Behavior of the aluminum cast alloy EN AW 4047 to friction stir processing

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1. Introduction

The continuous development of the priority scientific and technological fields of research at European level, which are targeting new manufacturing processes, new materials, restructuring and modernization of some industrial sectors in order to adapt them to the current requirements of quality and performance, has imposed the development of new processes and techniques for processing and joining of metallic materials.

To reduce the cost of manufacturing products in different priority industrial areas (e.g. the automotive, aeronautic and aerospace, shipping, public transport), it is necessary to reduce the mass of products and increase their quality by using more and more light materials (e.g. aluminum, magnesium, etc.), as well as using some of technically and economically efficient processing and joining techniques.

The development of the priority areas imposes special requirements for the joining processes regarding the following aspects: technical (materials, shapes, dimensions, structures, loads), economical (productivity, consumption, cost) and environmental (pollution, noxious). These requirements can not be fully met by the joining and processing of materials that are currently used at industrial level.

In the last years, ISIM Timisoara has carried out numerous own researches for the development and implementation some of unconventional processing methods of materials: ultrasonic welding [1], HVOF thermal spraying [2], water jet cutting [3], laser beam processing [4].

In this context, ISIM Timisoara intends to develop the materials processing technique using friction stir processing FSP, aiming the development of FSP technologies for cast metallic materials from the category of aluminum alloys used in industrial applications, the promotion of a environmentally friendly technique for materials processing, with a high degree of innovation, applicable in different industrial fields.

Innovative friction stir processing (FSP) has developed from the friction stir welding process FSW, with possibilities to apply on a wide range of metallic materials. In case of FSP processing, the work tool is moving on the surface of a single plate, on an established trajectory, with the aim to obtain microstructural changes and improving the properties in the processed area. The friction stir processing is applied to a single base material and involves rotating of the processing tool with a certain rotational speed, penetrating of the tool pin into the material to be processed, until a firm contact between the tool's shoulder and the base material surface, followed by the movement of the rotating tool on an established path (processing direction). The heat generated by friction dissipates both in the processed material and in the tool material, causing the increase of temperature and plasticizing of the processed material [5-7].

In view of these considerations, it is possible to modify some of mechanical properties of materials, which may be useful in industrial applications.

2. Processing material and processing tools

The behavior of cast aluminum alloy EN AW 4047 (AlSi12) with 8 mm thick, to friction stir processing FSP in a single-pass, has been presented and analyzed in the paper. Table 1 shows the chemical composition of this material.

Table 1. Chemical composition EN AW 4047 (AlSi12).

Chemical composition, [%]								
Si	Fe	Mn	Mg	Cr	Pb	Ti	Sn	Al
11.93	1.02	0.24	0.008	0.01	0.12	0.05	0.122	balance

Aluminum-silicon alloys have an equilibrium diagram with eutectic transformation at 11.7% Si and 577ºC, with an insignificant variation in solubility (1.65% Si at 577ºC and 0.05% Si at 20ºC) [8].

Al-Si alloys have very good casting properties (very high fluidity), are impermeable to liquids and gases, have good weldability, are insensitive to hot cracks, have superior corrosion resistance compared with pure aluminum, having low mechanical properties after normal casting. Hypereutectic alloys with 12÷13% Si, have a coarse casting structure consisting of eutectic and needles or Si plates, which lead to low properties: mechanical resistance (130÷160 N / mm^2), plasticity (A = 1÷2%) and hardness (HB = 50÷60).

The cast alloy EN AW 4047 (AlSi12) has a content of 11.93% Si, which puts it slightly above the content corresponding to the eutectic transformation (Table 1).

Unlike most phase diagrams, practically, Al has no solid solubility in Si at any temperature; therefore, it will develop purely Si instead of a β phase. As with any other eutectic binary system, alloys with a composition on either side of the eutectic point, will affect the primary phase that it firstly developed, and this will modify the alloy properties.

