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Assessing the influence of fieldshaper material on magnetic pulse welded interface of Al/Cu joints

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Abstract

Fieldshaper (FS) is a widely used component in magnetic pulse forming and welding to improve the efficiency of the process. It enables to increase the magnetic pressure experienced by the workpieces during forming and welding. Recent developments in this subject focuses to increase the life time of the fieldshaper and to improve the efficiency by introducing shape optimized designs. In this study, we compare the efficiency of four fieldshapers made of Cuprofor, Siclanic, CuBe2 and Steel. The main focus is given to the effect of material properties while the same geometry was considered for those four fieldshapers. The same welding conditions (discharge voltage of 6kV and air gap of 1.64 mm) are used to weld Al/Cu. Fieldshaper made of steel could not successfully produce a welding under the aforementioned welding conditions. Welding performed using CuBe2 and Siclanic fieldshapers produces similar features of the welded interfaces, those have wavy zone, swirls, cracks, discontinuous intermediate (IM) layers, and a few IM pockets. Cuprofor fieldshaper also generates these features but the welded interface reveals significantly large kinetic instabilities due to the presence of large vortex, large holes within swirls and porous intermediate phases (IMP). These results clearly show the importance of choosing the appropriate fieldshaper material to produce successful welds and the resulting instabilities features at the interfaces.

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1. Introduction

Joining process of hybrid materials has gained an importance and increasing interest among researchers since they can be used in various industrial applications such as in aeronautics, transportations, medical and naval industry. The increased demand for hybrid materials lead to reduce the material consumption of rare and expensive materials, promotes economic growth and technological developments [1, 2]. However, conventional joining methods for fabricating hybrid structures consisting of dissimilar metals are not suitable due to metallurgical incompatibilities and the difference of melting temperatures.

Dissimilar welding using conventional joining processes (e.g, arc welding) heats the metals up to their liquid state. The metals then solidify rapidly leading to the formation of intermetallic compounds (IMC) at the interface of the welds which deteriorates the mechanical properties of the joints. To limit the above phenomenon during the joining processes, various solutions have been proposed which include reducing the time of welding and keeping the materials always at their solid-state during welding known as solid state welding. Various solid state welding techniques have been demonstrated to overcome the shortcomings of traditional joining methods and becoming suitable methods for joining wide range of dissimilar metals [3, 4, 5, 6].

The exploration of solid state welding processes has offered more flexibility among which high speed impact welding (HSIW) that enables joining both similar and dissimilar metallic combinations. High pressure, short duration (~10^{-6}s) [7] and low temperature bonding are the main characteristic of these methods [8]. Among high speed impact welding methods known in the literature are explosive welding (EXW) [6, 8], laser impact welding (LSW) [9], magnetic pulse welding (MPW) [1, 3, 5], and vaporizing foil actuator welding (VFAW) [10].

MPW is one of the most promising impact technologies in terms of cost, flexibility, reliability, ease of use, rate of work, no requirement of consumable and eco-efficiency [1]. The MPW and crimping process consists of generator (generates intense time-varying current), coil (produces the magnetic field), optional FS (concentrates the magnetic field in the working area), flyer part and target part which are workpieces. The processes require a specific generator to produce the required electric pulse that passes through the coil and induces eddy current in the fieldshaper and flyer part, it thus produces a significant Lorentz force in the flyer part. Thus, during MPW process, the flyer part accelerates with a high velocity towards another fixed part (target) causing a collision and creating a bonding interface between the two workpieces.

FS is a widely used MPW component to improve the efficiency of this process. It enables to increase the magnetic pressure experienced by the workpieces during forming and welding. However, FSs are prone to have fatigue damage due to the use of high frequency impulse current and the subsequent cyclic loadings during the process [11]. Various studies were focused on the improvement of FS longevity [11, 12] and efficiency by introducing shape optimized designs suitable for specific applications [13, 14]. However, FS effects on the weld features has not been considered in such investigations. And the influence of the air gap and discharge voltage on the interface behaviour can be found in our previous study [15]. Therefore, this paper focus on this effect on Al/Cu interface while comparing for FS nature (Steel, CuBe2, Siclanic, Cuprofor) made of same geometry. Observations and recommendations are addressed.

