white rod-shaped structure (marked as point A in Fig. 8b) was identified as the Al-Si eutectic phase.

During the CAWB process using a taper cutting tool, the oxide film on the steel surface was removed, which greatly accelerated the dissolution of Fe atoms into the molten pool. However, a large number of net-like precipitates were produced in the welded seam (Fig. 8c, d), and the EDS analysis showed that this net-like phase (marked as B) was composed of Fe 11.8 at.%, Cr 2.12 at.%, and Al 86.08 at.%, and this structure was determined in the \( \text{FeAl}_6 \) non-equilibrium phases [18, 19]. As seen in Fig. 9, the area ratio of \( \text{FeAl}_6 \) phases is shown.

| Table 4 | EDS results of points A–C in Fig. 8 |
|---------|-------------------------------------|
| Point   | Elements (at.%)                   | Possible phase       |
| A       | Fe: - 11.04  Si: - 88.96          | \( \text{Al-Si eutectic} \) |
| B       | Fe: 11.8  Si: - 2.12  Cr: 2.12  Al: 86.08 | \( \text{FeAl}_6 \) |
| C       | Fe: 12.11  Si: 7.48  Cr: 4.35  Al: 76.06 | \( \tau_{\alpha}(\text{Fe,Cr})(\text{Al,Si})_3 \) |

![Fig. 9](image-url) Relationship between precipitated phase ratio and cutting tool geometries.
phases was 11.1% and these net-like FeAl₆ phases on large scale could increase the brittle nature of the joint.

When the cutting tool step number increased to 6 steps, the obtained welded seam was mainly made up of block-like phases and small-scale FeAl₆ phase, which was a uniform distribution in the welded seam (Fig. 8e, f). At the magnified SEM image of point C in Fig. 8f, the block-like phases were identified as τ₄ phase with Cr solid solution. In addition, the block-like IMC particles were predominant in the welded seam, and the area ratio of IMC particles and FeAl₆ phase was 4.2% and 2.3%, respectively. It should be noted that IMC particles can be generated from the transformation of steel chips or cut from the interfacial reaction layer. In addition, the stirring capacity of the cutting tools has been strengthened, which would help break the FeAl₆ phase on a large scale under the 6 steps cutting tool. These uniformly dispersed IMC particles and small-scale FeAl₆ phases could be considered strengthening phases. Therefore, the particle-reinforced weld metal was fabricated using the CAWB method, which had the potential to improve the joint tensile properties. Finally, the large difference in coefficient of thermal expansion of Al/steel joints could be effectively alleviated.

3.4 Tensile properties and fracture analysis

Figure 10a presents the effect of cutting tool geometry on the tensile strength of joints. It can be seen that the tensile strength first increased and then decreased. Particularly, they had a maximum tensile strength of 156.7 MPa, and an average value of 152.3 MPa, 75% that of the 5052 aluminium base metal under the 6 steps cutting tool. According to XRD analysis seen in Fig. 10b, this proved that the Fe, α-Al, and τ₅-Al₈Fe₂Si phases existed on the steel fractured surface. In addition, the energy spectrum results show that the phase (marked as I) in Fig. 10c was identified as τ₅-Al₈Fe₂Si phase (71.33 at.% Al, 11.25 at.% Si, 3.71 at.% Cr, 13.70 at.% Fe). The EDS identified results of the fracture surface agree with quantitative one confirmed by XRD pattern. Moreover, the fracture surface of the joint was analyzed as shown in Fig. 10c and d; the fracture mode was quasi-cleavage fracture with tearing ridges. Therefore, it suggested that the

![Graph of the joints tensile strength at different cutting tool geometries.](image)

![XRD pattern of the steel fracture surface at 6 steps.](image)

![Fracture surface at the steel side.](image)

![High magnification SEM of area d](image)
fracture path appeared not only in the welded seam, but also at the interface of the joint. Adopting the 6 steps cutting tool, the Al/steel joint had the highest tensile strength among these five joints.

3.5 Joint formation mechanism

Based on the above findings, the schematic diagram of the mechanism of the CAWB process for Al/steel joints can be illustrated in Fig. 11. The process includes melting, cutting and wetting, growing and breaking, and cooling.

