Friction stir processing in multiple passes of cast aluminum alloy EN AW 4047 (AlSi12)

L.-N. Boțilă, R. Cojocaru, C. Ciucă

National Research-Development Institute for Welding and Material Testing ISIM Timisoara, Romania

E-mail: lbotila@isim.ro

Keywords

Friction stir processing, multiple passes, cast aluminum alloy, EN AW 4047 (AlSi12), experiments

1. Introduction

Use and promotion some of ecological techniques for processing of metallic materials, which are efficient from technical and economically point of view, having a high degree of innovation and with possibilities for implementation in industrial activities, could contribute to the development some of important industrial fields (e.g. automotive, aeronautic and aerospace, shipbuilding industry, public transport).

Friction stir processing FSP represent a field of interest for ISIM Timisoara, following the development of technique / method of FSP processing of nonferrous metallic materials from the cast aluminum alloys category, the development of FSP technologies for these materials used in industrial applications, as well as promotion of an ecological processing technique of materials, having a high degree of innovation and with applicability in various industrial fields.

The innovative friction stir processing FSP has been developed from the friction stir welding FSW and is based on the same principle, being applied on the surface of a single base material. During the FSP process, the heat generated by friction between processing tool and base material to be processed is dissipated in the processed material and in the tool material, leading to increase their temperature and plasticization of the processed material [1] - [3].

As a result of application of friction stir processing, the local modification of some mechanical characteristics/properties occurs. This fact could be useful in some industrial applications, friction stir processing could be applied for a wide range of metallic materials.

2. Base material and FSP processing tools

The base material to be processed is aluminum alloy AlSi12, with chemical composition presented in table 1.

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

Cast aluminum alloy EN AW 4047 (AlSi12) contains 11,93% Si, a little bit over the content that correspond to the eutectic transformation (11,7% Si) [4].

Al-Si alloys used as casting materials have a low melt viscosity and are thus used to make components with complex geometries having minimal defects and low shrinkage [5] - [7]. Al-Si alloys have very good casting properties (very high fluidity), but may also have some disadvantages: low mechanical properties after normal casting, lower operating characteristics, various casting defects, non-metallic inclusions, inhomogeneity, rough structure, etc. To improve the properties and mechanical properties of Al-Si alloys, additional alloying elements (e.g. manganese - to increase the mechanical strength, titanium - to finish granulation and toughness, etc.) are added. A solution to eliminate some casting defects and to improve/modify some properties and mechanical characteristics of materials used in industrial applications is represented by applying of the friction stir processing method.

In the present paper, two types of processing tools, shown in Figure 1, were used for the FSP processing in multiple passes of the 8 mm thick EN AW 4047 (AlSi12) cast aluminum alloy.

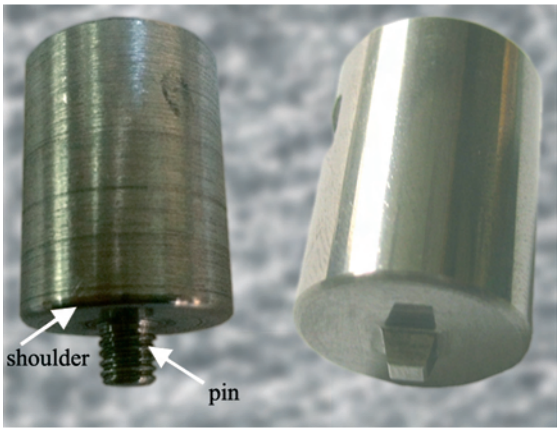


Figure 1. Processing tools used in the experimental program. a) Threaded cylindrical pin tool; b) Conical pin tool with 4 flat bevels.

The FSP processing tools were made of C45 steel treated at ca. 42-46 HRC (Figure 1a), as well as sintered tungsten carbide type P20S (Figure 1b), having pin length L_{pin}=5 - 6mm and smooth shoulder with diameter $Ø_{shoulder}$ = 20 - 22 mm.

3. Experimental program

The experimental program of friction stir processing in multiple passes of the 8 mm thick aluminum alloy EN AW 4047 (AlSi12) was performed on the FSW 4-10 welding machine from ISIM Timisoara (Figure 2) using the processing tools of Figure 1. Successive passes were carried out under identical conditions of experimentation with respect to the process parameters.