2. Materials and Methodology

Al6060 T6 was chosen as the flyer tube and pure copper was used as inner part material in this study. The chemical compositions of both materials are reported in Table 1.

Table 1. Standard chemical compositions of the Al6060 T6 and Copper used

Material	Mg	Si	Fe	Mn	Cr	Zn	Ti	Cu	Al
Al6060T6	0.8-1.2	0.4-0.8	0.7	0.15	0.04-0.35	0.25	0.15	0.15-0.4	Balance
Copper	-	-	-	-	-	-	-	99.9	-

The welding tests are performed on tubular assemblies using a single turn coil with various fieldshapers (Steel, CuBe2, Siclanic and Cuprofor, as shown in Fig.1a) connected to a magnetic pulse generator PULSAR MPW. The discharge pulse frequency is 20 kHz which was measured by a Rogowski probe inside the working station. Mechanical and electrical properties of those four fieldshapers are given in Table 2. A schematic of the assembly cross section used in this investigation is shown in Fig. 1b. The inner part with a diameter of 15.94 mm is inserted inside the flyer tube having an outer diameter of 22.22 mm and a thickness of 1.50 mm. The air gap and overlap distance between flyer tube and inner part are 1.64mm and 10 mm, respectively. The typical welded sample as presented in Fig. 1c.

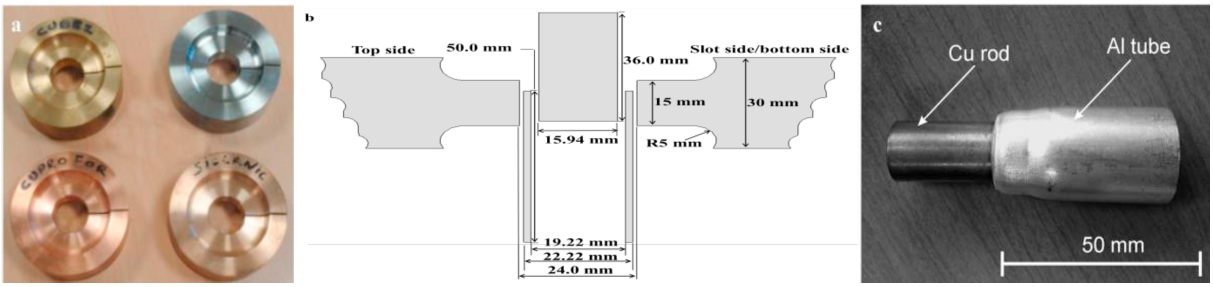

Fig 1 (a) Four different fieldshapers used in the welding process: CuBe2, Steel, Cuprofor, Siclanic (b) cross section of the assembly configuration used for the tests (c) magnetic pulse welded Al/Cu sample

Table 2. Mechanical and electrical property of the fieldshaper used in the experiment

Fieldshaper	Steel	CuBe2	Siclanic	Cuprofor
Electrical Conductivity (10^7S/m)	0.58	1.45	2.67	5.16
Young's Modulus (GPa)	210	125	130	140
Poisson's Ratio	0.29	0.29	0.29	0.29
Density (g/cm^{-3})	7.9	8.2	8.9	8.9

3. Results and discussion

This section addresses the effect of FS on the interface feature. Results are presented in ascending order of the electrical conductivity of FS. For each respective Al/Cu joint, macrographic and microscopic observations of the interfaces, using optical microscope (OM) and scanning electron microscope (SEM), are provided. The specimens were cut along the longitudinal direction and then prepared with standard grinding and polishing operations, prior to OM and SEM examination.

