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SONG WEIWEI[1,2,3*], PU JIAFEI[1,2,3], JIANG DI[1,2,3], GE XIAOLE[1,2,3], DONG QI[1,2,3], WANG HONGFENG[1,2,3]

ANALYSIS OF THE MICROSTRUCTURE AND HARDNESS OF ALUMINUM ALLOY GRADIENT PLATE PREPARED BY FRICTION STIR

The aluminum alloy performance gradient plate was prepared by friction stir joining. Analysis results of the macro morphology, microstructure, and hardness of the aluminum alloy performance gradient plate prepared under various parameters show that when the feed speed of the stirring tool is 250 mm/min, the downward pressure of the stirring tool is 6.6 mm, and the rotation speed of the stirring tool changes from 200 rpm to 800 rpm. The macroscopic morphology of the aluminum alloy gradient plates prepared by the method first changed from burr to smooth, and vice versa. There is a different cross-section morphology of the prepared aluminum alloy gradient plates, however, the aluminum alloy plates are stirred and involved with each other, and the grains of the prepared plates are refined. The hardness of the upper and lower surfaces of the aluminum alloy gradient sheet decreases, whereas that of the upper surface of the side increases, and that of the middle and bottom sides also decreases. However, the hardness of the middle side of the sheet prepared with the rotation speed of the stirring tool at 800 rpm increases, but that of the bottom side still decreases. Obtained through analysis that the performance of the aluminum alloy gradient sheet prepared at the stirring tool rotation speed of 500 rpm increases in equal proportion to achieve a good performance gradient change.

Keywords: Friction stir joining; Aluminum alloy; Performance gradient; Microstructure; Hardness

1. Introduction

Friction stir is a new technology to prepare aluminum alloy gradient plate materials based on the dissimilar aluminum alloy friction stir joining technology combined with the friction stir lap technology.

It involves the application of various aluminum alloy materials in practical engineering applications, such as large aircraft manufacturing, including the joining of dissimilar aluminum alloys and applying aluminum alloy lap technology. At present, there are various research on friction stir bonding of dissimilar aluminum alloys and friction stir lap bonding technology of the aluminum alloys. She et al. [1] primarily studied the friction stir joining of 2A12 and 7075 aluminum alloys and found that the joining zone was asymmetrical, and the heat-affected zone on the return side of the joining zone showed grain coarsening and partial strengthening phase dissolution. This is a weak area. Gao et al. [2] conducted a frictional stir joining study on 6061-T6/7075-T6 dissimilar aluminum alloys and analyzed that the joining zone had the weakest hardness, which was composed of two aluminum alloys (6061-T6 and 7075-T6). Dynamic recrystallization occurred in the joining zone, and the grain size was close to 10 μm. Zhao et al. [3] analyzed that the friction stir joining zone of 6082-T6/7075-T6 dissimilar aluminum alloy has a dense structure, and the hardness distribution of the joining zone is W-shaped. The hardness of the retracting side near 7075-T6 is higher, that of the advancing side near 6082-T6 is lower, and the hardness of the joining center is the lowest. Liu et al. [4] analyzed the friction stir joining zone of L6/LY16 dissimilar aluminum alloy and found that the dislocation density at the joining location increased, various cellular substructures appeared, new recrystallized grains were formed, and the hardness values of the heat affected zone in the joining area barely changed. Liu et al. [5] studied the friction stir joining zone of 6061/7075L dissimilar aluminum alloy and found that the grain tension of 6061 aluminum alloy as the forward side of the joining zone presents a linear distribution with coarse grains, while the grain tension of 7075 aluminum alloy as the retracting side presents a flat and massive arrangement. The hardness of the side near 6061 aluminum alloy is lower, followed by that near

[1] HUANGSHAN UNIVERSITY, SCHOOL OF MECHANICAL AND ELECTRICAL ENGINEERING, HUANGSHAN 245041, P.R. CHINA
[2] ANHUI SIMULATION DESIGN AND MODERN ENGINEERING RESEARCH CENTER, HUANGSHAN 245041, P.R. CHINA
[3] ANHUI PROVINCE TEA CHRYSANTHEMUM INTELLIGENT PROCESSING EQUIPMENT ENGINEERING RESEARCH CENTER, HUANGSHAN 245041, P.R. CHINA

* Corresponding author: sww@hsu.edu.cn

7075 aluminum alloy, and the hardness of the center of the joining zone is the highest. Peng et al. [6] studied the hardness distribution of the 5A06/6061 dissimilar aluminum alloy friction stir joining zone by nano-pressing, and the hardness distribution of the joining zone was asymmetrical. In addition, the hardness of the 5A06 aluminum alloy side was almost unchanged, and the hardness of the 6061 aluminum alloy heat-affected zone showed a sharp decline. Wang et al. [7] analyzed the microstructure and properties of the friction stir joining zone of 2195-T8/2219-T87 dissimilar aluminum alloy and obtained that the joining zone showed a basin shape, the grain size of the heat-affected zone of the joining zone dramatically changed, and the hardness of the joining zone was the highest on the side of 2195-T8 aluminum alloy and the lowest. Fang et al. [8] studied the friction stir lap of 2A12-T4/7A09-T6 aluminum alloy and obtained that the interface curve between the lap plates was curved when the lap was from 2A12-T4 (1.2 mm) to 7A09-T6 (4 mm). Moreover, when the lap is from 7A09-T6 (4 mm) to 2A12-T4 (1.2 mm), the surface curve between the lap plate bending is small in a horizontal state. Huang et al. [9] studied the friction stir lap joining of 7N01 aluminum alloy and found boundaries appeared in the lap zone, and the hardness of the joining zone slightly changed, however, the hardness of the center of the joining zone was low but reached 70% of the hardness of the base material. Liao et al. [10] conducted a study on the friction stir joining zone of 5052 aluminum alloy and found that the grain in the joining zone was refined, grain bending and growing appeared in the heat-affected zone, and the hardness distribution in the joining zone showed a "W" shape, and the heat-affected zone has the lowest hardness. Chen et al. [11] conducted friction stir lap bonding on 5083 aluminum alloy and analyzed the microstructure and hardness of the joining zone. The grain refinement and grain size of the joining zone were significantly smaller than that of the base material, while the hardness value of the joining zone was higher than that of the base material. Furthermore, Zhao et al. [12] analyzed the friction stir lap region of 6063 aluminum alloy and found that dynamic recrystallization occurred in the grains in the joining region, and the grains were refined into equiaxed grains. Meanwhile, Tian et al. [13] used the friction stir lap joining method to lap 6 mm thick 2219 and 2 mm thick 5A06 dissimilar aluminum alloys. The grains in the side joining zone near 5A06 aluminum alloy were primarily composed of fine equiaxed crystals, whereas the grains in the heat-affected zone near 2219 aluminum alloy were coarse, and the hardness of the joining zone was higher than that of the two aluminum alloy base metals. The hardness of the heat-affected zone near 5A06 aluminum alloy is lower than that of the base metal, whereas the hardness of the heat-affected zone near 2219 aluminum alloy is higher than that of the base metal. Song et al. [14] performed friction stir lap joining on 2024/7075 dissimilar aluminum alloy with a thickness of 5 mm and they found hook defects in the lap area.

