Study of the microstructure of the alloy AMG3 after friction stir welding

E A Guseva, M V Konstantinova

Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia

E-mail: el.guseva@rambler.ru; mavikonst@mail.ru

Abstract. The article contains data on the results of the study of the microstructure of samples of AMg3 alloy, which was subjected to melt and stir welding. For this purpose the methods of optical and electron microscopy, as well as the method of diffraction of backscattered electrons were used. It was found that there were four zones in the area of the welded seam, each of which had its own microstructure. The reasons of for formation of this or that microstructure taking into account the influence of temperature difference and plastic deformation in the welding zone are explained.

1. Introduction

Aluminium alloys are often preferred when choosing materials for various applications in aircraft construction. Their physical and operational properties and cost are determined by alloying elements, as well as technological peculiarities of processing. Relatively inexpensive aluminium-magnesium alloys are widely used, the first of which was described in [1]. Its composition corresponds to the composition of the modern domestic alloy AMg5, containing magnesium 5 %, manganese 0,45 %, titanium 0,1 %.

Magnesium can be dissolved in aluminum up to a maximum content of 17.4%, as well as in the system of aluminum - magnesium - there are a number of intermetallic compounds. Deformable alloys of this system contain no more than 7% magnesium, and such alloys are not subject to thermal treatment. They are characterized by a low density (since magnesium is lighter than aluminum), which provides good specific strength values, as well as good corrosion resistance in a number of environments, which is important for aircraft.

Alloys are quite technologically advanced, but in the manufacture of products with the use of welding technology there are a number of difficulties due to the presence on the surface of the alloy dense oxide film, low modulus of elasticity of aluminum and its high thermal conductivity [2, 3].

When welding by melting there is an uneven temperature distribution in the welding zone, and the volume of the melting zone increases. This causes the manifestation of porosity, cracks and other defects, resulting in increased sensitivity of the welded joint structure to welding conditions. In order to prevent undesirable defects, preliminary operations are carried out, for example, heating of metal up to 100-150 °C, which is done to reduce the heat sink rate and reduce the rate of crystallization of the welding bath [4, 5].

Another defect in aluminium alloys is the appearance of hot cracks, which reduces corrosion resistance in the welded area. This effect is explained by the fact that column-shaped crystals are formed, along the boundaries of which eutectics with low melting point is formed. This has a negative effect on...
the value of mechanical properties in the welded joint zone.

These difficulties made us look for ways to solve the problem in the direction of development of new technologies, in which the microstructure of the welded joint is formed at a short-term significant thermal effect on the joint area. This makes it possible to significantly reduce the volume of the molten metal bath or even to avoid melting at all [6,7].

Laser welding and friction stir welding (abbreviated as STP) are examples of the use of high technologies used to obtain a butt joint of aluminum alloys to solve the problem. Fig. 1 shows the basic scheme of friction stir welding (Frictionstirwelding, abbreviated as FSW). It uses a rotating tool. The rotation of the tool causes friction of the working finger and shoulder on the workpiece, which results in the release of a significant amount of heat. This brings the alloy in this area into a plasticized state. The physics of the thermomechanical welding process involves a simultaneous thermal and mechanical action on the workpiece to be welded. In the process of friction stir welding, the microstructure of the weld is formed by simultaneous heating and plastic deformation. Deformation is caused by the tool pressure on the workpiece surface and the plunging of the working rod to a certain depth, as well as the feed movement [7,8].

The microstructured zones are shown in Fig. 2.

The following welded joint zones are distinguished: ZTI - zone of thermal influence; ZTMI - zone of thermomechanical influence; welding point core.

Main advantages of the described welding in comparison with fusion welding:
- porosity prevention;
- significantly less deformation of the welded structure;
- quality joints on alloys prone to hot cracks;
- no additional materials are required for welding;
- easy connections regardless of the position of the joint;
- no harmful radiation;
- high process automation.

At the moment there are many works of both domestic [9-15] and foreign authors[16-24] on the theory of thermal and deformation influence on the metal. The peculiarities of the microstructure and mechanical characteristics of aluminum alloys after FSW are well studied.