3.1 Al/Cu interface in case of steel FS

Among those FSs, the steel FS fails to generate a welded interface under the tested welding conditions, whereas the other FSs lead to a successfully weld Al to Cu as detailed hereafter. The interface is not bonded when using steel FS due to more electrical losses caused by the low electrical conductivity of steel. That is, the induced magnetic field is not sufficiently high to produce the required Lorentz force, thus the experiment does not enable to meet both requirements of pressure and impact velocity for welding. To obtain a weld using steel FS, more energy is required. Generally, increasing the charging voltage allows such achievement but it impairs the FS's service life due to the subsequent increase in mechanical stresses [11]. For this reason, effective welding may be incompatible with maintaining a good service life of FS. Thus, the use of low conductive FS becomes tricky when large weldability window is required.

3.2 Al/Cu interface in case of CuBe2 FS

The electrical conductivity of the CuBe2 FS is twofold higher compared to that of steel FS. This difference is sufficient to create a welded joint under the tested conditions. Fig.2 shows a cross-sectional view of the whole interface and finer details from SEM observations. The aluminium flyer is effectively welded on the Cu part over a distance of 3.6 mm approximately, from a region of about 4.1mm away from the zone where flyer impact the fixed rod first as shown in Fig.2. A wavy nature of the weld starts at the zone 1 that means an onset of excessive shearing causing such interfacial instability [15]. There is a development of this wavy morphology along the welded interface before it collapses after certain distance 5.0 mm to give a straight welded interface, i.e a zone where shear instability begins to disappear (from zone 5). The waves amplitude does not exceed 30 µm and the wavelength varies between 100-200µm from to zone 1 towards the zone 5. The interface feature also includes the presence of IMP (which could have trapped jetted materials, remaining surface oxide layer and intermetallic compounds) within the wavy zone (WZ). Caused by a confined melting and abrupt solidification [16], this IMP characterizes a rather harmful nature of the welded joint due to cracking and fragmentation they create during solidification. Along the interface, the IMP appears as discontinuous pockets (zone 2) and also continuous layers with heterogeneous thickness (zone 3) which varies from a few microns up to about 40µm. Within some sites of the interface, the instability evolved towards advanced stages that are vortices and swirls due to excessive shearing. Zone 2 shows several vortices with some swirls containing IMP. These features evidence that from steel FS to CuBe2 FS, the change in electrical conductivity strongly affect the weld formation and development.