Results found that there are almost no studies on the preparation of multi-layer aluminum alloy by friction stir and the change of performance gradient. Most researchers focus on the research of friction stirs joining of dissimilar aluminum alloy and friction stir lap of aluminum alloy. However, this research can provide basic theoretical and practical technical support for the in-depth study of the friction stir preparation technology of multilayer aluminum alloy with gradient distribution properties. This study mainly applies to the manufacture of aluminum alloy interface for valve body and pipe connection. This study carried out three kinds of dissimilar aluminum alloy friction stir preparation based on the actual engineering needs to obtain a new aluminum alloy plate with gradient performance distribution, meet the needs of different applications, analyze the microstructure and hardness distribution law of the prepared plate, and provide technical support for practical engineering applications.

2. Materials and experiments

The experimental materials were rolled 5052-H32 aluminum alloy (3 mm thick), 6061-T6 aluminum alloy (2 mm thick), and 7075-T6 aluminum alloy (3 mm thick). The chemical compositions of the three aluminum alloys are shown in TABLE 1.

For the preparation of the aluminum alloy performance gradient plate, 5052-H32 aluminum alloy, 6061-T6 aluminum alloy, and 7075-T6 aluminum alloy sizes are 200 mm × 200 mm × 3 mm, 200 mm × 200 mm × 2 mm, and 200 mm × 200 mm × 3 mm, respectively. When preparing the graded aluminum alloy sheet, the stacking sequence of the three aluminum alloys is as follows: 5052-H32 aluminum alloy, 6061-T6 aluminum alloy, and 7075-T6 aluminum alloy from top to bottom. This is because 6061 aluminum alloy has good plasticizing performance, which is easy to be stirred and fused with 5051 aluminum alloy and 7075 aluminum alloy in the process of friction stir joining, and can prepare a gradient material with good performance.

The aluminum alloy performance gradient plate was prepared by FSW-LM-A10 friction to stir joining equipment produced by Beijing Syfost Technology Co., Ltd. The diameter of the prepared stirring tool and the length of the pin is 18 and 6.5 mm, respectively. The prepared equipment and stirring tool and schematic diagram of friction stir preparation process are shown in Fig. 1.

TABLE 1

Chemical Composition of Aluminum alloy (wt%)

	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Al
5052-H32	0.10	0.25	0.40	0.10	2.2-2.8	0.10	0.15-0.35	/	Balance
6061-T6	0.15-0.40	0.40-0.80	≤0.7	≤0.15	0.80-0.12	0.25-0.50	0.40-0.35	≤0.15	Balance
7075-T6	1.20-2.00	0.40	0.50	0.30-1.50	2.10-2.90	5.10-6.10	0.40	0.06	Balance

(a) Friction stir joining equipment (b) Stirring tool (c) Preparation process

Fig. 1. Photos of equipment and stirring tool for preparing aluminum alloy gradient sheet by friction stir and schematic diagram of friction stir preparation process

TABLE 2

Process parameters of aluminum alloy gradient sheet prepared by friction stir

Sample number	Rotation speed of the stirring tool ω (rpm)	Feed speed of the stirring tool v (mm/min)	Downward pressure of the shoulder Δ (mm)
1	200	250	0.1
2	300		
3	400		
4	500		
5	600		
6	700		
7	800		

The technological parameters for the preparation of aluminum alloy performance gradient plate are as follows: the rotation speed of the stirring tool is 200-800 rpm, the feed speed of the stirring tool is fixed at 250 mm/min, and the downward pressure of the shoulder is 0.1mm. See the selection of specific experimental process parameters in TABLE 2.

When the aluminum alloy performance gradient plate is prepared by friction stir, the surface of each brand of aluminum alloy plate is first cleaned and dried with water, and then the surface is cleaned and dried with anhydrous ethanol. In addition, if there is any polluted surface, the surface is cleaned and dried with acetone and rinsed with water, and then it is cleaned and dried again with anhydrous ethanol. After cleaning the aluminum alloy plates of each brand, they are stacked and placed on the workbench for fixing following the above protocols. The stirring tool moves outward from the center of the plate in a circular track in turn, and the offset of each turn of the stirring tool is 5 mm.