After reaching the melting temperature of the filler metal, the liquefied Al-Si filler metal could not flow into the inter-space of bonding joint by capillarily due to the oxide film on the surface of steel base metal. During the CAWB process, the oxide film was removed, and the fresh steel surface manifested a strong wetting reaction with the Al-Si molten filler metal. Different degrees of plastic deformation were achieved on the steel substrate as the number of cutting tool steps increased from four to seven, resulting in the millimetre-sized self-locking interface at the macroscale. Especially, when the cutting tool step number was 6 steps, the microscale self-locking interface and the thin IMC thickness were beneficial in enhancing the mechanical properties of the joints.

In recent years, some particles with low CTE which have been added to the filler metal in an appropriate amount were investigated, which indicated that the larger difference of CTE and Young’s modules of dissimilar materials were reduced [21, 22]. During the CAWB process, the small-scale FeAl₆ phases and massive τ₄ IMC particles with low CTE were in dispersive distribution in the welded seam. It would help to release the thermal stress and reduce the mismatch of the CTE and Young modules between steel and aluminium alloy.

4 Conclusions

(1) Cutting-assisted welding-brazing (CAWB) method without using of flux was proposed and applied in joining of aluminium alloy to stainless steel, and the cutting tool can disrupt and extrude the oxide film on the surface of steel.

(2) When using the taper step-shape cutting tool, the millimetre-sized self-locking interface was achieved at the macroscale. The value of interface wavelength was 1999.4 μm at the 2 steps cutting tool; this was 3–4 times smaller than the ones at 2 steps as the step number increased to 7 steps.
(3) The joint interface made of 6 steps cutting tool showed a microscale self-locking structure, and this thin and wavy IMC layer was identified as \(\tau_5\)-Al\(_9\)(Fe,Cr)\(_2\)Si phase with the minimum thickness of IMC layer which was only approximately 3.3 \(\mu\)m.

(4) The dispersion distribution of \(\tau_4\) IMC particles and FeAl\(_4\) phases on a small scale can be considered reinforcement phases in the welded seam, which would help to release the thermal stress in the joint. The maximum tensile strength of joints produced by the 6 steps cutting tool reached 152.3 MPa, representing 75% of the 5052 aluminium alloy base metal.

Author contribution Hubin Xu: conceptualization, writing—original draft, methodology, funding acquisition. Wei Cong: investigation, methodology, writing—original draft. Donghua Yang: writing—review and editing, data curation, funding acquisition. Yanlong Ma: reviewing, methodology. Jiachun Yan: methodology, writing—review and editing, reviewing, supervision.

Funding This project was supported by the Natural Science Foundation of Chongqing, China ( cstc2021jcyj-sxmx0391), the State Key Laboratory of Advanced Welding and Joining of China (No. AWJ-Z16-02), and the University Innovation Research Group of Chongqing (no. CXQT20023).

Data availability All data generated or analyzed during this study can be included in this published article. The experimental data in this article can be used for scientific research, teaching, etc.

Code availability Not applicable.

Declarations

Ethics approval The authors state that the present work is in compliance with the ethical standards.

Consent to participate and for publication All the authors listed have approved the manuscript, consented to participate, and consented for publication.

Conflict of interest The authors declare no competing interests.

