EFFECT OF WELDING SPEED ON MECHANICAL PROPERTIES OF DISSIMILAR FRICTION STIR LAP-JOINT WELDING BETWEEN AA6061 AND C1100 COPPER

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ABSTRACT

Nowadays, renewable energy such as wind and solar energy can be employed for marine application to enhance clean and green technology. So, using battery is necessary to apply power for ship activities. To contribute sustainable development, optimizing structure in electric transmission such as bimetal connector Cu-Al is necessary to improve joint quality. This study focused the influence of welding parameters on the quality of the lap-joint between AA6061 aluminum alloy and C1100 copper. Experimental results indicate that the welding interface was sensitive to welding speed. Some welding defect was found in the joint such as tunnel and hook defects. The highest tensile strength produced by the welding speed of 200 mm/min was approximately 1100 N. In all experimental regimes, the weld zone structure, hardness distribution, tensile strength, fracture location, and local deformation were analyzed and discussed in detail.

Keywords: *Friction stir welding, microstructure, mechanical properties, hardness*

I. INTRODUCTION

Friction stir welding (FSW) technology is considered a green technology due to its energy saving efficiency and environmental friendliness [1]. The development of FSW has demonstrated its unique advantages such as lower temperatures, distortion, residual stress compared to conventional fusion welding [1]. These advantages avoided some welding defects such as cracks and voids [2]. Therefore, this technology not only produced good similar joins but also dissimilar joints [3]. Despite the widespread application of dissimilar FSW lap-joints in industries like aerospace, electronics, and automotive, their efficiency remains a challenge [4] due to differences in melting points and mutual solubility between materials [5]. While some studies have investigated FSW of Al-Cu joints [6, 7], there are still gaps in understanding the optimal welding parameters for achieving high-strength welds. Although FSW technology has been successfully applied to aluminum alloy joints [8-13], its application in Al-Cu lap-joints is still limited in Vietnam.

This study aims to explore the impact of welding parameters on the welding interface, defects, microstructure, and mechanical properties of FSW lap-joints between AA6061 aluminum alloy and C1100 copper. Local strain in the lap-joint was examined using digital image correlation (DIC) technology.

II. MATERIALS AND METHODS

1. Materials and fabrication of lap-joint

The materials used in this work are AA6061 aluminum alloy and C1100 copper plates with dimensions of 150×50×3 mm and 150×50×2 mm, respectively. The thickness of the two plates is selected based on the practical manufacturing of the products. The chemical composition and mechanical properties of AA6061 and C1100 are presented in Table 1 and Table 2, respectively.

Table 1. Chemical composition of AA6061 aluminum alloy and C1100 copper [12]

Chemical elements of AA6061								
Element	Cu	Mg	Si	Fe	Mn	Zn	Ti	Al
Percentage composition (%)	0.05	0.05	0.25	0.4	0.05	0.07	0.05	Bal.

Chemical elements of C1100				
Element	Cu	Pb	Fe	Ni
Percentage composition (%)	≥ 99.9	≤ 0.005	≤ 0.005	≤ 0.005

Table 2. Mechanical properties of AA6061 aluminum alloy and C1100 copper [12]

Mechanical properties of AA6061				
Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness (HV)	Elastic modulus (GPa)
276	310	12-17	107	68.9
Mechanical properties of C1100				
Hardness	Tensile strength (MPa)	Elongation (%)	Hardness (HV)	
1/4 H	215 – 275	≥ 25	100	

The lap-joint of AA6061 aluminum alloy and C1100 copper plates is fabricated using a friction stir welding machine at the friction stir welding laboratory of Nha Trang University. The welding tool is made of SKD61 steel with a geometry of cylindrical pin. The diameter of shoulder and pin was 18.0 mm and 5.0 mm, respectively. The length of the welding pin was 3.1 mm. The schematic of friction stir FSWed lap-joint of AA6061 and C1100 alloys is depicted in Figure 1. Based on the practical experience in literature [8-13], four welding speeds are utilized to fabricate lap-joint, as shown in Table 3. The rotational speed was fixed at the value of 900 rpm for all samples.

