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Effect of Post-weld Heat Treatment on Microstructure and Mechanical Properties of Friction Stir Welded SSM7075 Aluminium Alloy

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Abstract: 7XXX series aluminium alloys generally present low weldability by fusion welding methods because of the sensitivity to weld solidification cracking, vaporization of strengthening alloys and other defects in the fusion zone. Friction stir welding (FSW) can be deployed successfully with aluminium alloys. We presented the effect of post-weld heat treatment (PWHT) on the microstructure and mechanical properties of SSM7075 joints. Semi solid plates were butt-welded by FSW at a rotation speed of 1110 r/min, welding speeds of 70 and 110 mm/min. Solution treatment, artificial aging, and T6 (solution treatment and artificial aging combined) were applied to the welded joints, each with three samples. It was found that the T6 joints at the speed of 70 mm/min yielded the highest tensile strength of 459.23 MPa. This condition best enhanced the mechanical properties of FSW SSM7075 aluminium alloy joints.

Key words: friction stir welding (FSW); SSM7075 aluminium alloy; post-weld heat treatment (PWHT)

1 Introduction

Friction stir welding (FSW) was developed at The Welding Institute (TWI), UK in 1991[1]. It is a solid state joining process, in which a cylindrical shouldered tool with a profiled pin is inserted into the joint line between two pieces of material. The basic principle of the FSW process is illustrated in Fig.1. The microstructure of a friction stir weld can be classified into four different zones, as shown in Fig.2. The nugget zone exhibits a recrystallized fine grain structure, with grain sizes increasing from the weld region to the base metal.

In recent years, Semi-Solid Metal (SSM) has become popular for various applications and SSM7075 is one of them. This alloy has wide application in aircraft industry. Its mechanical properties can be improved by heat treatment process and its high strength was obtained by the fine precipitation of $MgZn_2$ and Al_2CuMg phase formed at aging temperatures below 200 ℃[2].

This alloy is difficult to weld using conventional fusion techniques. This is due to the extreme sensitivity to weld solidification cracking and other weld defects[3,4]. Furthermore, vaporization of Zn and Mg by very high vapor pressures from fusion welding reduces the effect of hardening and, therefore, the lowering of tensile strength[5]. However, in FSW the workpiece does not reach the melting point. These defects did not occur on the weld. A general investigation employed in this study is the post-weld heat treatment (PWHT) process. Mahoney *et al*[6] reported that the loss of the ultimate tensile strength (UTS) within the weld nugget can be linked to changes in the microstructure. A reduction in fine precipitate and dislocation within the nugget zone contributed to the lower strength in FSW of AA7075-T651. Elangovan K *et al*[7] studied the influences of PWHT on AA6061. They had shown that finer strengthening precipitates, smaller grain sizes, lack of precipitate free zones (PFZs) and higher dislocation density are the reasons for superior tensile properties in artificial aging. In a similar work by CG Rhodes *et al*[8] the post weld aging (121 ℃/24 h) on FSW samples of AA7075-T651 increased the hardening of the precipitates and the development of PFZs at grain boundaries. Feng JC *et al*[9] studied AA2219-O and reported that PWHT results in the coarsening of

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the grains in the nugget zone, with increases in the coarsening degree and tensile strength with increasing solution temperature. Azimzadegan T *et al*[10] revealed that there is an optimum rotational speed which gives the highest tensile strength and elongation in which the thermal cycles and aging kinetics are well balanced to provide the appropriate mechanical properties.

In this work SSM7075-T6 specimens were post-weld heat treated. Three samples were solution treated, three were subjected to artificial aging, and another three were solution treated followed by artificial aging (T6) after being joined by FSW. The effects of post-weld heat treatment have been investigated for its microstructure, tensile strength and hardness.

2 Experimental

The matrix material used in this investigation was a 4 mm thick plate semi solid 7075-T6 aluminium alloy. It was prepared into the required dimensions of 100 mm× 50 mm by hacksaw cutting and milling. Square butt joint configuration, as shown in Fig.3 was prepared to fabricate FSW joints. Its chemical composition is presented in Table 1. The cylindrical pin was used for friction stir welding as shown in Fig.4. The diameter of the shoulder was 20 mm. The diameter and length of the pin were 5 and 3.6 mm, respectively. The welding tool was rotated in the clockwise direction, and the specimens, which were tightly attached to the backing plate, were traveled. In this work, the welding speeds were 70 and 110 mm/min. The constant tool rotation speed was 1110 r/min and the tilt angle was 3˚.