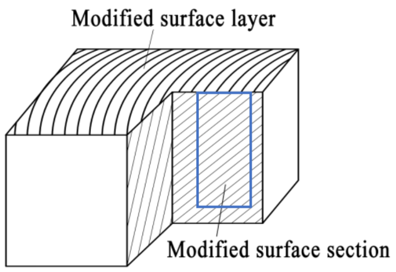
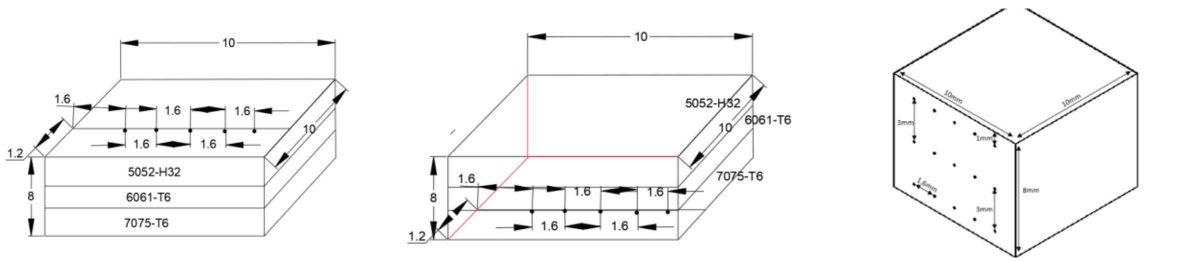


Fig. 2. Schematic diagram of metallographic sample sampling

Subsequently, the microstructure and hardness of the prepared gradient aluminum alloy sheet were analyzed. The microstructure was observed by the MDS400 inverted metallographic microscope produced by Beijing Sebiao Science and Technology Co., Ltd. After the microstructure observation sample was cut from Fig. 2, it was polished and polished, and corroded with 20% aqua royalty +5%HF + 75%H_2O. The hardness tester HVST-1000Z-shaped Vickers Hardness tester produced by Laizhou Weiyi Test Instrument Manufacturing Co., Ltd. was selected for the hardness test. The location of the hardness test was shown in Fig. 3. During the hardness test, three tests were conducted on each point, and the average value was the hardness value of the point. During the hardness test, the pressure was held for 10 s and a pressure of 500 g was applied.



(a) Upper surface hardness test point (b) Lower surface hardness test point (c) Cross section hardness test point

Fig. 3. Schematic diagram of hardness test points

3. Analysis of experimental results

3.1. Macroscopic morphology analysis

Fig. 4 shows the macro morphology of the aluminum alloy gradient sheet prepared by friction stir under the parameters. As shown in the figure, when the rotation speed of the stirring tool reaches 800 rpm, the surface forming of the aluminum alloy gradient sheet is poor, with more flying edges, and the flatness of the whole sheet plane is the worst, as shown in Fig. 4(g). The second worst is the aluminum alloy performance gradient sheet obtained when the stirring tool rotation speed is 700 rpm, as shown in Fig. 4(f). Although the surface flying edge is less, various burrs remain and the surface smoothness is also lacking. Although there are few burrs in Figs. 4(a) and (b), there are more concentrated flying edges in the middle and deep arcs between each circle of modification. There are a few burrs in Fig. 4(e) and the overall effect is slightly better than in Figs. 4(a) and (b). Meanwhile, Figs. 4(c) and (d) have good surface morphology with few burrs. In particular, both the middle position and the whole prepared surface in Fig. 4(d) are smooth and have the best effect. Based on the aluminum alloy gradient sheet prepared by each parameter in Fig. 4, a reasonable selection of the preparation process parameters can obtain a better surface topography.

3.2. Microstructure analysis

Fig. 5 shows the metallographic microstructure of the aluminum alloy gradient sheet prepared by friction stir under the parameters. As shown in the figure, when the feed speed and downward pressure of the stirring tool are fixed, the micro-