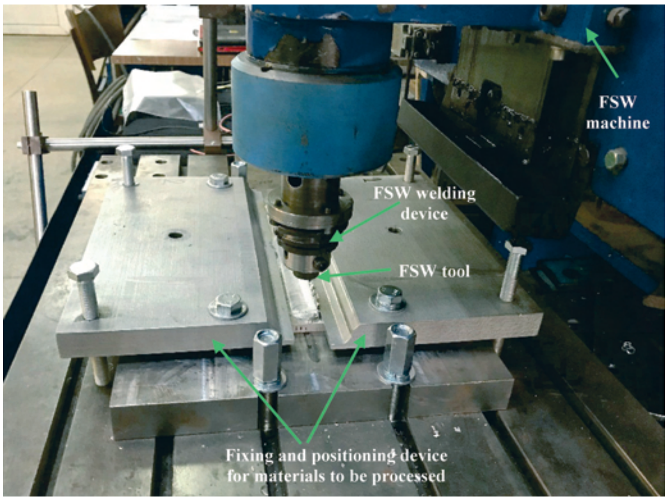


Figure 2. FSW welding machine and related elements.

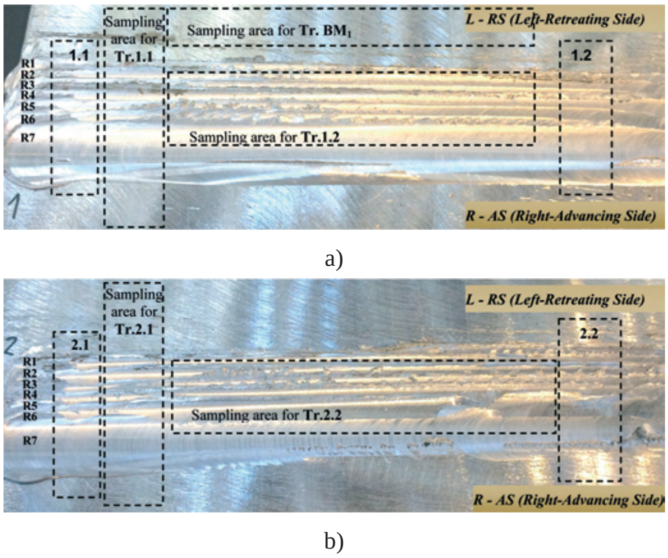


Figure 3. Surface aspect of the processed material and sample drawing plan: a) Exp. 1, b) Exp. 2.

Friction stir processing experiments, in multiple passes, for EN AW 4047 (AlSi12) cast aluminum alloy having the dimensions 200mm x 300mm x 8mm were performed with the technical data presented in Table 2.

The FSP processing tools used in these experiments were shown in Figure 1 and were made in its own design, as follows:

- M6 threaded cylindrical pin tool - made of C45 steel, treated at approx. 42-46 HRC, with shoulder diameter $Ø_{shoulder}$ = 22 mm and pin length L_{pin} = 6 mm.
- Conical pin tool with four plane bevels - made of P20S tungsten sintered carbide, with shoulder diameter $Ø_{shoulder}$ = 22 mm and pin length L_{pin} = 5 mm.

According to Table 2, the process parameters used in the FSP processing experiments (seven passes having partial overlapping, with step p = 4 mm) were: tool rotational speed n = 1450 rpm, horizontal displacement speed of the tool on the material to be processed v = 150 mm/min, the sense of rotation being anti-clockwise.

The aspect surface of the processed material and the specimen sampling plane for the above experiments is shown in Figure 3 a, b.

Figure 3 shows the aspect of successive processing with a partial overlapping of the processed rows with step p = 4 mm (step - determined in correlation with the tool pins dimensions). The step has been established so that the processing of the material in the pin tool action zone to have continuity, thus avoiding the occurrence of unprocessed material areas (between passes).

4. Results. Discussions

For the evaluation and characterization of the processed materials (macroscopic and microscopic analyzes, harnesses), specimens were taken from the FSP processed material for each experiment. Two specimens were taken for macroscopic, microscopic and hardness measurements, as well as specimens for tensile testing (perpendicular to the process area, as well as longitudinal to the process area).

The macroscopic appearance of samples taken for FSP experiments on the cast aluminum alloy EN AW 4047 (AlSi12) is shown in Figure 4.

Analyzing the processed materials, from macrostructures point of view, it can be observed that:

- *at Exp. 1:*
  - for both samples (1.1 and 1.2), in the processed area, under the influence of the FSP tool, the nugget is well consolidated for each pass (rows R1-R7), characteristic for friction stir processing (Figure 4a, b);
  - the material flow lines around the pin of the processing tool (Figure 4 a) are observed in section;
  - the macroscopic appearance is clean, without defects, with the well-defined and consolidated processed area, the successive passes being well-highlighted (Figure 4a, b).

This is mainly due to the correct setting of the technological parameters, respectively of the step between successive passes - 4mm. The processed area is compact due to overlapping on a larger volume of the processed areas at each pass.