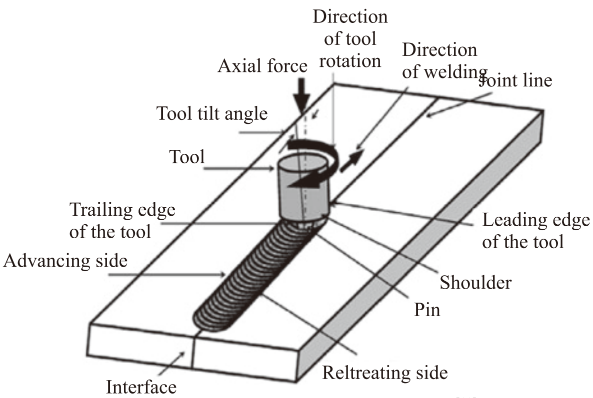
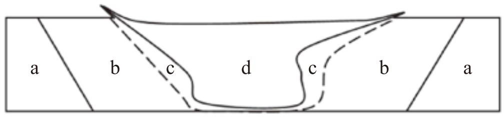


Fig.1 Illustration of the FSW process[11]

The welded joints were grouped into four different types: as-welded joint (AW), solution treated joint (ST), artificial aged joint (AG), and T6 joint (T6). Solution treatment of ST joint was carried out at 480 ℃ for 4 h. After solution treatment, the samples were quenched in water at 25 ℃. Artificial aging of AG joint was carried out at 120 ℃ for 36 h. For T6 joint, both of the heat treatment procedures (ST 480 ℃/4 h and AG 120 ℃/36 h) were applied sequentially to obtain the combined effect of the heat treatments.



(a) Base Metal (BM)
(b) Heat Affected Zone (HAZ)
(c) Thermo Mechanical Affected Zone (TMAZ)
(d) Nugget Zone (NZ)

Fig. 2 Different zones of FSW joint

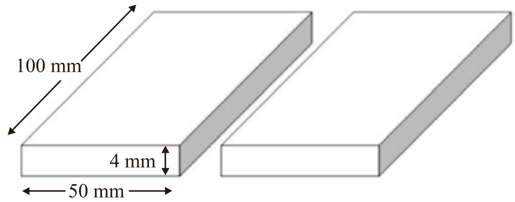


Fig.3 Dimensions of the square butt joint

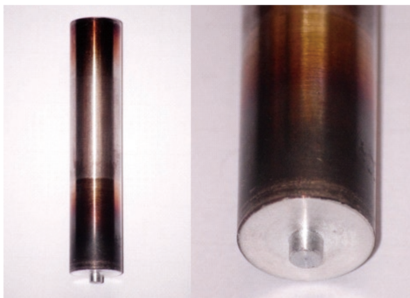


Fig. 4 Tool pin profile

Table 1 Chemical composition of SSM7075/wt%

Zn	Mg	Cu	Fe	Cr	Others	Al
6.08	2.5	1.93	0.46	0.19	0.45	Balance

After post weld heat treatment, the welded parts were sliced using a hacksaw and polished by a milling machine. Tensile properties of the welded parts were determined from transverse tensile specimens prepared according to ASTM E8-04 specification. The tensile test was carried out on an electronic 10 kN universal testing machine. The tests were performed at room temperature, using a Hounsfield, UK; model: H25K-S. Results were compared with the base material.

Microstructural analysis was carried out using an optical microscope (Olympus, Japan; model: BH_2-UMA). The prepared welded parts were polished and finally etched with Keller's reagent: 190 mL H_2O, 5 mL HNO_3, 3 mL HCl, and 2 mL HF. The specimens were etched for 5 s. in order to study the grain structure of the nugget zone and other areas by optical microscopy. Vickers hardness (Highwood, Japan; model: HWDM-3) was measured on the cross-section at 2.5 mm from the specimen surface and at 0.5 mm intervals, all with 100 gf load for 10 s.

3 Results and discussion

3.1 Macro and microstructure

Fig.5 reveals the cross-section of a typical FSW joint. On the welded zone, there are the retreating side and the advancing side. For the retreating side the range of microstructural changes is narrow, similar to a compressed microstructure, whereby travelling of the tool pin and the workpiece is in the opposite direction. As a result, a large portion of the flash occurred on this side. For the advancing side similar microstructure was elongated over a wide area, whereby travelling of the tool pin and the workpiece is in the same direction.