Table 3. Parameters of the experimental welding regimes

No.	Rotational speed (rpm)	Traverse speed v (mm/min)
1	900	300
2	900	200
3	900	135
4	900	100

2. Testing methods

The quality of the weld joint is evaluated through: (1) observation of the microstructure of the joint on an Olympus Kruss MMB200 optical microscope; (2) hardness distribution of the joint on a Vicker MMMT-X microhardness

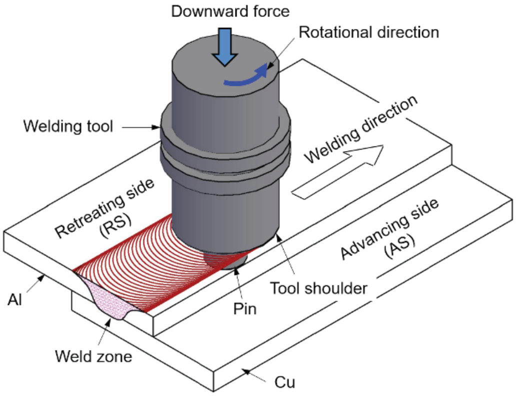


Figure 1. Friction stir welding process of the joint.

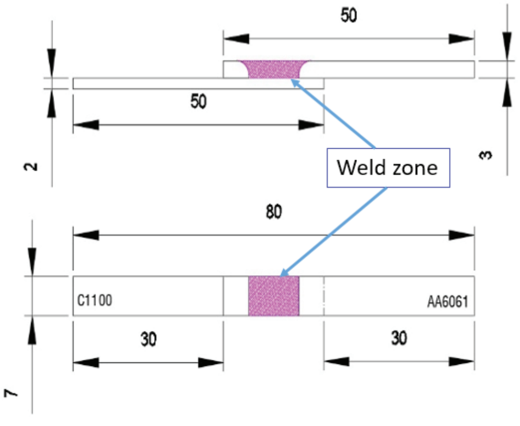


Figure 2. Dimensions of the test samples of AA6061 and C1100 alloy plates.

tester using a 200 gf with a dwell time of 10 seconds; (3) tensile strength testing of the joint performed on an Instron 3366 machine with a maximum tensile force of 10 kN with rate of 1 mm/min, and (4) examination of local strain by DIC technology during the tensile test. Specimens for the tensile test are prepared by cutting from the friction stir welded plate, as depicted in Figure 2. The samples underwent polishing using a range of sandpaper grades from 1000 to 4000, followed by treatment with alumina solution, before being etched with Keller reagent.

III. RESULTS AND DISCUSSION

1. Characteristic of welding interface

The samples underwent microscopic examination after polishing to assess surface quality and joint defects, as depicted in Figure 3. It was evident that the welding speed significantly influenced the welding interface. No cracks or fractures were observed at the interface between the copper and aluminum metals within the lap-joint. However, diffusion and mixing between copper and aluminum were noted in the weld zone. A strong bonding was distinctly achieved at the weld zone under the welding regimes of 200 mm/min and 135 mm/min. Conversely, the welding regimes of 300 mm/min and 100 mm/min resulted in the appearance of some tunnel and hook defects on the joints. These defects were attributed to the inappropriate traverse speed of the pin, leading to inadequate stirring effectiveness and a lower temperature in the weld zone. Moreover, the shape and depth of the welding pin contributed to insufficient frictional heat generation in the weld zone, resulting in weak bonds in the weld joint. Such defects often initiate crack formation during tensile strength testing, significantly diminishing the joint quality.