Al-Si alloys are used commonly as casting materials. This class of Al alloys has a low viscosity of the melt and allows components with complex geometries to be produced with minimal defects and low shrinkage [9-11]. However, in order to improve alloy performance to meet the other demanding requirements, additional alloying elements are usually added. Depending on the composition and silicon content (Si), the microstructure that develops will vary and this will in turn lead to modify the alloy properties.

Aluminum casting alloys must have characteristics and properties that make them suitable for this processing mode, such as high fluidity at low temperature, low thermal shrinkage, low susceptibility to the thermal cracking and pore formation. All of these are characteristic of a eutectic structure or which contain a significant amount of eutectic. This structure was obtained by alloying mainly with silicon, to which other alloying elements have added in order to improve the mechanical properties of the alloy, such as manganese - for increasing of the mechanical strength and titanium - for microstructure finishing and tenacity increasing, etc.

The advantages of casting alloys are accompanied by some disadvantages: lower exploitation characteristics, different casting defects, non-metallic inclusions, inhomogeneities, rough structure, etc. The FSP process can be a solution for eliminating some of casting defects, as well as for improving of the exploitation properties and increasing the quality of the casting parts, respectively.

In view of these considerations, it is possible to modify some of mechanical properties of materials, which may be useful in industrial applications.

In this paper are presented preliminary results obtained by FSP processing of cast aluminum alloy AW 4047 (AlSi12) having 8 mm thickness, processed with three different types of processing tools, presented in figure 1.

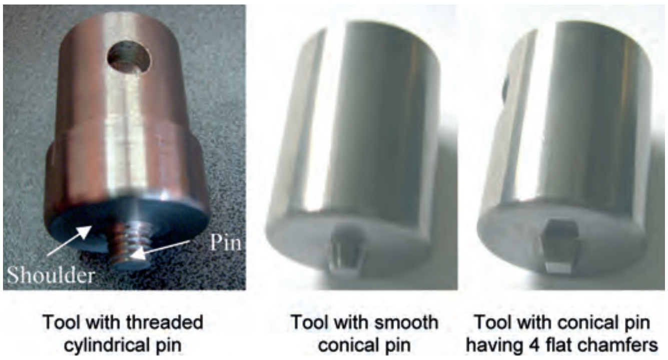

Figure 1. FSP Processing tools used in experimental program.

The M6 threaded cylindrical tool was made of X38CrMoV5 steel with pin length L_{pin} = 4.5 mm and shoulder diameter $Ø_{shoulder}$ = 22 mm. The tools with smooth conical pin and conical pine with four flat chamfers, were made of tungsten sintered carbide type P20S, with pin length L_{pin} = 4.5 mm, respectively 5mm and shoulder with diameter $Ø_{shoulder}$ = 20 mm.

3. Experimental program. Results

Preliminary research programs of friction stir processing have been performed to study the processing behavior of the cast aluminum alloy EN AW 4047 (8 mm thick), using three types of processing tools (mentioned at chapter 2) and the same experimental conditions as outlined in Table 2. The experiments were carried out using the equipments of Figure 2: FSW 4-10 welding machine (pos.1), positioning and fixing device of the material to be processed (pos.2); tool and port-tool device (3), system for tracking and controlling the pressing force of the tool shoulder on the base material during the FSP process, with a force transducer (pos. 4a) fixed to a device on the FSW machine, using a data logger, a modular voltage source and a PC for data acquisition, storage and processing (pos.4b) as well as temperature monitoring system (pos. 5) at the surface of the base material (BM) to be processed in the shoulder area of the tool, using an infrared thermography camera mounted on a positioning device and a PC for data acquisition, storage and processing.