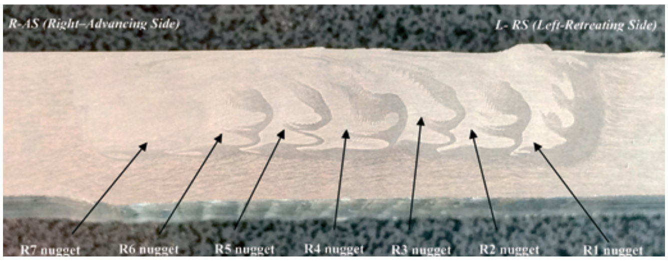
- *at Exp. 2:*
  - for sample 2.1, sampled at 15 mm from the beginning of the FSP process, the processed area under the influence of the FSP tool, the well-defined nugget for each pass (R1-R7 rows), are clearly observed. It also shows how the material is engaged in the joint as well as the flow lines (Figure 4c);

Table 2. Technical data for FSP experiments, in multiple passes - EN AW 4047 (AlSi12) cast alloy

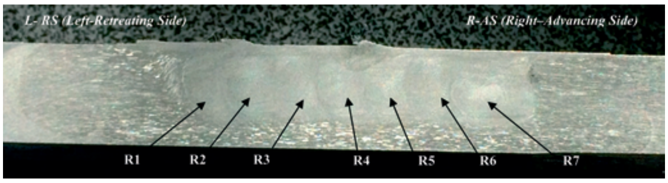
Experiment No.	Base material	Processing tool				Process parameters		
		Material	Pin type	Shoulder diameter [mm]	Pin length [mm]	Rotational speed, n [rot/min]	Processing speed, v [mm/min]	Rotation sense
1	EN AW 4047 cast alloy (s = 8 mm)	C 45	M6 threaded cylindrical pin	22	6	1450	150	counter-clockwise
2		P20S	Conical pin with 4 flat bevels	20	5			

- for sample 2.2, sampled to the end part of the processed length, channel type defects with small dimensions (area A) have been formed in the R5 and R6 rows area, as well as a large "channel" defect at the end of the last processed row, R7, near the keyhole (Figure 4d). These defects may be due to the use of another type of processing tool (with 4 flat bevels) smaller in diameter than the previous one. The FSP tool type chosen for this experiment may not be the optimal one. The size of this type of defect has increased at the last pass. This type of defect may have occurred similarly to the previous rows, but by applying the processing in successive passes with partial overlapping, the amount of these defects is reduced by mixing the material (from row to row).

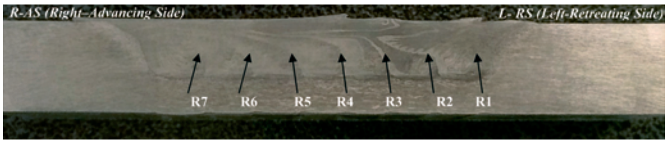
Monitoring of the FSP process was carried out from the point of view of the temperature developed in the area of the processing tool shoulder. Monitoring the temperature evolution during FSP processing was performed for each pass (R1-R7). For example, Figure 5 shows the temperature evolution diagrams for the row R1 to Exp.1, respectively the row R1 to Exp.2.



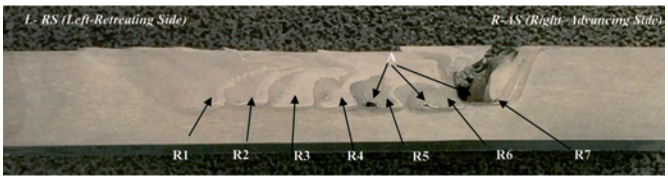
a)



b)



c)

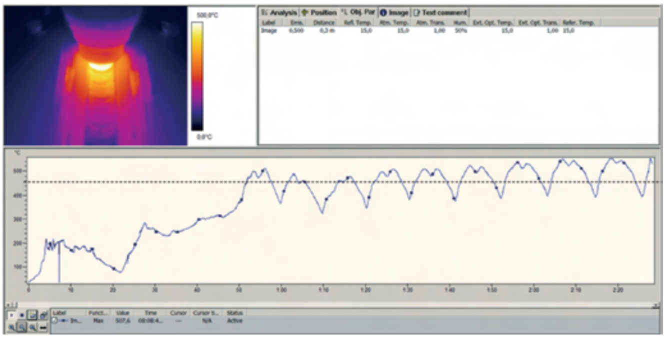


d)

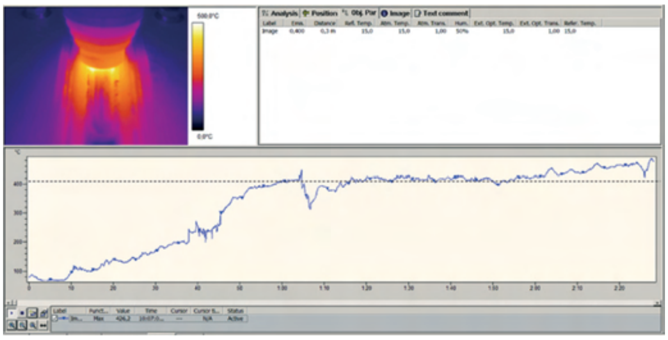
Figure 4. Macroscopic appearance of samples:
1.1 (a) and 1.2 (b) - Exp.1; 2.1 (c) and 2.2 (d) -Exp.2.