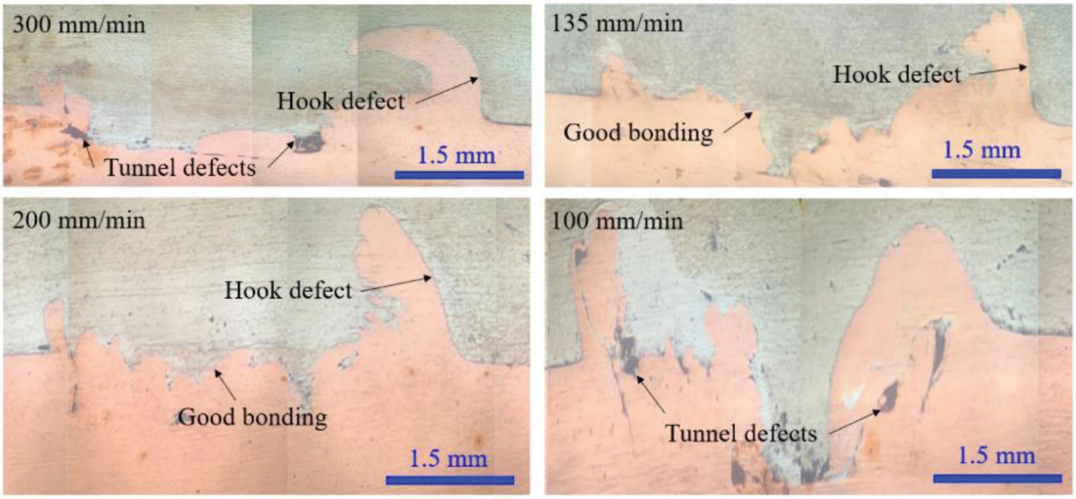


Figure 3. Welding interface between C1100 and AA6061 produced by various welding speeds.

The welding surface after etching revealed four distinct regions on the AA6061: the stirred zone (SZ), the thermo-mechanical affected zone (TMAZ), the heat-affected zone (HAZ), and the base metal (BM), as shown in Figure 4.

The aluminum grain structure within the four weld zones is further observed in Figure 5. The stirred zone exhibited the finest grains with a uniform grain structure compared to the other zones. In the thermo-mechanical affected zone, the structure is highly distorted, with elongated grains deformed along the material flow. For

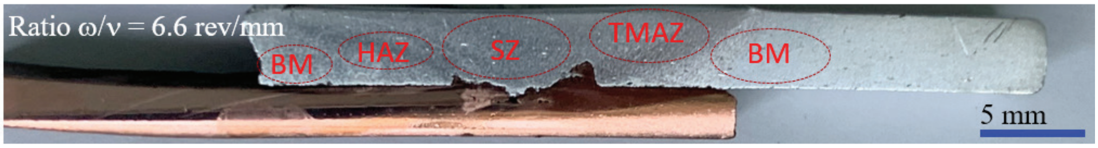


Figure 4. Formation of the weld zone between AA6061 and C1100.

the heat-affected zone, it has only undergone cycles of high temperatures due to friction without experiencing plastic deformation, resulting in a coarse grain structure. The base metal zone remained unaffected by heat, retaining its elongated grain structure from the initial metal plate manufacturing process.