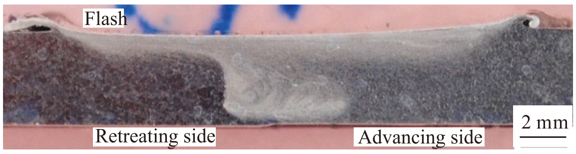


Fig.5 Macro cross-section view of FSW joints

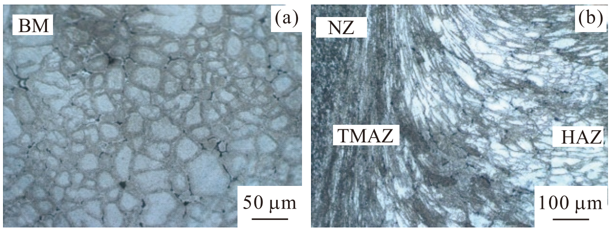


Fig.6 Four different zones associated with FSW: Globular grains in the BM, Deformed grains in the TMAZ, Fine recrystallized grains in the NZ, and Non-deformed grains in the HAZ

The investigated material was an alloy of aluminium and zinc. It had undergone a T6 heat treatment composed of a solution treatment, a quench in water and an artificial aging. It follows that $MgZn_2$ precipitation occurs. The microstructure of the base metal consists of eutectic precipitates $MgZn_2$ embedded in α-aluminium matrix[12]. Fig.6(a) depicts a globular grain structure in the order of 30 to 70 μm in diameter present in the parent SSM7075-T6 plate. Fig. 6b shows the grain size, increasing from the weld region to the base metal. The region adjacent to the nugget zone, TMAZ, is characterized by a highly deformed structure at high temperature without recrystallization. In the HAZ, there are no plastic deformations occurring in this area.

Fig.7 shows the optical microstructure in the nugget zone at welding speeds of 70 and 110 mm/min under different PWHT conditions. The recrystallized grains exhibit low dislocation density. However, certain investigators[7,13,14] reported that the small recrystallized grains of the nugget zone contained high density sub-boundaries, subgrains and dislocations. The higher temperature and severe plastic deformation resulted in grains smaller than that of the base metal. Figs.7(a)-7(d) reveal a fine equiaxial grain structure in the order of 5 to 20 μm, which is smaller than that occurred under ST and T6 conditions. Figs.7(e)-7(h) show the coarse grains after the solution treatment, with a grain structure in the order of 10 to 50 μm diameter presented in the nugget zone.

The AW joint at the lower welding speed of 70 mm/min exhibited a larger grain size compared to the joint at the higher welding speed of 110 mm/min. The recrystallized grain size can be reduced by decreasing the ratio of tool rotation speed/welding speed or increasing the welding speed at a constant tool rotation speed. For the AG joint, the precipitates within the grain were coarsened at the time of aging for 36 h when the ή/η phase formed, but the grain size itself was not coarsened under this aging condition.

For ST and T6 joints, the coarsening grains occurred under solution treatment condition at 480 ℃. In accordance, both Rhodes CG *et al*[8] and Feng JC *et al*[9] reported that grain growths occurred when the solution temperature was higher than the maximum temperature during FSW, which reached between 400 and 480°C in the 7075 Al. On the other hand, post weld aging at 120 ℃ for 36 h of the T6 joint after solution treatment incurred no effect to the grain size.

Micro-cracks, influenced by quenching after solution treatment, were observed in the stir zone of ST and T6 joints at higher welding speed of 110 mm/min, as depicted in Figs.7(f) and 7(h). On the other hand, the ST and the T6 at lower welding speed of 70 mm/min had not incurred micro-cracks. This is because recrystallized grain sizes resulted from the higher welding speed are smaller than that from the lower welding speed. The recrystallized fine grains exhibit higher strain, higher hardness and dislocation than the coarse grains, resulting in cracking after quenching from high temperature to room temperature.

3.2 Microhardness

Microhardness measurements (Vicker Hardness; HV) have been conducted for all joints in order