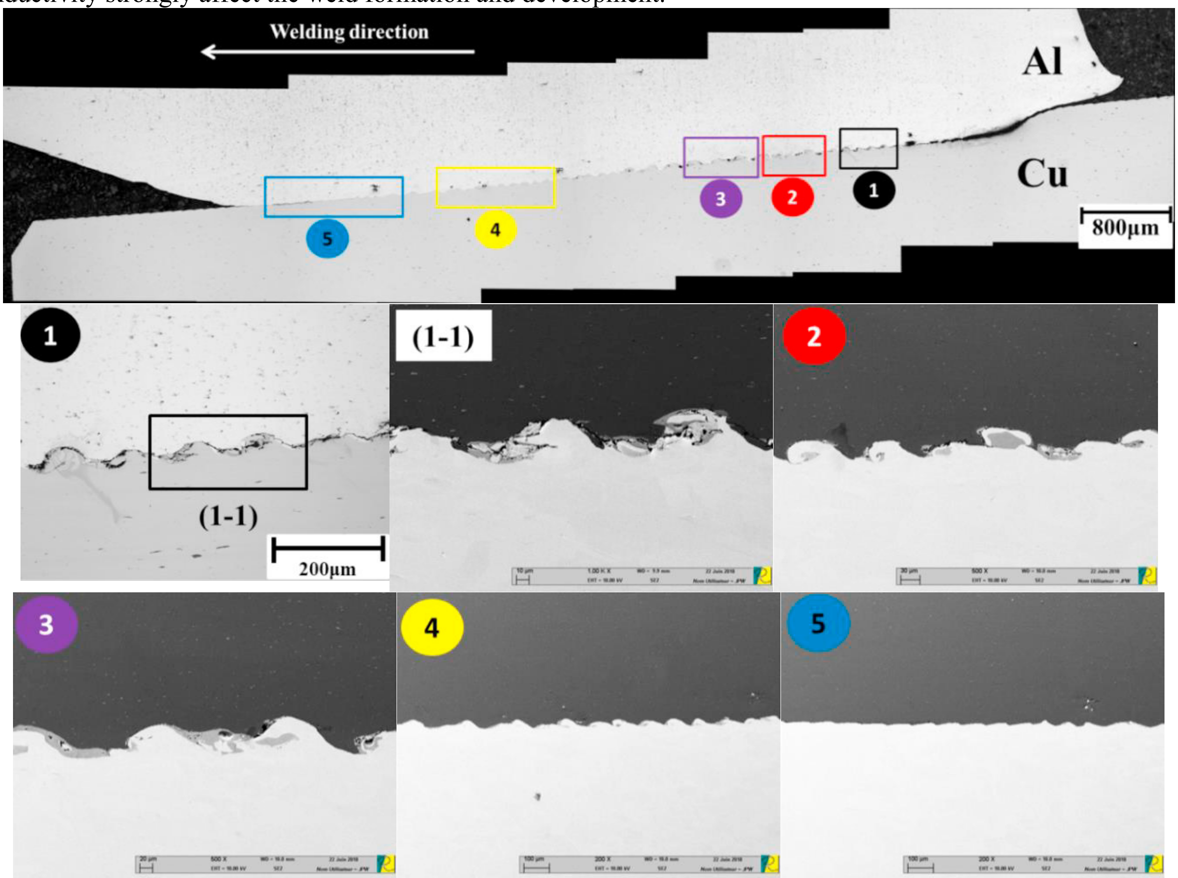

Fig 2. Typical cross-sectional view and interfacial phenomena of various zones along the interface produced with fieldshaper made of CuBe2 during MPW

3.3 Al/Cu interface in case of Siclanic FS

The interface characteristics produced during MPW with Siclanic FS are displayed on Fig.3. Basically, the macroscopic interface observations of both CuBe2 FS and Siclanic FS cases are similar. Onset of instabilities produced by the CuBe2 occurs also for the Siclanic case, viz the wavy shape where the collision starts (zone 1) and the progressive development of this instability along the welded joint until the collapse at the end zone. The wavelength and the amplitude of the waviness are about 100 µm, and 20 µm, respectively. The effective weld length is also about 4.2 mm that starts about 3mm away from the onset of the collision. Onset of swirls exists with WZ as illustrated in zone 2 and zone 3. There is less intermediate phase affected zone (IPAZ) compared to the CuBe2 FS case, but the intermediate (IM) zones (zone 1, zone 5) exhibit similar features in terms of morphology (discontinous layers and pockets) and defects (cracks). The Siclanic FS case generates thiner IMP maximum of 9µm and mostly free of interface defects which indicates that the weld has strong mecanical strength compared to the weld produced with CuBe2 FS.