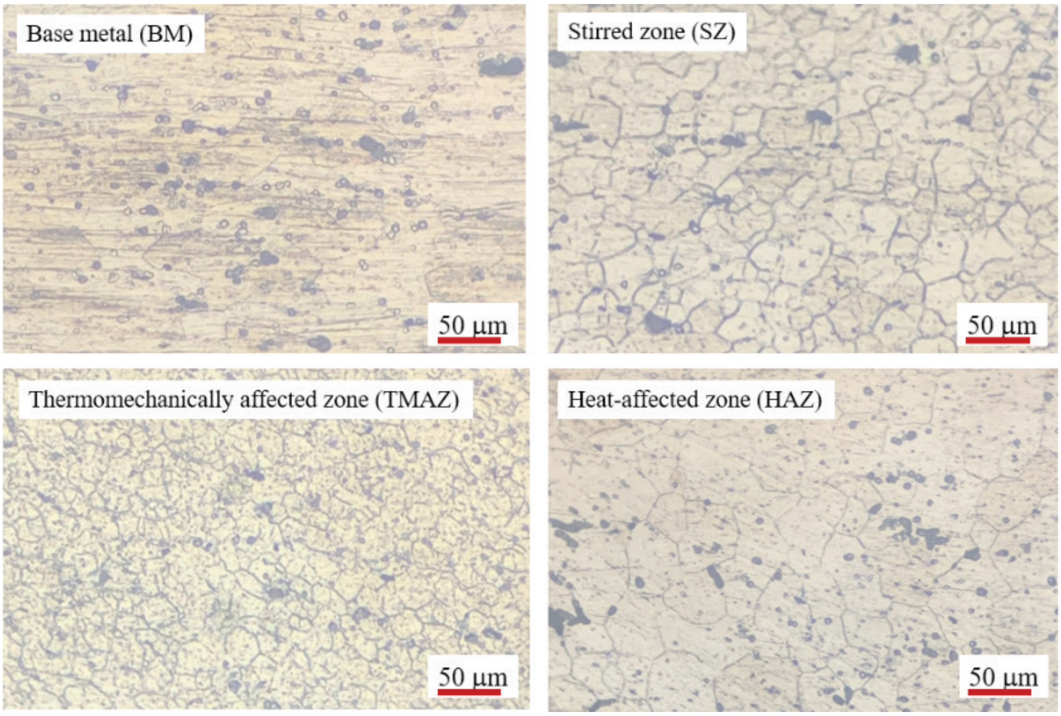


Figure 5. Grain structure at different zones of AA6061.

2. Microhardness of lap-joints

The distribution of microhardness along the cross-section and the thickness of the joint are shown respectively in Figures 6 and 7, respectively. Microhardness values along the cross-section of the joint ranged from 55 HV to 80 HV. Microhardness tended to decrease in the heat-affected zone (HAZ) and the stirred zone (SZ) due to plastic deformation of two metal layers, leading to a recrystallization phenomenon in the weld zone, which significantly reduced microhardness of samples. Away from the weld zone, the microhardness increased due to being within the thermomechanically affected zone (TMAZ) and the base metal (BM). Microhardness values

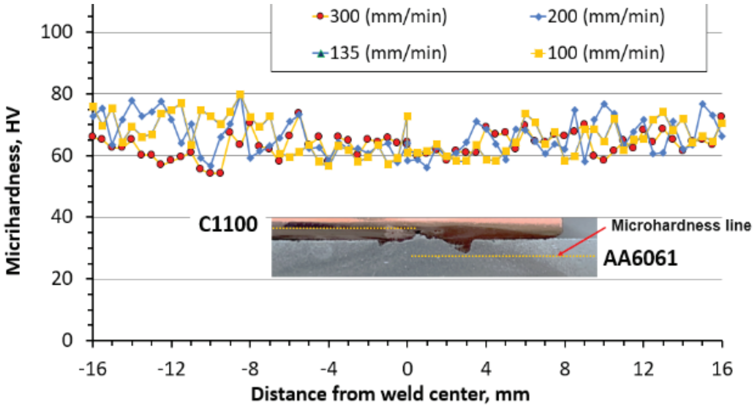


Figure 6. Microhardness distribution along the cross-sectional of AA6061 and C1100.

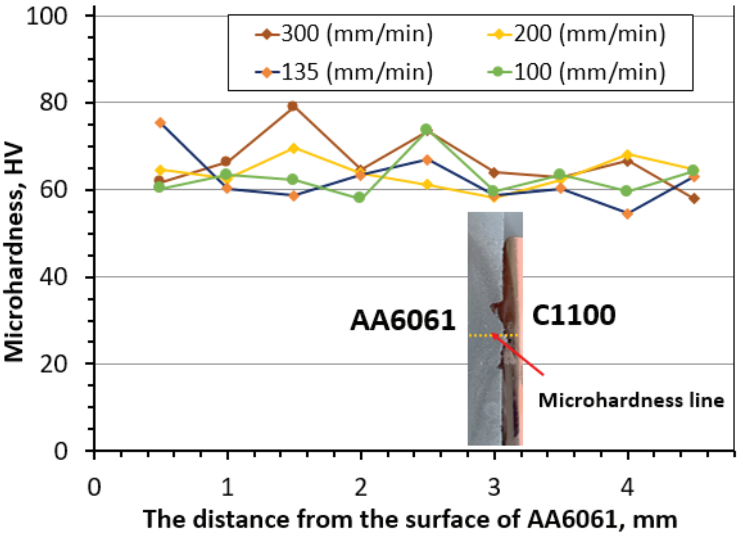


Figure 7. Hardness distribution across the thickness of lap-joint of AA6061 and C1100.