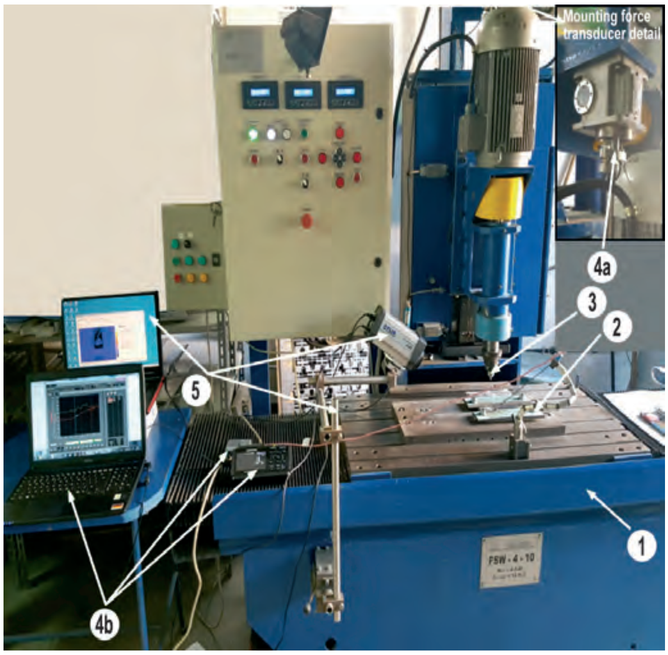

Figure 2. Work equipments for FSP processing.

Table 2. Technical data for FSP experiments - cast aluminum alloy - EN AW 4047 (AlSi12).

Ex. no.	Base material	Processing tool				Process parameters		
		Material	Pin type	Shoulder diameter [mm]	Pin length [mm]	Rotational speed, n [rot/min]	Processing speed, v [mm/min]	Direction of rotation
1.1.	Cast EN AW 4047 (s = 8 mm)	X38CrMoV5	M6 threaded cylindrical	22	4.5	1450	100 and 200	counter clockwise
1.2								
2.1		P20S	Conical with 4 flat chamfers	20	5.0			
2.2								
3.1		P20S	Conical smooth	20	4.5			
3.2								

Table 2 presents technical data for the FSP processing experiments of the cast aluminum alloy EN AW 4047 (AlSi12), included information on: the material to be processed, the features of the FSP processing tool and the technological parameters that are used.

Three series of FSP processing experiments were performed on the cast aluminum alloy EN AW 4047 alloy (8 mm thick), corresponding to the three types of FSP tools. In all experiments performed, were maintained constantly: the rotational speed of the processing tool - n = 1,450 rpm and the counter clockwise direction of rotation for the processing tool. For each type of processing tool, FSP experiments were performed with two values of the processing speed on the processing direction, i.e. v = 100 mm / min and v = 200 mm / min, respectively.

The evaluation of the processed materials was carried out according to the following plan: visual examination of the FSP processed material, thermographic analysis and of the pressing force of the tool shoulder on the surface of the material to be processed, sampling of the base material and of the processed material FSP, macroscopic and microscopic structural analysis, hardness and roughness measurements for the base material and for the FSP processed material, respectively comparison of the results obtained for the FSP processed material with the base material.

For example, Figure 3 shows the appearance at the surface of the processed material.

Figure 3. Appearance at the surface of the processed material.

One aspect of the processed surface, that is specific to use of friction stir processing / welding technique, was observed.

Figure 4 shows the macroscopic analyzes for experiments performed with the three processing tools and using the two longitudinal speeds.

The processed area under the influence of the FSP tool and the well consolidated core (characteristic for friction stir processing) can be observed for experiments 1.1 and 1.2, respectively 2.1 and 2.2 (made on EN AW 4047 cast aluminum alloy, with FSP tools having cylindrical threaded pin and conical pin with 4 flat chamfers, using processing speeds of 100 mm / min and 200 mm / min). No defects are detected in the processed material.

For experiments 1.2 and 2.2, in the base material is distinguished a “void of material” casting defect, away from the processed area. In the base material, there can be distinguished such “void of material” casting defects, predominantly with small dimensions.