In Russia, friction stir welding technology has been implemented by CJSC "Sespel" for the production of tank trucks, and the technology is being developed by the Polyot Production Association, Khrunichev State Research and Production Space Center. The research of this process is conducted at the All-Russian Institute Of Aviation Materials [25], Tomsk Polytechnic University [26], South Ural State University [27] and other universities in Russia. Abroad, studies and attempts to implement this process are conducted, for example, by ESAB, SAPA (Sweden), The Eclipse Aviation Corporation (USA), EADS (France, Germany), Institut de Soudure (France), DanStir (Denmark), etc. [27].
Figure 2. Schematic diagram of weld formation process:
Section A is the base material;
Section B - heat-affected zone;
Section C - thermal deformation zone;
Section D - stirring zone

It should be recognized that to date the undisputed criteria to assess the obtained welded joints have not been developed, that also meet a certain level of quality when applying the method of welding. Such criteria can be developed as a result of comprehensive study of the features of microstructure and properties of welded joints using different methods of research.

The proposed article describes the results of the study of the microstructure of AMg3 alloy after friction stirring welding.

2. Materials and methods of the research
The experimental part of the work was carried out with the use of a training and research unit created on the basis of a vertical milling machine and a welding tool made with the recommendations[16-24]. The thickness of the samples was 5 mm, the speed of rotation of the tool was in the range from 315 to 1000 rpm, the feed rate of the tool was in the range from 40 to 125 mm/min. Some workpieces were preheated before welding.

For the subsequent metallographic study of the microstructure, samples of welded joints were prepared. All samples used for microscopic analysis were cut out perpendicular to the welding direction. After grinding and polishing, two types of reagents were pickled on the samples. One of them is a modified Keller etchant which includes 2 ml HF, 3 ml HCl, 5 ml HNO₃ and 190 ml H₂O. After using this etchant, a high-quality image of the grain structure can be obtained. The other is a NaOH solution with a concentration of 2%, and after the use of this etching reagent, the characteristic microstructure associated with the oxide layer, such as S-lines and onion rings, can be clearly seen. All etched samples were examined through an optical microscope.

Electron microscopic studies were carried out on the basis of IRNTU with the use of the electron scanning microscope of multi-beam system JEOL, equipped with electronic and ion gun JIB-4501 and equipped with a nonnitrogenic system of energy dispersive microanalysis, and translucent electron microscope of the brand Tecnai G2 20F S-TWIN FEI.

3. Research results and discussion
Fig. 3 demonstrates the sample after friction stir welding.
The degree of deformation and temperature history influence the evolution of microstructures. From the microstructural point of view, the welded joint section can be divided into several characteristic zones shown in Fig. 4. Although some of the names of the zones (Fig. 2) differ from source to source [16-25], the following zones are most often used. Depending on the heating temperature and the degree of deformation associated with the welding process, in our experiments we almost always record the formation of four zones - the base metal (BM), the zone of thermal influence (ZTI), the zone of thermomechanical influence (ZTMI) and the zone of mixing (ZM).

The first zone is the unaffected base metal (OM). This is the area furthest from the weld. Despite the possible temperature fluctuations in the area of the base material, it retains the same microstructure and mechanical properties as before the welding process.

The second zone is the heat-affected zone (HAZ), which is the next zone towards the center of the joint. An increase in temperature in this zone is sufficient to change the microstructure and mechanical characteristics. No plastic deformation of the metal was observed.

Thermomechanical influence zone (TMIZ) is the third zone, where, in contrast to ZTI, the alloy experienced severe plastic deformation under the influence of tool movement.

Fourth zone - stirring area where recrystallization (ZM) takes place.

At all welding modes the surface of the formed weld had a typical look (Fig. 1). It reflects the layer-by-layer flow around the working tool. Samples for the preparation of metallographic grinding wheels were cut out in the transverse direction.

The joint has an asymmetrical structure and is divided into upper and lower parts. The microstructure of the AMg3 alloy by its main zones is shown in Fig. 4.
The microstructure of the welded joint in its upper area is formed by the rotation of the shoulder pads, which rub against the surface of the workpieces to be welded. In the near-surface layers the plasticized metal flows parallel to the outer surface. At the same time, there is a natural decrease in the value of deformation at the cross section of the product inland.