measured along the thickness of the weld joint, as shown in Figure 7, indicate that with a pin length of 3.1 mm and a total thickness of the two welded materials being 5 mm, the influence of the traverse speed ω of the pin on the hardness of the material zone is not clearly evident.

3. *Tensile shear strength of the lap-joints*

The influence of the traverse speed of the weld on the quality of the FSWed lap-joint between AA6061 and C1100 is depicted in Figure 8. It is evident that traverse speeds of 135 mm/min and 200 mm/min resulted in the best tensile strength of the joint. A welding speed of 100 mm/min and 300 mm/min, the tensile strength is lower compared to the former two cases. As indicated in Figure 3, the formation of welding defects might be reason for the low strength. The difference in tensile breaking force between materials reaches up to 32% when comparing the highest and lowest tensile forces, indicating that the lap-joint has the best quality at a traverse speed of 200 mm/min.

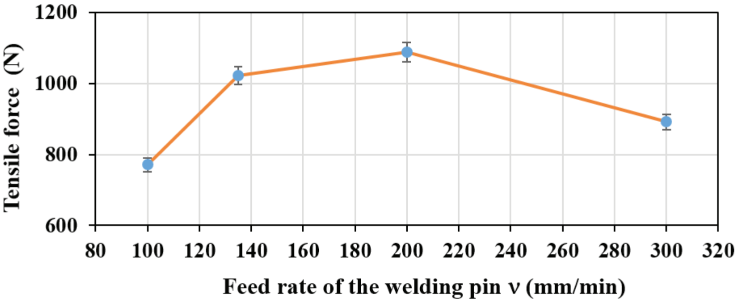


Figure 8. Tensile strength of the lap-joints between AA6061 and C1100 at different welding speeds.

At high traverse speeds of 200 mm/min and 300 mm/min, the lap-joint failure exhibited material tearing at the interface between aluminum and copper, with clear tearing observed in the copper layer firmly adhered to the aluminum, and material fracture occurring at the aluminum region outside the weld joint. In contrast, at traverse speeds of 100 mm/min and 135 mm/min, the lap-joint separated at the weld region, with the two weld materials detaching from each other, without any material tearing, as shown in Figure 9. Among the four cases, the lap-joint achieved the best quality with welding parameters of a rotational speed of 900 rpm and a traverse speed of 200 mm/min.

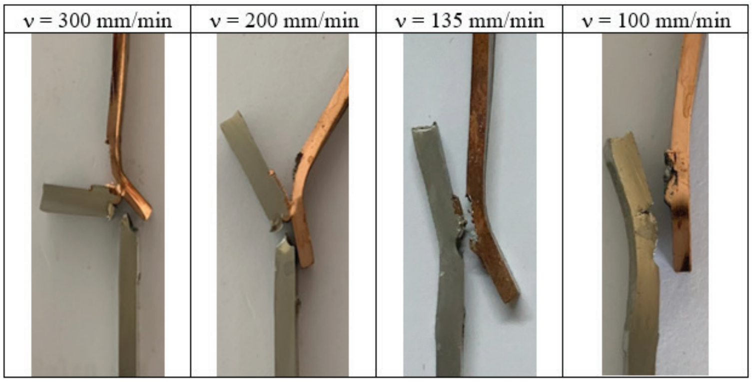


Figure 9. Fracture locations of lap-joint at different welding speeds.