In experiment 2.1, in the action area of the pin tool tip, there may be a area characterized by “lack of adhesion”.

Experiments 3.1 and 3.2 show major defects both at the surface of the process area and in its depth (irrespective of the processing speed used). The defects are mainly due to the geometry of the processing tool, which in this case does not favor the fulfillment of conditions for obtaining a “clean” processed area, without defects, and with optimal characteristics and properties.

The FSP processes have been monitored from the point of view of the temperatures developed in the area of the processing tool shoulder, as well as the forces with which the processing tool presses on the base material. Figure 5 shows the temperature evolution during FSP processing. The maximum recorded temperature (using infrared thermography) for the FSP processing of EN AW 4047, has ranged from 385÷500^{o}C, depending on the type of tool and the processing speed used (Table 3).

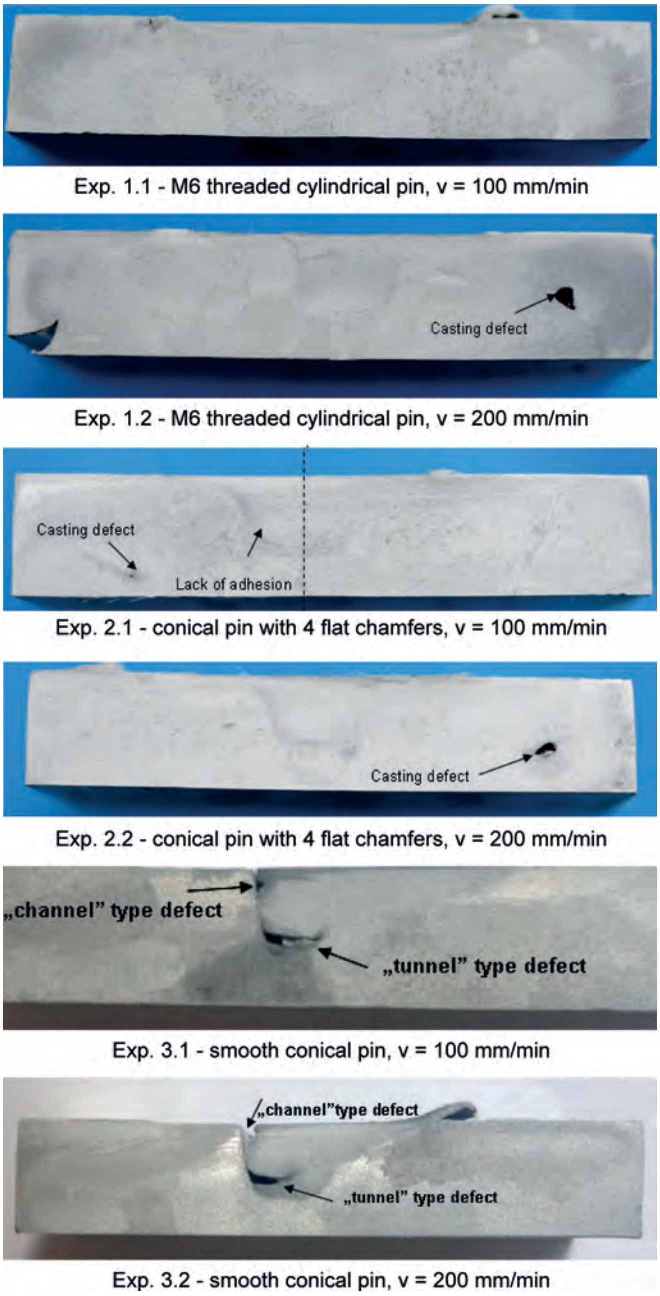

Figure 4. Macroscopic analysis – Exp.1, 2 and 3.

For example, figure 5 shows the temperature evolution graphs in experiment 1, using processing speeds of 100 mm / min and 200 mm / min.