References

1. Lan SH, Liu X, Ni J (2016) Microstructural evolution during friction stir welding of dissimilar aluminum alloy to advanced high-strength steel. Int J Adv Manuf Technol 82:2183–2193
2. Das T, Das R, Paul J (2020) Resistance spot welding of dissimilar AISI-1008steel/Al-1100 alloy lap joints with a graphene interlayer. J Manuf Process 53:260–274
3. Hirata T, Li P, Lei F, Hawkins S, Mullins MJ, Sue HJ (2019) Epoxy nanocomposites with reduced coefficient of thermal expansion. J Appl Polym Sci 136:1–6
4. Wang PF, Chen XZ, Pan QH, Madigan B, Long JQ (2016) Laser welding dissimilar materials of aluminum to steel: an overview. Int J Adv Manuf Technol 87:3081–3090
5. Ma H, Qin GL, Bai XY, Wang LY, Liang ZD (2016) Effect of initial temperature on joint of aluminum alloy to galvanized steel welded by MIG braze-fusion welding process. Int J Adv Manuf Technol 86:3135–3143
6. Huang YX, Meng XC, Xie YG, Wan L, Lv ZL, Cao J, Feng JC (2018) Friction stir welding/processing of polymers and polymer matrix composites. Composites, Part A105:235–257
7. Yuan R, Deng SJ, Cui HC, Chen Y, Lu F (2019) Interface characterization and mechanical properties of dual beam laser welding-brazing Al/steel dissimilar metals. J Manuf Process 40:37–45
8. Furuya HS, Sato YT, Sato YS, Kokawa H, Tatsumi Y (2018) Strength improvement through grain refinement of intermetallic compound at Al/Fe dissimilar joint interface by the addition of alloying elements. Metall Mater Trans A Phys Metall Mater Sci 49:527–536
9. He H, Wu CS, Lin SB, Yang CL (2019) Pulsed TIG welding–brazing of aluminum–stainless steel with an Al-Cu twin hot wire. J Mater Eng Perform 28:1180–1189
10. Wu KL, Yuan XJ, Li T, Wang HD, Xu C, Luo J (2019) Effect of ultrasonic vibration on TIG welding–brazing joining of aluminum alloy to steel. J Mater Process Technol 266:230–238
11. Xu HB, Gao PY, Cong W, Li MY, Cai YH (2019) Arc joining of aluminum alloy to stainless steel with the aid of milling. Mater Sci Technol 35:107–115
12. Xu HB, Tang S, Xi HF, Gao PY, Li MY (2017) Joint interface during arc milling brazing of aluminum alloy to low carbon steel with cutter milling at various rotation speeds. Rare Met 36:872–877
13. Rivera J, Hosseini MS, Restrepo D, Murata S, Vasile D, Parkinson DY, Barnard HS, Arakaki A, Zavattieri P, Kisailus D (2020) Toughening mechanisms of the elytra of the diabolical ironclad beetle. Nature 586:543–548
14. Gupta SP (2003) Intermetallic compound formation in Fe-Al-Si ternary system: part I. Mater Charact 49:269–291
15. Chen J, Shalchi Amirkhiz B, Zhang R, Rona B (2020) On the joint formation and interfacial microstructure of casting metal transfer cycle step braze welding of aluminum to steel butt joint. Metall Mater Trans A Phys Metall Mater Sci 51:5198–5212
16. Du Y, Schuster JC, Liu ZK, Hu RX, Nash P, Sun WH, Zhang WW, Wang J, Zhang LJ, Tang CY, Zhu ZJ, Liu SH, Ouyang YF, Zhang WQ, Krendelsberger N (2008) A thermodynamic description of the Al–Fe–Si system over the whole composition and temperature ranges via a hybrid approach of CALPHAD and key experiments. Intermetallics 16:554–570
17. Yang J, Yu ZS, Li YL, Zhang H (2018) Influence of alloy elements on microstructure and mechanical properties of Al/steel dissimilar joint by laser welding/brazing. Weld World 62:427–433
18. Chama CC (1996) Distribution of Al\(_x\)Fe\(_3\)Si and (FeAl\(_x\))Si in a HIPed Al-10.71 wt.% Si casting. Mater Charact 37:177–181
19. Barmak K, Dybkov VV (2004) Interaction of iron-chromium alloys containing 10 and 25 mass% chromium with liquid aluminium Part II Formation of intermetallic compounds. J Mater Sci 39:4219–4230
20. Budak E (2006) Analytical models for high performance milling. Part I: cutting forces, structural deformations and tolerance integrity. Int J Mach Tools Manuf 46:1478–1488
21. Kim BG, Dong SL, Park SD (2001) Effects of thermal processing on thermal expansion coefficient of a 50 vol.% SiCp/Al composite. Mater Chem Phys 72:42–47

22. Gorsse S, Petitcorps YL, Matar S, Rebillat F (2003) Investigation of the Young’s modulus of TiB needles in situ produced in titanium matrix composite. Mater Sci Eng A 340:80–87

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.