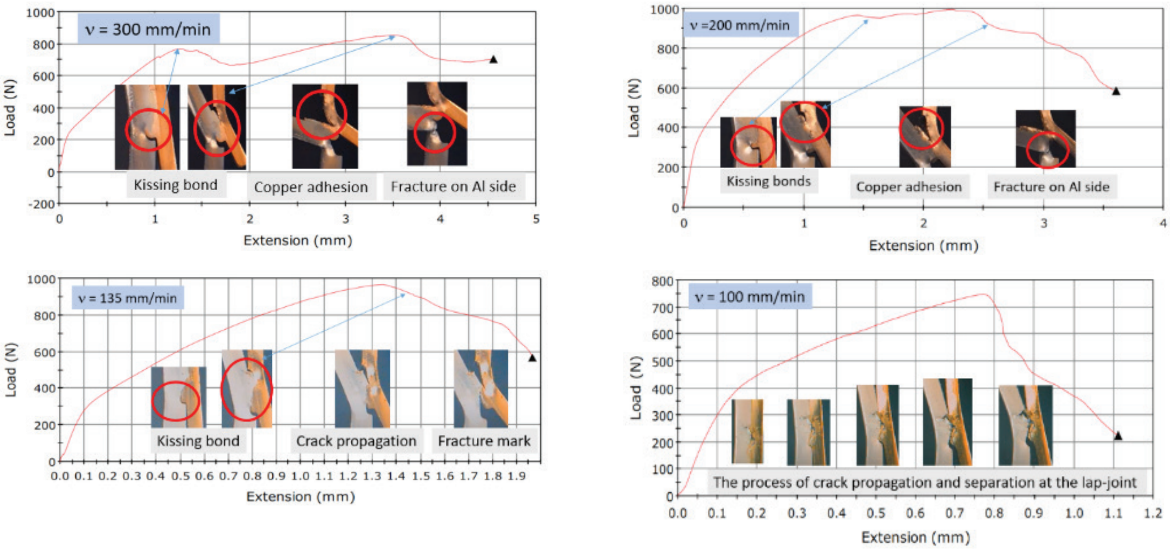
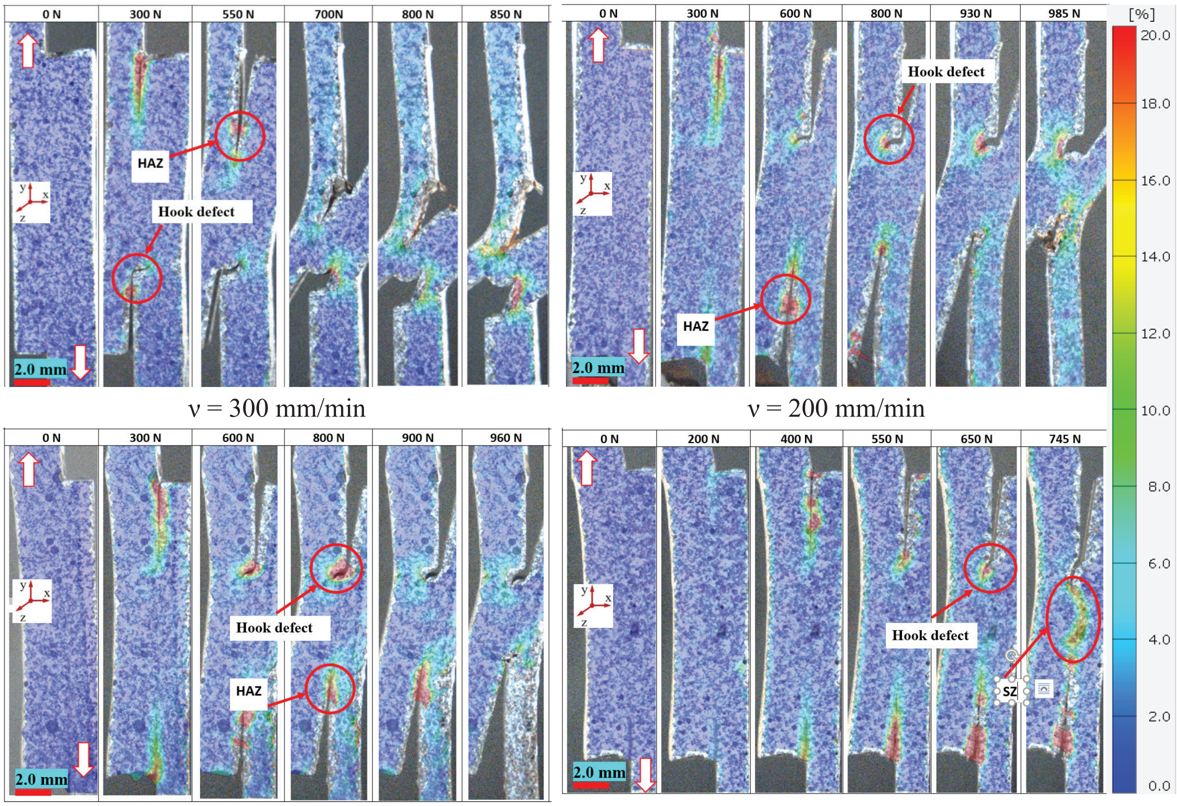