The analysis of the heat developed during the processing for all the experiments performed shows that in those achieved with the processing speed v = 200 mm / min (double compared with v = 100 mm / min), the temperature of the process was slightly lower (Table 3), considering that the process temperature evolves in inversely proportion with the FSP processing speed.

Table 3. Monitoring of FSP processes (temperature and force).

Ex. no.	Processing tool	Process monitoring (maximum recorded values)	
		Maximum temperature T_{max} [°C]	Maximum force F_{max} [N]
1.1	with M6 threaded cylindrical pin	500	12,500
1.2		440	9,500
2.1	with conical pin with 4 flat chamfers	400	9,400
2.2		385	8,400
3.1	with smooth conical pin	460	8,700
3.2		460	12,000

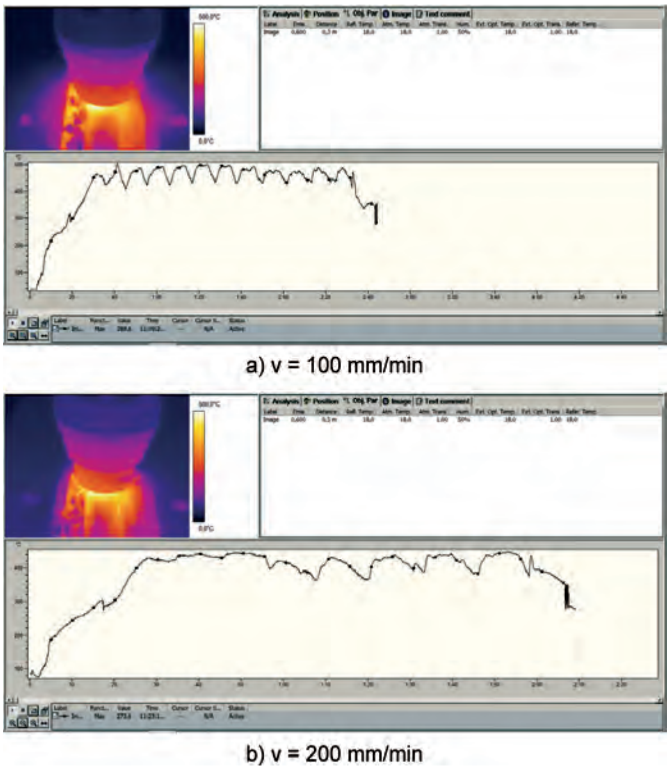

Figure 5. Temperature evolution graphs for friction stir processing of cast EN AW 4047.

The maximum values of the pressing force of the tool were recorded during its penetration in the base material, when achieving a firm contact between the tool shoulder FSP and the entire surface of the base material, depending on the type of tool and the diameter of the shoulder. The pressure force were higher for FSP tools having shoulder diameter $Ø_{shoulder}$ = 22 mm, compared to the $Ø_{shoulder}$ = 20 mm, these aspects regarding the pressing force being valid in all experiments. For the FSP processing experiments of the EN AW 4047 cast alloy, the maximum values of pressing force of the tool on the MB ranged from 8,400÷12,500N (Table 3).

Until now, a limited number of investigations have analyzed the behavior of cast aluminum alloys in FSP processing. The microstructure of the base material has modified during FSP processing, which can cause changes of the mechanical properties in the processed area.

Microstructural investigations carried out using an optical microscope revealed in the base material the existence of a rough casting structure, typical for this alloy, consisting of silicon plates embedded in a rich matrix in aluminum (Figure 6a).

These changes appear after the action of the FSP processing tool, the mixing and flow of plasticized material around and ascending-descending relative to the pin of processing tool.

The area formed by the direct action of the processing tool pin (nugget N) is a recrystallized zone (processed by FSP processing). In the nugget, the high degree of deformation due to the mechanical effect at the interaction between the base metal and FSP tool and the introduction of heat generated by friction, lead to a complete re-crystallization, which has as results a very fine grains structure.