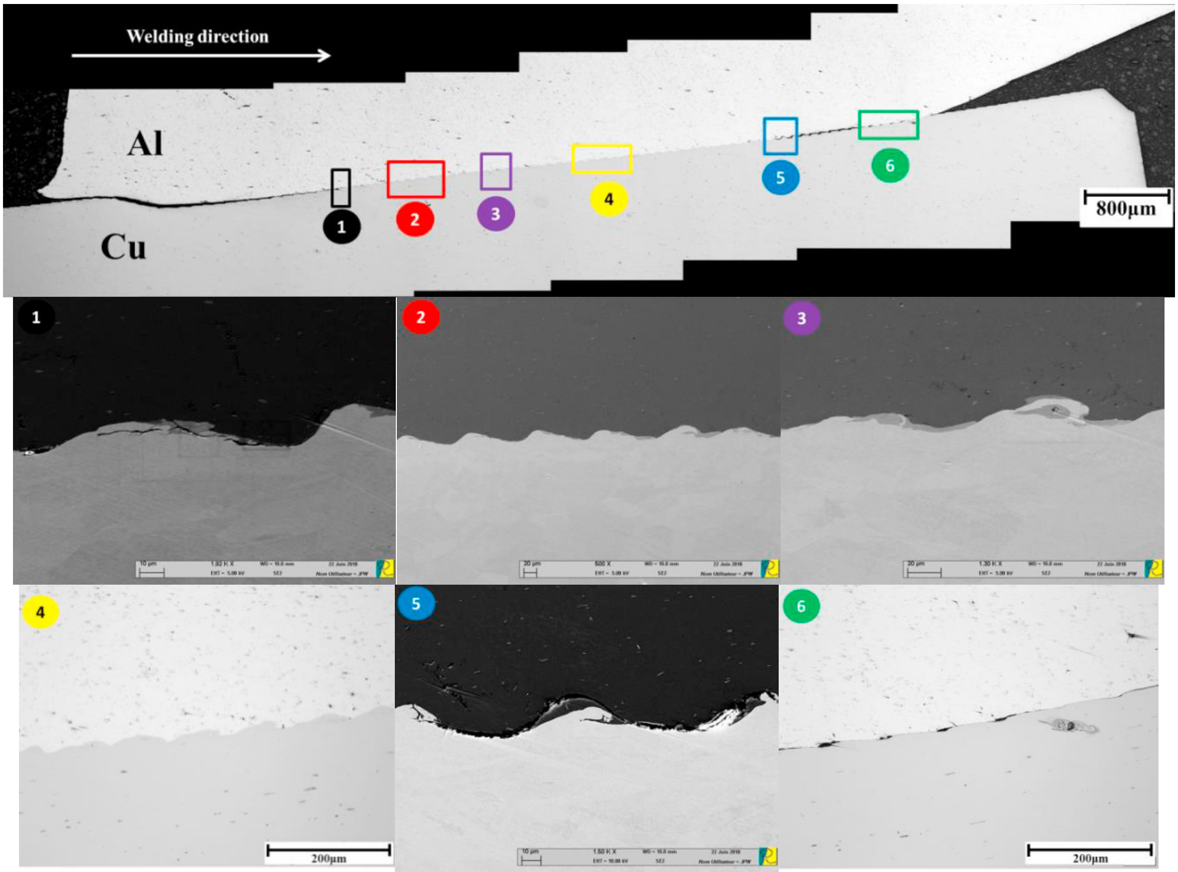

Fig 3. Typical cross-sectional view and interfacial characteristics of various zones along the interface produced with fieldshaper made of Siclanic during MPW

3.4 Al/Cu interface in case of Cuprofor FS

The cross-sectional view and high magnifications images of interface feautres in case of Cuprofor FS are presented in Fig 4. This FS induces higher velocity during MPW among those 4 FSs because of its high electrical conductivity. The length of weld joint is 3.2 mm (slightly shorter than the case of CuBe2). The previous interfacial characteristics similar to the one observed with CuBe2 and Siclanic FSs were also observed here, but the interface response produces more kinetic instabilities that result in large vortecis, large holes within swirls, cracks inside the intermediate layer and porous IMP. The welded joint subjected to higher impact velocity and then higher interfacial shearing becomes defective, globally. More cracking and fragamentation occur along the interface due the influence of IM media combined with the strong instabilities. The IM layers exhibit thicknesses of up to 37μm which can contain large holes with up to 7μm in diameter (zone 2). The IPAZ becomes porous (zone 2, zone 3) which is due to ultra high heating and cooling rates [17]. The location of the large hole at the center of the IM pockect confirms the further development of the intefacial swirls into vortex where centrifugal force due the swirling radially breaks the melted IM prior to solidification. This intense instability well corresponds to a phenomenon involved by more intense collision due to the higher electrical conductivity of the Cuprofor FS. At the end of weld, the interfacial instability creates significantly large voids whose size can exceed 35μm (zone 6). The formation of those very large voids can be explained as results of jetting of molten fluid, solidification shrinkage, and/or local fragmentation combined with particulates jetting governed by shear stresses [18]. The intensity of the impact is also revealed by the waves characteristics. The maximum wavelengths of 200μm and maximum amplitude of 35μm.