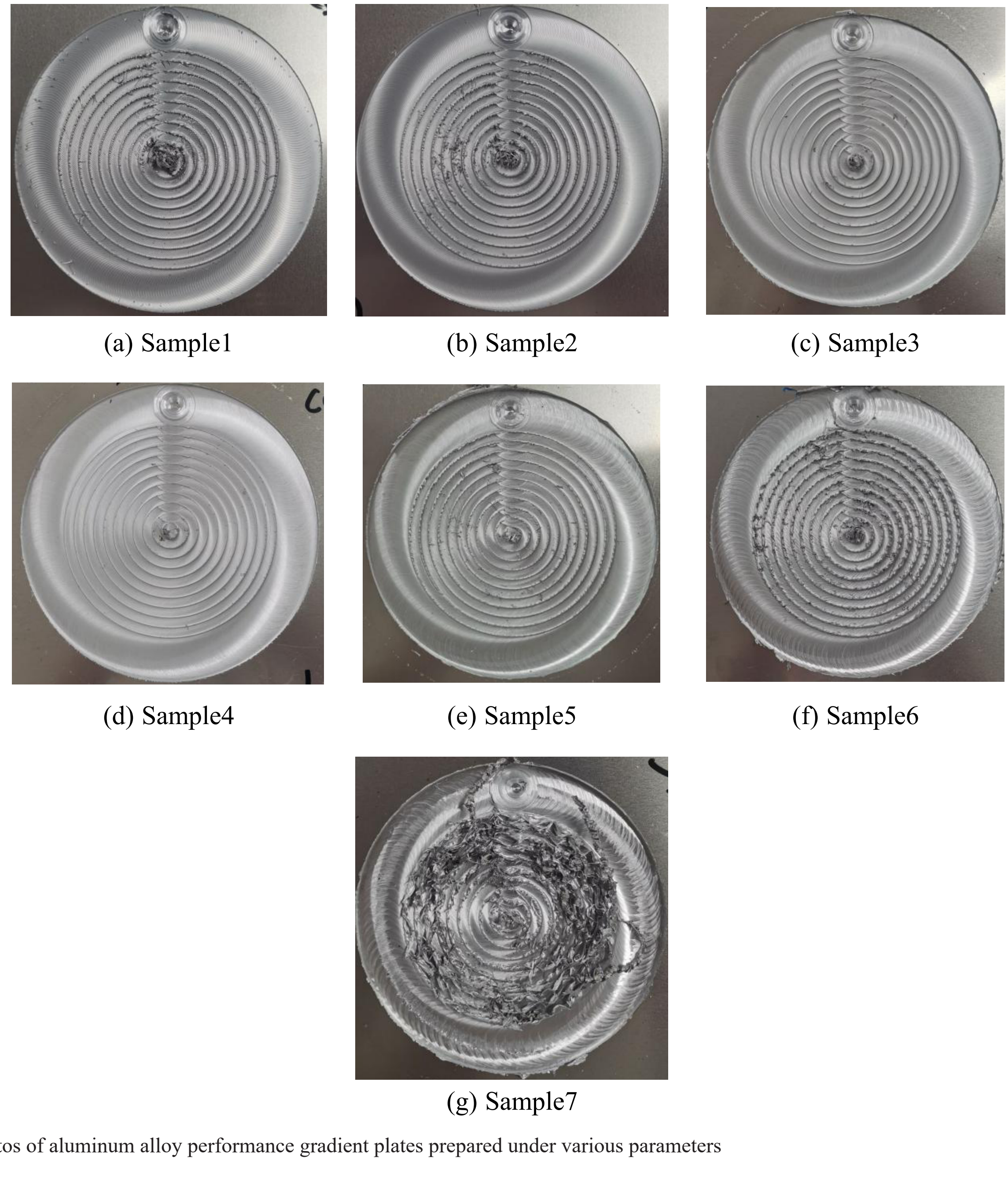
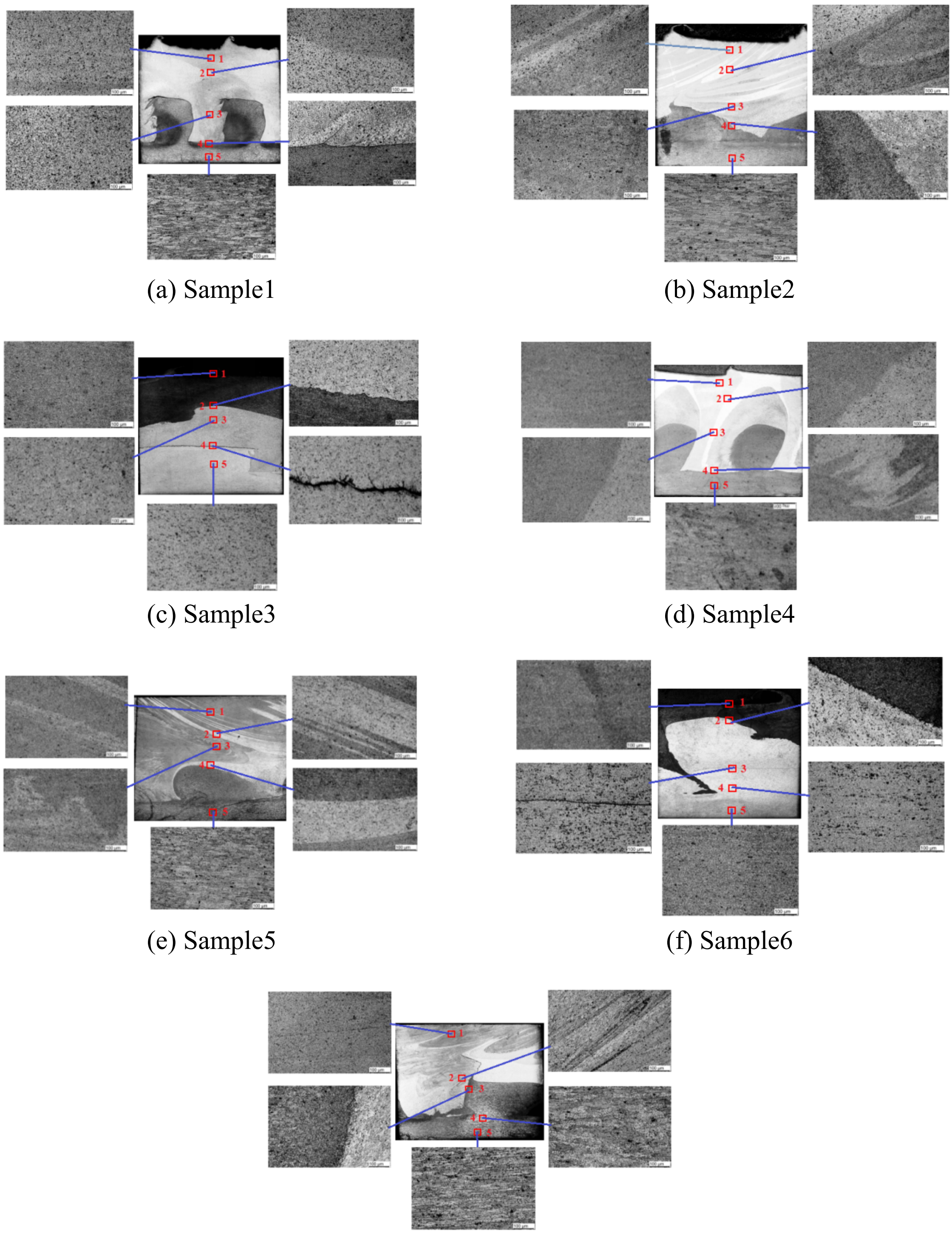


Fig. 4. Photos of aluminum alloy performance gradient plates prepared under various parameters



(a) Sample1 (b) Sample2

(c) Sample3 (d) Sample4

(e) Sample5 (f) Sample6

(g) Sample7

Fig. 5. Metallographic microstructure of aluminum alloy gradient sheet prepared under various parameters

morphologies of the section of aluminum alloy with performance gradient obtained by selecting different rotation speeds of the stirring tool are completely different. However, when the rotational speed of the stirring tool is not high, the obtained sectional molding metal flow remains to change regularly, that is, each layer of aluminum alloy plate still changes regularly with the forward direction of the stirring tool, as shown in Fig. 5(a). As the rotational speed of the stirring tool increases, the flow of the molded metal in the cross section is larger, and the plasticization and fusion of each layer of aluminum alloy sheet are serious, but the excessive area is still evident, as shown in Figs. 5(b) and (c). Meanwhile, as the rotational speed of the stirring tool continues to increase, the cross-section morphology is more clearly stratified. As shown in Fig. 5(d), the aluminum alloys in each layer are fused and have distinct layers, thereby forming an extremely effective gradient structure. Furthermore, with the increase of the rotation speed of the stirring tool, the fusion degree between each layer of aluminum alloy sheet was further improved, and the upper layer sheet effectively entered the lower layer sheet, thereby forming a characteristic performance-modified sheet, as shown in Figs. 5(e), (f), and (g).