Also, in the thermomechanically affected zone (TMAZ), located near the nugget, the silicon plates are more strongly fragmented resulting in a finishing of the granulation (Figure 6b). The grain dimensions are, however, larger than in the nugget (N), due to the fact that the degree of plastic deformation and the thermal effect in this area are lower than in N.

Unlike N and TMAZ, in the heat affected area (HAZ), which is at a distance from the action of the active elements of the FSP processing tool, only the heat generated during processing affects the material (Figure 6b). At the same time, the developed thermal field can favor in HAZ a slight dissolution of Si in Al-Si solution, which produces a reduction of the amount of Si crystals in the structure (Figure 6b)

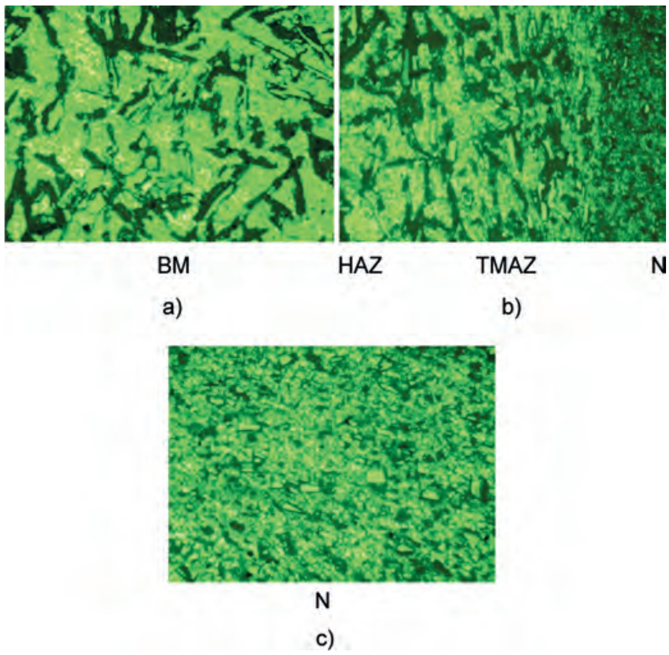

Figure 6. Microstructural analysis – cast aluminum alloy EN AW 4047 – FSP processed.

From the microstructural point of view, the following can be stated in principle:

- for all combinations of technological process parameters (FSP parameters, processing tools), the microstructural analyzes have revealed similar aspects;
- the morphology of the nugget area indicates the existence of deformations and a microstructural evolution determined by the process conditions or by the recrystallization phenomenon (Figure 6c). In the nugget area, the temperature reaches approx. 400÷440°C.

Vertical hardness measurements were made from top to bottom (on a line corresponding to the axis of the processing tool pin, starting from 1 mm below the processed surface, with 1 mm pitch), as well as horizontally (at 1 mm and 4 mm below the surface being processed, with 1 mm pitch). For example, Figure 7 shows graphs of hardness variation measured vertically (corresponding to pin axis) and horizontally (at 1 mm and 4 mm below BM surface).

Analyzing the hardness evolution for the processing of cast EN AW 4047, some assumptions can be made: in the processed area, in the nugget (N), the hardness prevailed in the range 56÷66 HV1, higher by approx. 15-17% on the advancing side of the processing tool (when using a processing speed by 200 mm / min); in HAZ and TMAZ the hardness varies between 59÷70 HV1, in the base material the hardness values vary between 54-64 HV1. Higher values in the nugget and TMAZ were recorded, especially at the 4 mm measuring depth. High values (over 70 HV1) were also recorded in BM areas due to some of characteristics / particularities (lack of homogeneous structure) of cast materials (EN AW 4047).

When using the threaded cylindrical tool, the roughness measurements (6.9÷9.93 µm) revealed a finishing degree of surface similar to that obtained from a mechanical machining by cutting. At the same time, analyzing the evolution of roughness values in various areas of the processed surface it has been observed a finishing of the processed material in the retreating side of the tool and on the center of the processed area, compared with the advancing side of tool.