Figure 10. Tensile force and elongation at different welding speeds.

Figure 10 illustrates the relationship between tensile force and deformation in four different welding modes. It can be observed that the failure of the weld samples began with cracks forming at hook defects. In the case of welding speeds of 300 mm/min and 200 mm/min, both samples fracture towards the aluminum. A notable observation is the presence of a thick layer of copper, approximately 0.4 mm thick, adhering to the aluminum in the weld zone on the pulled surface of the samples. This adhesion leads to significant elongation, reaching 4.5 mm and 3.6 mm, respectively, for these welding speeds. In contrast, at welding speeds of 135 mm/min and 100 mm/min, cracks form at hook defects, and these cracks propagate, resulting in fracture at the weld zone. Consequently, the elongation in these cases is relatively low, about 1.9 mm and 1.1 mm, respectively.

4. Local strain

Figure 11 illustrates the local strain of lap-joint under tensile loading for different traverse welding speeds. It is evident that the formation of the nugget zone primarily originated from hook defect regions and the HAZ, followed by the propagation of the nugget as the tensile force increases, ultimately causing tearing of the weld region. The HAZ experienced the thermal deformation, resulting in relatively low strength of the material in this zone, which accelerates the sample's failure process. For the sample welded at a traverse speed of 300 mm/min, local strain was clearly observed at weak bonding regions, leading to the tearing of the sample at a force of 850 N. For the welding speeds of 200 mm/min and 135 mm/min, both samples exhibited similar load-bearing capacities, with local strain occurring at hook defect regions and clear separation under a load of 800 N. The samples were fractured at forces of 985 N and 960 N, respectively. Particularly, the welding speed of 100 mm/min, the sample material separated at the SZ, indicating that the welding speed was insufficient to generate friction and mixing between the two materials. Consequently, this sample exhibited the lowest tensile strength compared to the other three samples.



ν = 300 mm/min

ν = 200 mm/min

ν = 135 mm/min

ν = 100 mm/min

Figure 11. Influence of traverse speed on the local strain of lap-joints under tensile loading.

IV. CONCLUSIONS

The lap-joint of AA6061 and C1100 aluminum alloys has been fabricated by friction stir welding (FSW). The influence of traverse speed on the mechanical properties of the joint has been investigated and analyzed in detail. Some findings were summarized as followings:

The welding interface of lap-joint was sensitive to welding speed. Some welding defects was found such as tunnel and hook defects. Using low or high welding speed would lead to the formation of these defects. The lap-joint without tunnel defect was observed at the joint produced by 135 – 200 mm/min.

The highest joint strength was reached at the welding speed of 200 mm/min. Increasing or decreasing welding speed reduced the joint strength. Local strain concentrated in hook defect that reduced thick plate.

The fracture location of the samples took place in the aluminum side for two cases of traverse speeds of 300 mm/min and 200 mm/min. Particularly, when the fracture occurred at the SZ by using the traverse speed of 100 mm/min.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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