Fig. 6 shows the metallographic structure of the three base metals. By comparing Figs. 5 and 6, the grain of the aluminum alloy performance gradient sheet prepared by friction stir is well refined. Relative to the metallographic structure of each base metal, the grain of each sample position in Fig. 5 presents an equiaxed crystal state, whereas the grain of the sheet in Fig. 6 is in strip shape, which fully indicates that during the process of friction stir preparation of aluminum alloy performance gradient sheet. High friction thermoplasticized aluminum alloy layers were generated in the region passed by the stirring tool, and heat storage was formed under the force of the stirring tool shoulder, the base metal in the pin area, and the bench bottom plate. Then, recrystallization of the grains in the stirring region was obtained, and uniform equiaxed crystals were finally formed, which was similar to the grain shape described in the literature [15-18].

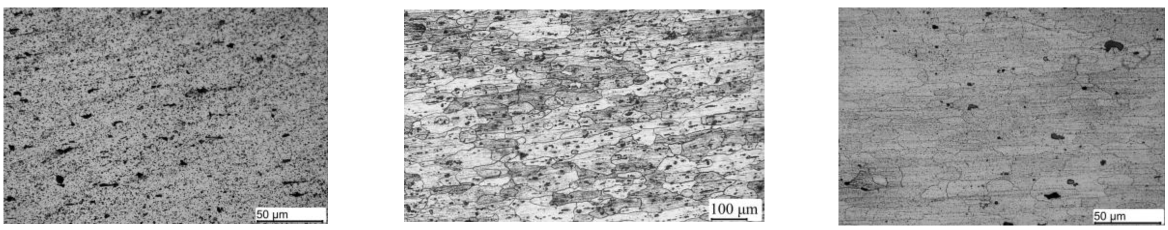
3.3. Hardness analysis

Fig. 7 shows the hardness curves of the upper and lower surfaces of the aluminum alloy performance gradient sheet samples prepared under different parameters. TABLE 3 lists the average values of the upper and lower surfaces of the aluminum alloy performance gradient sheet samples prepared under different parameters and the surface hardness values of the base metal 5051-H32 and 7075T6. As shown, the upper and lower hardness values of the aluminum alloy gradient sheet prepared under each parameter are lower than those of the corresponding base metal. This is because the 5052 aluminum alloy sheet on the upper surface and the 7075 aluminum alloy sheet on the lower surface generate a large amount of friction heat under the agitation of the stirring tool, which promotes the plasticization of the stirred metal. However, in the flow of the plasticized metal, there is no bottom plasticized metal entering the surface of 5052 aluminum alloy and the bottom of 7075 aluminum alloy, which corresponds to the previous metallographic photos,

TABLE 3

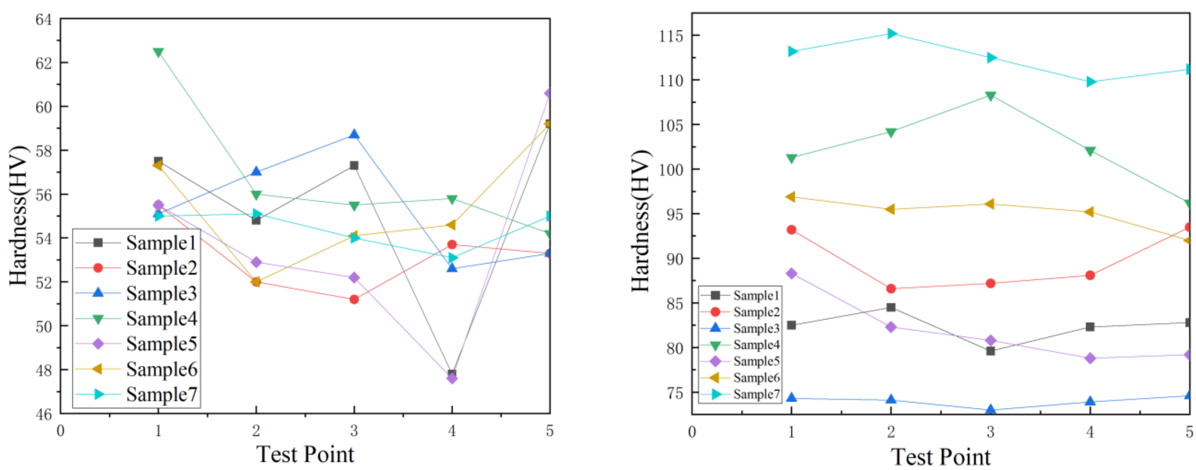
Average hardness values (HV) of the upper and lower surfaces of each sample

Sample number	Average hardness of upper surface	5052 aluminum alloy hardness value	Average hardness of lower surface	7075 aluminum alloy hardness value
1	55.319	63.37	82.338	159.34
2	53.156		89.716	
3	55.330		73.998	
4	56.812		102.416	
5	53.744		81.858	
6	55.459		95.132	
7	54.441		112.392	



(a) 5052-H32 (b) 6061-T6 (c) 7075-T6

Fig. 6. Metallographic structure of base metals



(a) Upper surface (b) Lower surface

Fig. 7. Upper and lower hardness values of aluminum alloy gradient plate prepared by friction stir

thereby fully indicating that in the process of preparing aluminum alloy performance gradient plate. The stirred metal in the middle of the stirring tool did not reach the surface of 5052 aluminum alloy and the bottom of 7075 aluminum alloy. And promote 5052 and 7075 aluminum alloy surface hardness decline is the reason is under the action of friction heat, 5052 aluminum alloy and 7075 aluminum alloy surface heated grain recrystallization, the original rolled plate grain into a more uniform equiaxed crystal. However, given the upper stirring tool shoulder and the lower table two-way action, 5052 and 7075 aluminum alloy surface heats cannot dissipate, and finally caused 5052 and 7075 aluminum alloy surface refinement equiaxed grain growth, thereby reducing the surface hardness.