The microstructure of the weld in its lower area is formed under the influence of a rotating finger. This rotation causes a transfer of the metal mass around the surface of the finger. The characteristic geometry of the tool leads to the movement of the metal mass both along the circumference and vertically. The shape of the weld is mushroom-shaped, with a peculiar layered structure in the mixing zone. The microstructure was called "onionring" or "onion rings" (onion structure). One can observe different fragments of this microstructure. The peculiarity of this microstructure is that the metal product alternates layers of equal thickness - approximately 0.2-0.4 microns each. These layers are oriented according to the direction of the applied forces.

The microstructure of AMg3 alloy in the zone of the main metal is represented by grains; some of them are deformed in the direction of rolling (Fig.4, section 1.2). The average grain size was (23±3) µm. The size of grains was on average (4.3±1.2) µm. These results coincide well with the literature data indicating that in the core (center) of the welded seam a microstructure with a sufficiently small grain is formed. The average grain size is in the range of 3-7 microns, regardless of the type of material subjected to welding, and the initial grain size [16–25].

Compared to the original microstructure, the processing of the alloy's grain was observed to result in several times' grinding. The formation of such a structure is explained by the active thermomechanical action, which is provided by friction of the rotating tool. Under these conditions can occur the process of dynamic recrystallization.

To clarify the nature of the occurring phenomena, one can rely on the value of the angle of disorientation of the crystal lattices of neighboring grains. To estimate the value of the disorientation angle, the method of EBSD (backscatter electron diffraction) was used. The boundaries are considered to be larger angles when the angle of disorientation of neighboring grains is greater than 15°. This is the value typical of the post-crystallization structure.
It has been used to establish that most grain boundaries in the area under discussion are more angular. This confirms the formation of a recrystallized structure in the central part of the weld.

Having analyzed the areas, which were not subjected to thermal influence, we found that almost half of the borders are of low angle. There is a deformed structure when the grains are stretched along the rolling direction.

There is no accumulation of dislocations inside the grains. Some of the dislocations are located near the boundaries and on the disperse particles located in the grain body. The average grain size is 50-500 nm. The combination of deformation and thermal influence of heating in the mixing zone leads to the development of the dynamic recrystallization process. The consequence of this is that the structure of the metal base, characterized by coarse grains, turns into a microstructure, where the grains have equal axes and are strongly disoriented.

The processes occurring at high temperatures of aluminum alloys and resulting microstructures are well studied in the works [29, 30].

There are three types of dynamic recrystallization:

- intermittent dynamic recrystallization (DDRX) is the result of the emergence and growth of new grains;
- continuous dynamic recrystallization (CDRX), including the formation of low-angle boundary arrays: a gradual increase in grain disorientation during hot deformation ultimately leads to the formation of new grains;
- geometric dynamic recrystallization (GDRX) resulting from collisions with toothed grain boundaries, which can occur when grains are extremely elongated due to severe hot deformation.

The implementation of any of the above mechanisms leads to the grinding of grain, and these different types of dynamic recrystallization can occur simultaneously. Their individual contribution is difficult to identify on the basis of available experimental data.

4. Conclusion

The experiments conducted by us show that friction stir welding has a strong enough effect on the internal structure of the studied alloy in the welded joint area. There is a decrease in the size of grains. Dynamic recrystallization is confirmed, which leads to natural changes in the microstructure. Coarse grains turn into fine grains, while the angle of misorientation of neighboring grain boundaries increases. In the core of the welded seam there are equiaxial grains, separated by more angular boundaries.

The described mechanism of transformation of the microstructure in the metal areas adjacent to the instrument is explained by the temperature drop and a significant amount of plastic deformation. At plastic deformation there is a process of sliding and turning of fine subgrains. As a result, the underlying alloy layers are deformed due to local stress increase. Taking into account this mechanism, a characteristic layered microstructure with fine grain in the welded joint is formed.

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