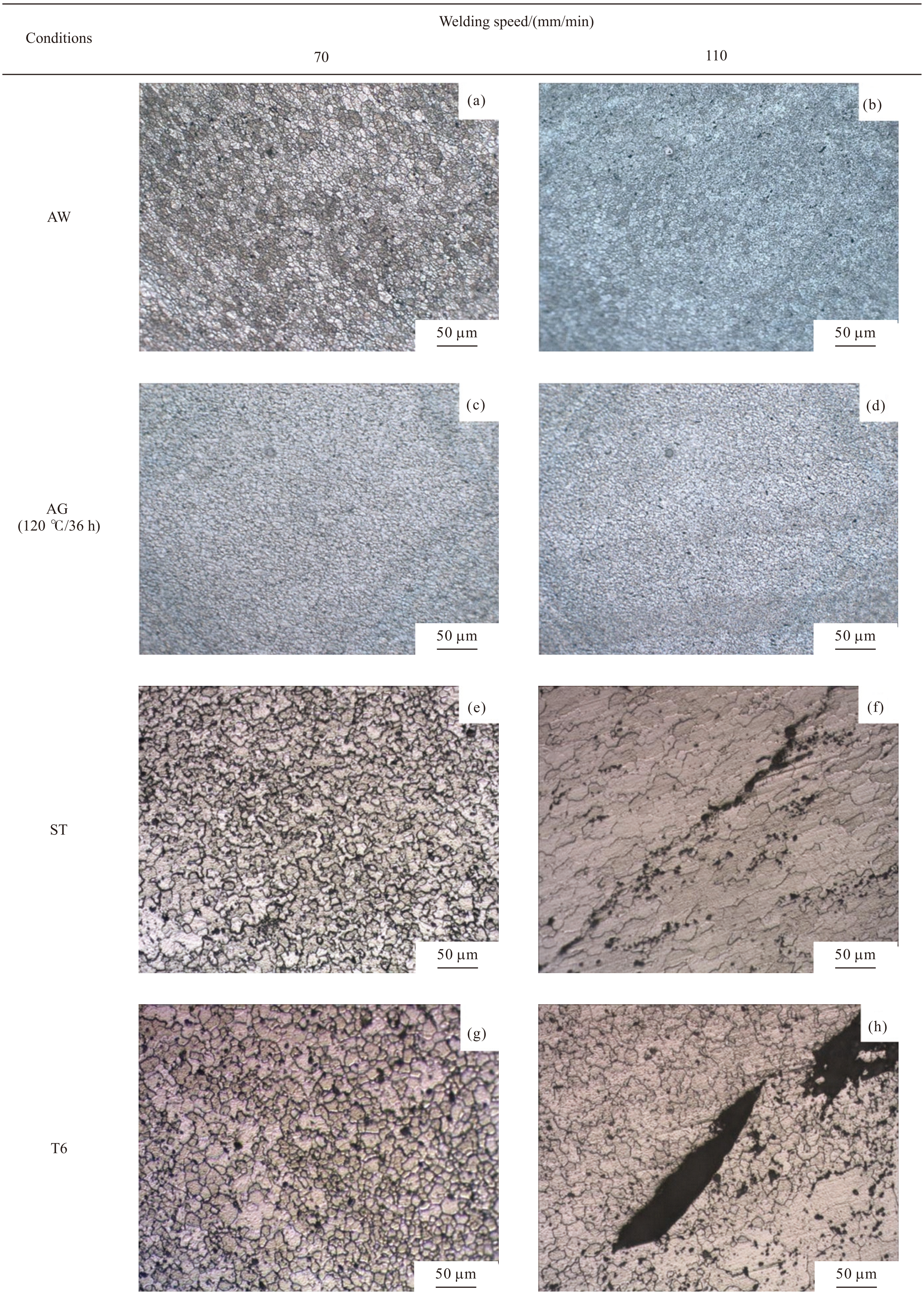


Fig.7 Microstructure of the nugget zone under different PWHT conditions: (a) AW; (b) 120 ℃/36 h; (c) ST; and (d) T6

to determine the hardness across the weld region. Hardness values in the weld middle section (2.5 mm from the top surface) for the four types of the prepared parent metal are detailed in Table 2. It is noted that the hardness of all welds increases after PWHT. For the base metal with hardness value of 102.40 HV the T6 joint at the welding speed of 110 mm/min, for example, has its hardness increased to 182.96 HV with the highest hardness of 197.30 HV in the NZ nugget zone. However, in the AW joint the hardness increases to only 109.47 HV in the NZ, which is a slight increase from that of the base material.

Of the three imposed conditions, ST, AG and T6, the microhardness of the ST joint yields the least increase from that of the base metal. This is due to the replacement of fine precipitate ή/η phase within the grains by a coarse particle η phase or solid solution from solution treatment process at 480 ℃ for 4 h, resulting in the lower hardness comparing to the other two types of joints. On the other hand, precipitates are restored by post weld aging for the AG and the T6 joints.

