Friction Stir Processing of Aluminum Alloy 5556 With Different Pin Configuration of Tool

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Abstract. The paper investigates the features of the friction stir processing of aluminum-magnesium alloy using tools with a screw pin and with a square section pin. The conducted studies show that during the friction stir process with a tool with a square cross-section pins it is possible to form instabilities during treatment, leading to non-uniform longitudinal movement of the tool and formation of defects. One mechanism for this phenomenon could be contamination of the surface of the aluminum-magnesium alloy treating tool after working on aluminum-silicon alloys, resulting in unstable adhesion contact. This effect is less noticeable for treating by tool with a cylindrical pin. Mechanical properties of the treated material in 1-4 passes remain quite close and the average ultimate tensile strength of the stir zone is 325-335 MPa. The plasticity of the material decreases on average from 33% to 25-30%, but remains at an acceptable level. The average ultimate tensile strength and ductility values are slightly higher when processing with a square-shaped pin tool than when processing with a spiral-shaped pin tool.

1. Introduction

The use of friction stir process for hardening of machine parts and mechanisms made of aluminum, copper and other alloys is currently relevant in terms of obtaining wear- and corrosion-resistant coatings in the surface layers. The material subjected to friction stir process has, for a number of metals and alloys, increased mechanical properties, strength and plasticity. The mechanism of influence on the structure of friction stir process is similar to the mechanism of friction stir welding and is based on the effect of adhesion friction [1-3]. When a rotating tool (consisting of a pin and shoulders) is introduced into the material and passes along the processing line, metal grains are ground, ultrafine structure formation, structural-phase changes, etc. occur. Potentially, this type of processing has broad prospects for the formation of wear-resistant composites with a metal matrix on the surface of aluminum (titanium or magnesium) alloys and obtaining lightweight tribotechnical parts. Tools with different configurations of pins, shoulders and materials are used for processing metals and alloys. The most commonly used tools for processing aluminum alloys are tools made of heat-resistant stamped steels such as H11, H13, etc. As a number of previous works shows, the influence of tool configuration on the friction stir process and the formed structure of the stir zone can be quite complex and conditioned by quite subtle features. While processing with a cylindrical, helical or tapered tool pin shape is the easiest in terms of selecting processing parameters and obtaining a defect-free structure, processing with an octahedral, square or triangular cross-sectional tool can potentially result in more uniformly distributed in volume hardening phases due to a greater degree of deformation around the tool. The aim of the present work is to
investigate the regularities of friction stir process of aluminum-magnesium alloy 5556 by processing with a tool with different pin configurations.

2. Materials and methods
Samples were obtained by friction stir process with a tool with a square cross-section and a tool with a spiral pin on the experimental setup at the Institute of Strength Physics and Materials Science. The machining was carried out at a tool rotation speed of 500 rpm and a feed rate of 90 mm/min. The clamping force of the tool to the workpiece material was up to 1350 kg. Processing was carried out from one to four tool passes over the same area. Control of the tool position along the vertical axis during processing was carried out according to the non-rigid scheme with maintaining constant load. The friction stir process work cycle also included studies of process parameters for hardening aluminum-silicon alloys. For this reason, some of the samples were obtained by tools with the surface contaminated with aluminum-silicon alloy. Structural studies were performed by optical microscopy (Altami MET1C microscope). Mechanical tests of the specimens cut along the processing line were performed on a universal testing machine UTS110-M.

3. Results and discussions
When processing 5556 alloy with a tool with different configuration of the pin after machining AlSi12 alloy samples with the same tool, the process parameters selected earlier did not correspond to the formation of defect-free processed structures (figure 1, a). At the same time, the defects in the structure of the processing zone differed significantly. The samples processed with a square-section pin tool were characterized by the presence of structural heterogeneities alternating every few layers (a1–a5 and others in figure 1, a). For the samples obtained with a screw-pin tool, the heterogeneities in the structure of the processing area were not pronounced, and the main defect formed was the tool burial during processing at a constant load (figure 1, b).

Processing with a square-section tool with an attempt to change the sample-forming process parameters (normal pressure force within 1050-1350 kg) did not lead to the expected result (figure 2). Inhomogeneities of processed samples (a1–a5 and others in figure 2) have a regularly recurring structure and are represented by material extruded from the processing zone in such a way that the sample formation process appears to have a precession axis in addition to the tool rotation axis. Precession, in turn, indicates the instability of formation and destruction of adhesion bonds between the tool and material during processing, which is quite expected given the non-rigid tool coordinate control scheme along the vertical axis. Presumably, such effect is connected with the presence of adhered material of aluminum-silicon alloy AlSi12 on the tool surface, which leads to destruction of adhesive bonds between alloy 5556 and the tool and leads to manifestation of heterogeneity of the processing, which, in its turn, is partially confirmed by reduction of defect structure during processing after partial abrasion from tool surface of alloy AlSi12 (a1–a5 in figure 3).
The structure of the metal in the processing zone of the samples, with the presence on the surface of significant instabilities and oscillations, in some cases presented by a highly defective stir zone with extended zones of discontinuities larger than 1 mm in cross-section (figure 4, a).

After cleaning the tool and forming the stir zone without traces of precession or with traces of moderate process inhomogeneities, the metal structure in the stir zone has a defect-free appearance (figure 4, b). At the same time, the formation of the metal structure when processing with a screw-pin tool, even in the case of a tool contaminated with aluminum-silicon alloy residues, occurs with an almost complete absence of defects (figure 4, c). The processing area in all cases is represented by the thermomechanical affected zone (TMAZ), clearly separated on the advancing (AS) and retreating (RS)
sides, and the stir zone (SZ) with an ultrafine-dispersed structure (grain size less than 1-2 μm). The structure of the stir zone presented by the concentric rings (when processing with a screw pin tool), or by the non-uniform layers of close to rectangular shape (when processing with a square-section tool) is due to the layer-by-layer character of the connection formation process. This occurs through the extrusion of metal from the area in front of the tool - to the area behind the tool through a point on the retreated side of the connection and the adhesive transfer of metal due to the friction force of the tool and the processed metal.

The main effect on the mechanical properties of alloy 5556 is seen in the reduction of ductility from 33% to 25% when processing with a screw-pin tool (figure 5, a) and up to 30% when processing with a square-pin tool (figure 5, b). The ultimate tensile strength of the material remains at the level of the ultimate tensile strength of the sheet rolled metal and does not change significantly when processing in 1-4 passes. Processing with a square-tipped tool results in a stir zone with slightly higher ultimate tensile strength values, but the differences in this case are insignificant (figure 5, b).

![Figure 5](image_url)

**Figure 5.** Effect of number of passes (a) and type of tool (b) on mechanical properties of alloy 5556 after friction stir process (1-4 – number of passes, BM - base metal, st - instrument with a screw-pin tool, sq - instrument with square-pin tool)

### 4. Conclusion
This research shows that the influence of tool pin shape on the processing can be reflected in different tool resistance to surface contamination from processing other aluminum alloys. While tools with a square-shaped pins tend to exhibit motion instabilities when processing with "precession" of the rotation axis, tools with a helical pins show a tendency for increased burr formation and burrowing into the material. The structure of the metal in the processing area at an optimal ratio of the processing parameters is represented by a defect-free structure, with an average grain size of less than 1-2 μm. The mechanical properties of the material of the samples obtained without significant inhomogeneities of the processing are at the level of the properties of the base metal. Thus, it can be established that the friction stir process with tools with a helical pin and with a square pin does not lead to material softening and is potentially suitable for obtaining metal matrix composites by stir various powder particles into the volume of aluminum alloy.

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