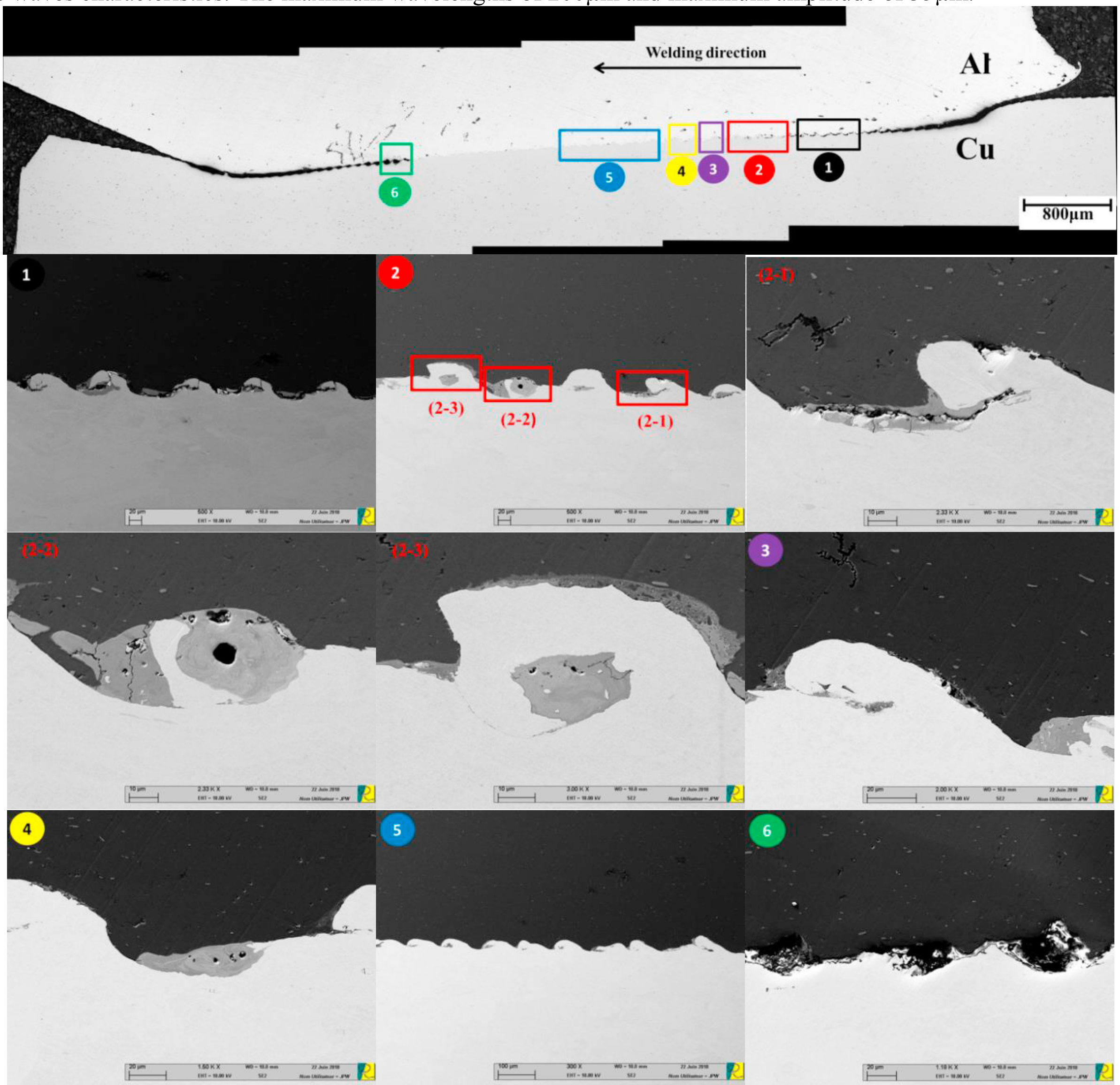

Fig 4. Typical cross-sectional view and interfacial phenomena of various zones along the interface produced with fieldshaper made of Cuprofor during MPW