Fig. 8 shows the curve diagram of the side hardness values of the aluminum alloy performance gradient sheet samples prepared under various parameters. TABLE 4 lists the average side values of the aluminum alloy performance gradient sheet samples prepared under various parameters and the side hardness values of the base metal 5051-H32 and 7075T6. As shown, the side hardness of the 5052 aluminum alloy sheet on the upper surface is improved, which indicates that the 6061 aluminum alloy in the middle layer effectively enters the 5052 aluminum alloy in the stirring process of the stirring tool, thereby greatly increasing the side hardness of the 5052 aluminum alloy, whereas the hardness of the middle layer of the aluminum alloy decreases (The hardness of 6061 aluminum alloy is 103.3HV). It is because the upper 5052 aluminum alloy enters into the 6061 aluminum alloy after the stirring tool action, thereby reducing the hardness of the 6061 aluminum alloy side. However, sample 7 instead increases the hardness of the side of the 6061 aluminum alloy, because during the stirring process, this phenomenon occurs when part of the 7075 aluminum alloy is fused into the 6061 aluminum alloy. This can be illustrated by the metallographic structure photograph in Fig. 5(g).

The lower side hardness of the 7075 aluminum alloy is because of the mixing of the 6061 aluminum alloy into the 7075 aluminum alloy layer, which reduces the hardness of the 7075 aluminum alloy side. The above hardness changes are consistent with those described in the metallographic photographs in Fig. 5.

It can be seen from Tables 3 and 4 that when the feed speed of the stirring tool and its downward pressure is fixed at 250 mm/min and 0.1 mm, respectively, the optimal rotation speed of the stirring tool for the preparation of aluminum alloy gradient sheet is 500 rpm. Not only do the upper and lower surfaces of aluminum alloy gradient plates prepared under these parameters have little changes in hardness values, but also the hardness values on the side of the plates have approximately equal proportional changes, thereby completely realizing the gradient change of hardness values on the side.

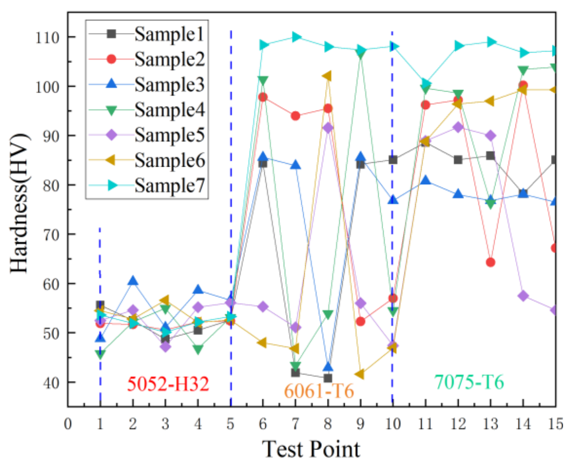


Fig. 8. Hardness value of cross-section of aluminum alloy gradient plate prepared by friction stir

3.4. Discussion and Analysis

In the above discussion, the preparation of samples 4 and 7 is better with a small height, but the hardness of sample 7 does not show a gradient, and the hardness of the middle layer is high. However, the hardness of the upper and lower sides is low and the gradient change effect is not achieved. Therefore, the preparation effect of sample 4 is the best compared with the above analysis. The photo analysis of the prepared metallographic structure of sample 4 is shown in Fig. 9, and the change of metallographic structure is analyzed at different positions in Fig. 9, as shown in Fig. 10.

As shown in Fig. 9, repeated stirring processes occur for each rotation and feed of the stirring tool. A position with periodic changes is selected in Fig. 9 for analysis. Thus, 12 special points represented in Fig. 9 are selected for metallographic structure

TABLE 4

Average hardness values (HV) from the upper to lower surfaces of each sample

Sample number	Average hardness of upper plate section	Average hardness of 5052-H32 section	Average hardness of intermediate plate section	Average hardness of 6061-T6 section	Average hardness of lower plate section	Average hardness of 7075-T6 section
1	51.98	49.92	67.28	100.10	84.58	149.58
2	51.76		79.32		85.02	
3	55.10		74.96		78.04	
4	50.58		71.98		96.36	
5	53.12		60.28		76.54	
6	53.72		57.08		96.16	
7	52.22		108.36		106.36	