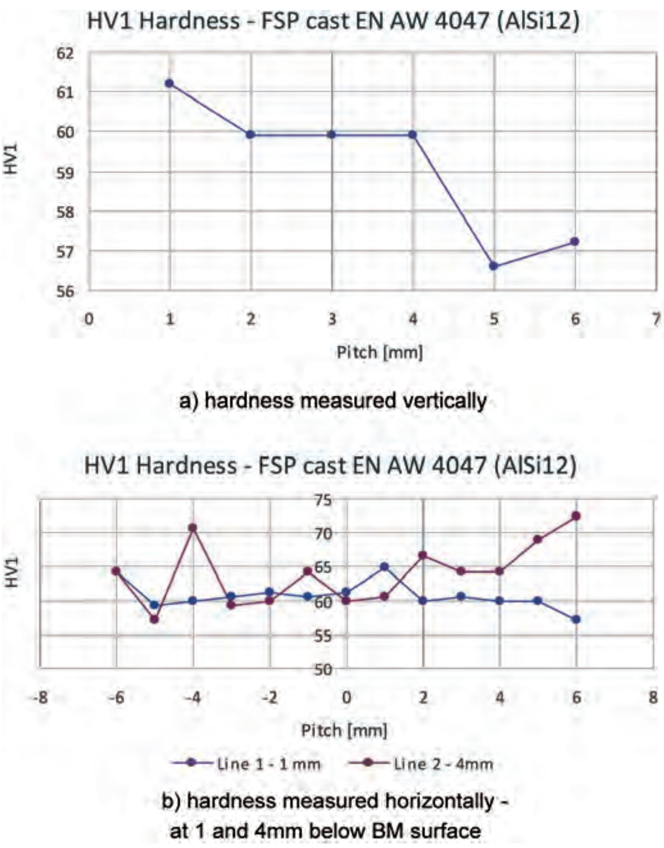

Figure 7. Graphs of hardness variation – FSP processing of cast aluminum EN AW 4047 (AlSi12).

A much improved quality of surface has been obtained when using FSP tools made of tungsten sintered carbide, compared to the use of tools made by steel (mainly due to the characteristics of the P20S carbide, which has resulted in an extremely fine exterior surface of the FSP tool). The specific characteristics of this material favors a very good quality of the processed surface, from the point of view of the roughness (4.65÷9 µm), when using P20S tungsten carbide tools.

4. Conclusions

The FSP friction process is developed by the friction stir welding process FSW and is applicable to a wide range of ferrous and non-ferrous metallic materials, such as steels, aluminum alloys, copper, magnesium, titanium, and others.

Cast aluminum alloys have a wide use due to their high corrosion resistance and very good casting properties, which offer a good quality of casting, even in complex forms, where the minimum values of the mechanical properties (obtained in reduced sections) are higher than those obtained when casting high strength alloys but with low casting properties.

In order to obtain good properties/mechanical characteristics of the processed materials, the following main aspects are very important:

- establishing the characteristics of the processing tool in terms of geometric configuration, dimensions (correlated with the thickness of the material to be processed) and the material from which they are made;
- establishing the process parameters correlated with the material to be processed and with the type and geometry of the processing tool;
- the processing equipment ,as well as the positioning and fixing devices of the material to be processed, must provide a rigid and robust fastening to avoid the occurrence of process disturbances.

The shape and design of the tool influences the heat generation, the plastic flow, the forces that develop during the process and the uniformity of the processed material. The shoulder generates the greatest amount of heat and prevents the expulsion of the plasticized material from the material to be processed (in the area undergoing processing), while both (the shoulder and the pine) influence the flow of the material.

Processing tools made of alloyed and hardened steels as well as those made of W-sintered carbide can be used to develop research and demonstration programs of the FSP process quality for cast aluminum alloys, more favorable results being obtained with tools having cylindrical threaded pin and conical pine with four flat chamfers.

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