Table 2 Microhardness distributions in the joints

Conditions	mm/min	Hardness/HV			
		Base Metal	AS-TMAZ	Stir Zone	RS-TMAZ
Base metal		102.4			
As-welded	70	109.16	112.51	111.66	106.38
	110	112.34	111.80	109.47	106.03
Solution Treatment ST	70	140.54	130.66	131.70	134.08
	110	136.24	130.40	136.28	134.24
Artificial Aging AG	70	157.66	147.75	143.60	163.38
	110	159.82	172.65	161.76	168.70
Combined ST+AG T6	70	179.58	194.85	189.69	179.16
	110	182.96	190.53	197.30	192.11

The hardness in the NZ tends to be higher than that of the base metal because the hardness in this zone recovers slightly due to recrystallization into very fine equiaxed grain structure[15]. As for the T6 joint, the microhardness and the strength significantly increase due to re-precipitation of fine precipitates during artificial aging after the solution treatment. The microstructure of the joint in the PWHT reveals fine and uniformly distributed hardening precipitates[16]. This is the main reason for the enhanced hardness and improved tensile strength in the T6 joint. And those micro-cracks have no effects on the hardness value

3.3 Strength properties

Transverse tensile properties of the friction stir welded SSM7075 aluminium alloy joints are presented in Fig.8. All values shown are the average results of six tests. The base metal has a yield strength and a tensile strength of 361.84 and 452.3 MPa, respectively. In all cases, except the T6 at 70 mm/min weld speed, reductions in yield strength and ultimate tensile strength are noted. The yield strength and the UTS of the T6 joint at the welding speed of 70 mm/min are 367.40 and 459.23 MPa, respectively. This corresponds to a joint efficiency of 101.52%. However, the T6 joint at welding speed of 110 mm/min exhibits a yield strength of 319.30 MPa and an UTS of 399.13 MPa, giving a joint efficiency of 88.24% comparing with that of the SSM7075-T6 parent material.

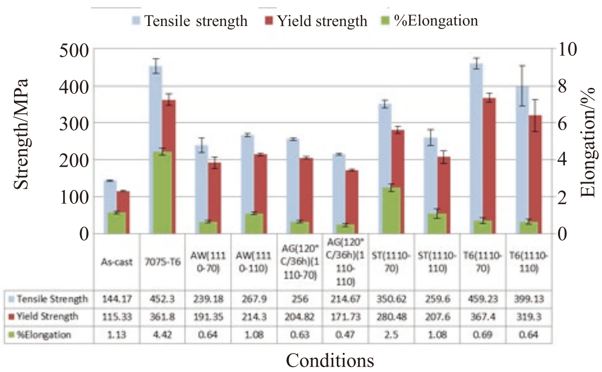


Fig.8 Transverse tensile properties of FSW SSM7075 joints

Of the three remaining types of joints at different welding speeds, the ST joint yield the corresponding highest YS and UTS. Nevertheless, in the ST joint few strengthening precipitates remain after welding. These precipitates disappear during solution treatment after FSW. In this process the solution strengthening precipitates are instead diffused into the matrix aluminium and thus inhibit the strength development while in the T6 joint the fine precipitates are restored by artificial aging after the solution treatment. This combined effort contributes to an increase in precipitate density and a more uniform precipitate distribution, resulting in an improvement in the strengths than the ST by itself.

Results on elongation are also shown in Fig. 8. All weld specimens exhibit lower %elongation than the parent metal. This is due to the Fe rich and copper rich intermetallic phases, which were detrimental to the toughness and fatigue performance, and hence degradation of age hardenability of the alloy[17]. From the tests, the highest % elongation of 4.42% obtained from the base metal 7075-T6 drops to 2.5% for the ST joint at 70 mm/min weld speed. This best after-welding figure further drops to 0.69% for the strongest T6-70 mm/min joint.

4 Conclusions

In this study, the effects of post-weld heat treatment (PWHT) on the microstructure and the mechanical property of friction stir welded (FSW) SSM7075 aluminium alloy are investigated. The following conclusions can be drawn:

a)The nugget zone (NZ) exhibits a recrystallized fine grain structure with grain size increasing from the weld region to the base metal.

b)The grain size at the NZ of the ST and T6 joints coarsens due to solution treatment at 400 - 480°C.

c)The T6 joint by FSW at the welding speed of 70 mm/min yields the highest strength compared to the other types of joints.

d)The maximum yield strength (YS) and the ultimate tensile strength (UTS) obtained are 367.40 and 459.23 MPa, respectively, rendering a 101.52% of joint efficiency.

e)Micro-cracks occur in the NZ at welding speed of 110 mm/min in the ST and T6. This is influenced by quenching after solution treatment.

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