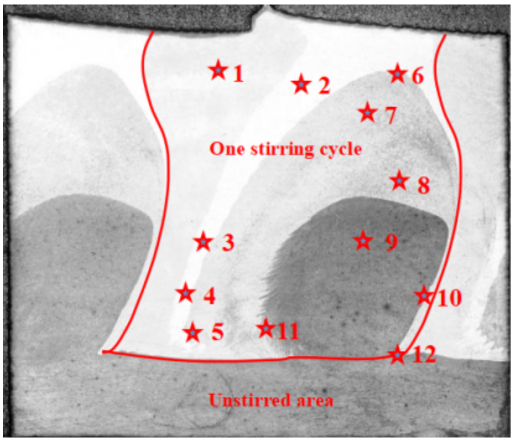
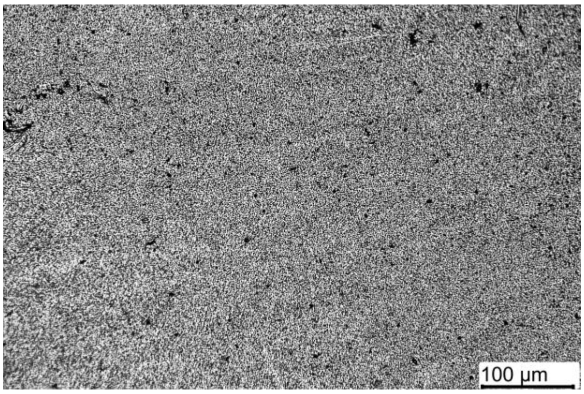
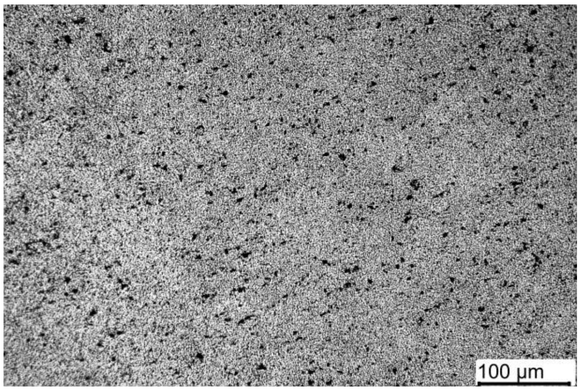


Fig. 9. The total microstructure of sample 4

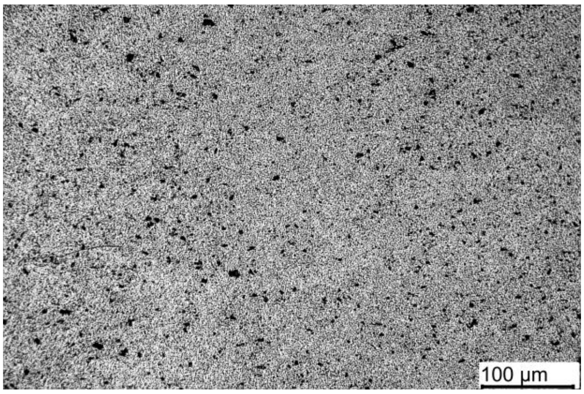
analysis to better analyze the change of metallographic structure in this figure, as shown in Fig. 10. From Fig. 9, there are approximately three-color changing regions with different depths, namely white, light gray, and dark gray regions. In addition, the changes in these three colors show a progressive process, thereby indicating that the preparation process is also consistent with the previous hardness analysis, that is, under the rotation of the stirring tool, the 6061 aluminum alloy enters into the 5052 aluminum alloy above. The 5052 aluminum alloy will also move down the thread of the stirring tool to 6061 and 7075 aluminum alloys; the 6061 aluminum alloy will also move down to 7075 aluminum alloy, and the 7075 aluminum alloy will rise to 6061 aluminum alloy. However, from the point of view of the metallographic structure analysis, the 7075 aluminum alloy is