3.5 Summary and recommendations

Table 3 shows the similarity and dissimilarity of the interface features generated with different fieldshapers during MPW. In the case of CuBe2 FS, lower velocity was obtained and there is no sufficient jetting that can involve the higher instabilities in the interface, but the thickest intermediate phases (40 micron) which may contain jetted materials and intermetallic compounds were found in the weld interface among the three welded cases. The weld produced using Siclanic FS is highly promising and it indicates an accurate jetting and resulted in a regular feature. Interface produced under this case only has a maximum of 9μm IMP, For Coprofor FS, the welded region presents significant instability which may result from melting solidification, also possible formation of thick intermediate phase likely composed of intermetallic compounds (relatively thick compare to Siclanic). Among those FSs cases, the longest effective welded length (4.2 mm) was found at Al/Cu interface produced in case of Siclanic FS. These results demonstrated that Siclanic FS can achieve the best welding interface compared to the other three cases under the above welding condition.

Table 3. Similarity and dissimilarity of the interface produced with various fieldshapers during MPW

Fieldshaper			Steel	CuBe2	Siclanic	Cuprofor
Interface features	similarity	-	-	wavy zone, swirls, votex, cracks, IM layers and pockets		
	dissimilarity	Effective welded Length	-	3.6 mm	4.2 mm	3.2 mm
		Maximum thickness of IMP	-	40μm	9 μm	37 μm
		Period of waves	-	**Length:** 100-200 μm **Amplitude:** 0-30 μm	**Length:** about 100 μm **Amplitude:** about 20μm	**Length:**100-200 μm **Amplitude**: about35μm
		Other phenomena	-	fragmentation	regular wave, a small amount of IM layers and cracks	large vortex, large holes, porous IMP, large voids with size exceed 35μm

From the above experiments, we know that an appropriate impact velocity is crucial to obtain a good welding. Various FSs have different electrical conductivities which can produce different velocities, and thus influence the quality of the interface. However, blindly selecting a FS with high conductivity material may cause excessive speed and damage the weld interface. Increasing the charging voltage is another method to improve velocity when using low conductive FS materials, but it impairs the FS's service. Therefore, further work should be performed on the welded joint influenced by different charging voltages and FS with various electrical conductivities, and study the service life of FS under different input voltages which can help to identify and optimize the process conditions for effective applications. Numerical simulations can also be used to further investigate the interfacial instability and governing mechanisms under those welding conditions.

4. Conclusions

Fieldshaper made of steel cannot successfully produce a welding under the welding conditions with discharge voltage of 6kV and air gap of 1.64mm. Fieldshaper made of Cuprofor, Siclanic, CuBe2 produce a successful welding joint while with a difference interface features. In the sound welding region, the effective welded length produced by using CuBe2 FS, Siclanic FS and Cuprofor FS was 3.6 mm, 4.2 mm and 3.2 mm, respectively. And effective bonding was observed always take place few mm away from the zone where flyer impact the fixed rod first. Intermediate phases were found in all the sound welds. However, the quantity and maximum thickness of the intermediate phases were different. The thickest intermediate phases (40 micron) were found while using the CuBe2. Welding performed using CuBe2 FS and Siclanic FS produce similar features of the welded interfaces, those have wavy zone, swirls, cracks, discontinuous IM layers, a few IM pockets. Cuprofor FS also generates these features, but the welded interface reveals significantly large interfacial instabilities resulting with the presence of large vortex, large holes within swirls and porous IMP. A combination of Siclanic FS and weld conditions with discharge voltage of 6kV and air gap of 1.64mm resulted in a good weld quality when compared to other three cases because of the presence of regular features and thin IMP, thus the weld produced with Siclanic FS is expected to have a higher mechanical strength.

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