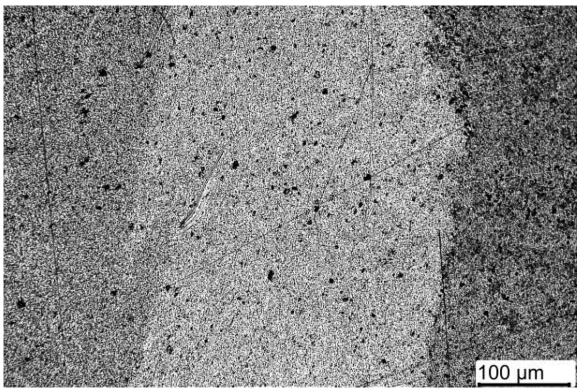
(a) Position1



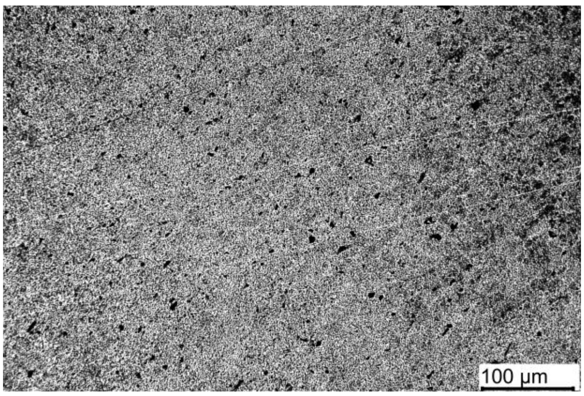
(b) Position2



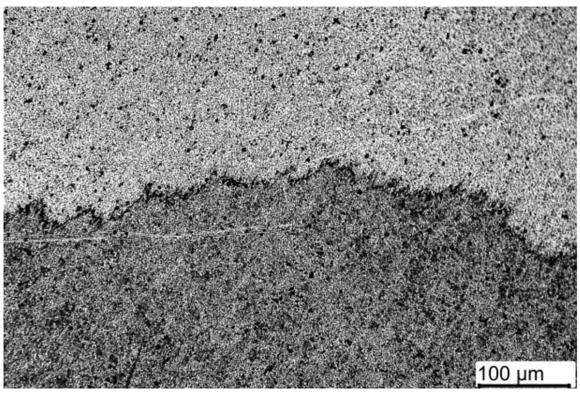
(c) Position3



(d) Position4



(e) Position5



(f) Position6

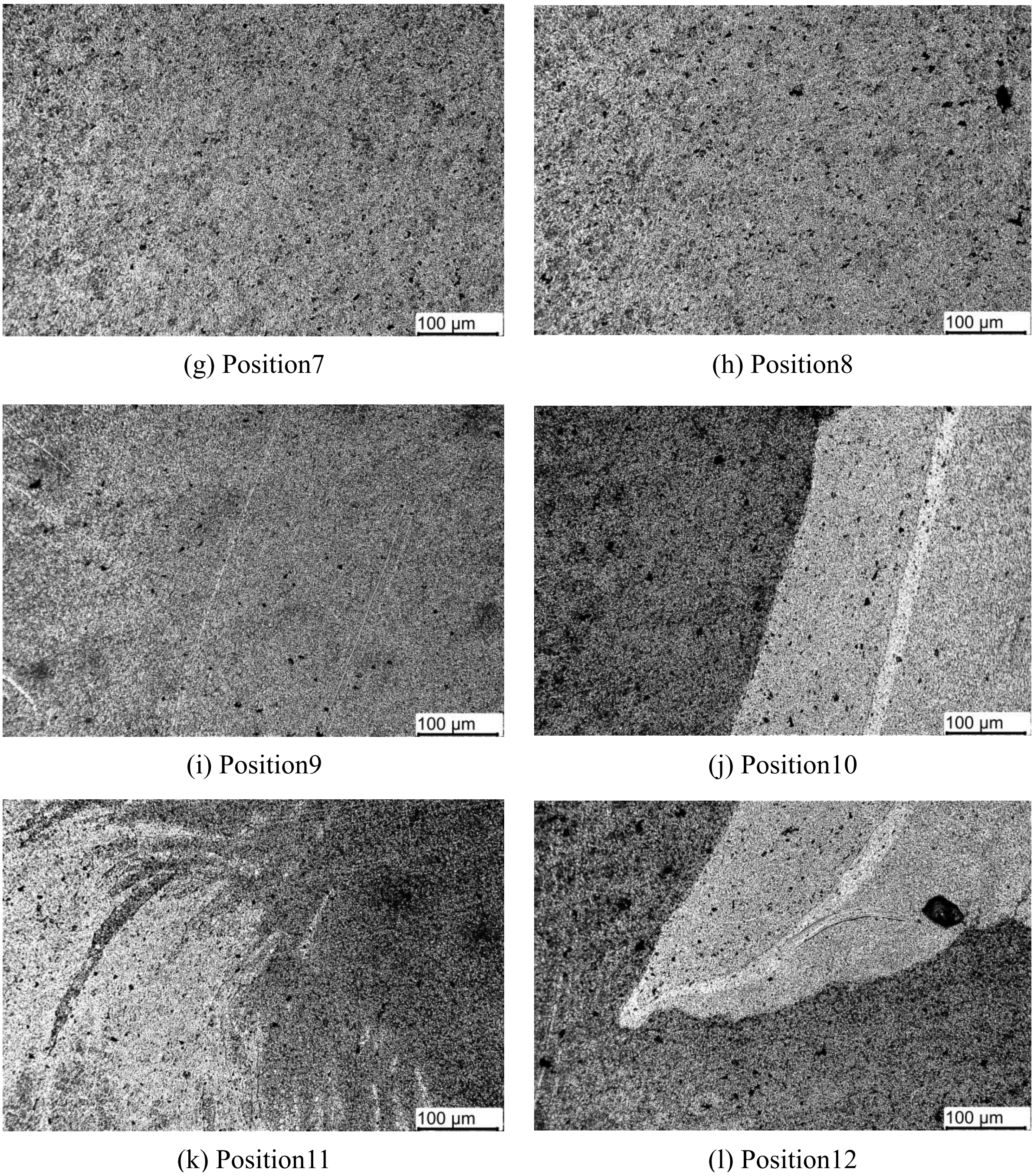


Fig. 10. Photos of metallographic structure at different positions in Fig. 9

difficult to fuse into the upper body of the 5052 aluminum alloy, which is also related to the 7075 aluminum alloy itself, its high hardness, and poor plasticity. The rotation along the stirring tool thread is also difficult to rise to the upper surface, hence, the side performance of 5052 aluminum alloy is improved, and the side performance of 6061 and 7075 aluminum alloys is reduced.

As shown in Fig. 10(a), 6061 aluminum alloy enters into the 5052 aluminum alloy in position 1; position 2 should be the original part of the 5052 aluminum alloy, as shown in Fig. 10(b); and positions 3 and 4 indicate that 5052 aluminum alloy enters into the stirred sandwich before and after 6061 aluminum alloy, as shown in Figs. 10(c) and (d). Moreover, traces of stirring of 5052 aluminum alloy into 7072 aluminum alloy can be seen In Fig. 10(e); traces of stirring of 5052 aluminum alloy into 6061 aluminum alloy can be seen in Figs. 10(f), (g), and (h), corresponding to positions 6, 7, and 8 in Fig. 9, respectively. In Fig. 10(i), 7075 aluminum alloy enters into 6061 aluminum alloy; position 11 in Fig. 10(k) can see the fusion of three aluminum alloy metals, and the three are permeated with each other. Positions 10 and 12 in Fig. 10(j) and (l) can also show the fusion among the three. The plasticizing flow process of the dissimilar aluminum alloy in Figs. 9 and 10 is described in the document [19], which also has distinct hierarchical feeling and interface transition zone. However, the metallographic morphology of the dissimilar aluminum alloy is consistent with that of Fig. 5(g).

4. Conclusions

(1) When the feed speed of the stirring tool is fixed at 250 mm/min and the downward pressure of the shoulder is 0.1 mm, the optimal rotational speed of the stirring tool for the preparation of the aluminum alloy gradient sheet is 500 rpm.

(2) The cross-section microstructure of aluminum-alloy gradient plates prepared with different stirring tool rotation rates is completely different, but the grains of the prepared plates are refined.

(3) The hardness of the upper surface of the graded aluminum alloy plates prepared by different stirring tool rotation speeds is lower than that of the 5052 aluminum alloy surface. The hardness of the lower surface of the graded aluminum alloy plates prepared by different stirring tool rotation speeds is lower than that of the 7075 aluminum alloy surface. The hardness value of the upper surface of each sample cross-section is higher than that of the 5052 aluminum alloy cross-section, but the hardness value of the middle surface of each sample cross-section is lower than that of the 6061 aluminum alloy cross-section. Similarly, the hardness value of the lower surface of each sample cross-section is lower than that of the 7075 aluminum alloy cross-section.

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