The analysis of the temperature evolution in the experiments for the FSP processing of the cast aluminum alloy EN AW 4047 (AlSi12) revealed the following aspects:

- when using the threaded cylindrical pin M6, the temperature measurements showed that:
  - maximum temperatures of the R1 - R7 rows have values in the range 540 - 580°C;
  - average temperatures for the R1 - R7 rows have recorded values in the range 450 - 500°C;
  - the average temperature values of the 7 processed rows is 471°C.
- when using the conical pin with four bevels, the temperature measurements showed that:
  - maximum temperatures of the R1 - R7 rows have values in the range of 390 - 480°C;
  - average temperatures for the R1 - R7 rows have recorded values in the range 320 - 440°C;
  - the average temperature values of the 7 processed rows is 393°C.



R1- Exp. 1 (T_{R1max} 540°C, $T_{R1average}$ ~ 460°C)

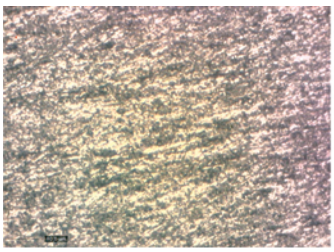


R1-Exp. 2 (T_{R1max} ~ 480°C, $T_{R1average}$ ~ 410°C)

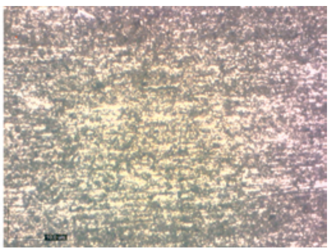
Figure 5. Evolution of temperature during FSP processing

The lowest average process temperature (320°C) was recorded when using the conical pin tool with four flat bevels. This is due to the constructive solution of the pin tool, its edges acting as a cutting tool (it is easier to displace the material to be processed, reduce the friction forces and thereby lowering the process temperature).

Figure 6 shows, for example, the microstructural appearance for the base material BM and the material from the processed area (Experiment 1).



a)



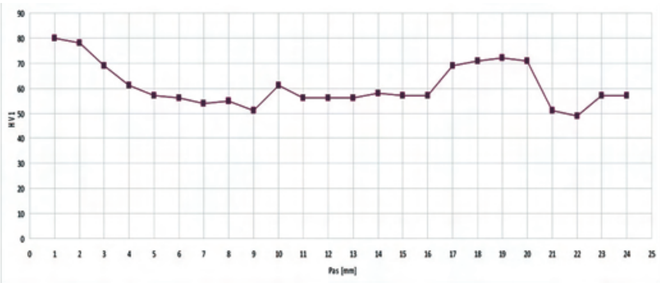
b)

Figure 6. Microstructural appearance:
a) BM base material; b) Processed area.

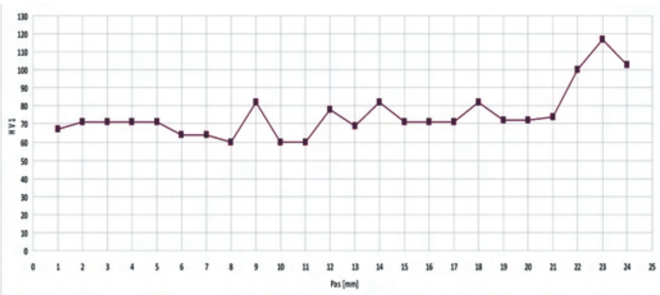
Microstructure analysis was performed for each processed row of the experiments. Microstructures for each of the processed rows were found to be similar. Compared to the base material BM, grains finishing and microstructural homogenization have been obtained.

The HV1 hardness measurements were made horizontally on a line located at 2.5 mm below the top surface of the material to be processed, the distance between the measuring points being 2 mm.

Figure 7 shows the graphs with the cross-section hardness distribution for Exp.1 and Exp.2.



a)



b)

Figure 7. Hardness graphs HV1 – FSP processing of AlSi12 aluminum alloy :a) Exp. 1; b) Exp. 2.

Sclerometric analysis allowed the following assessments:

- hardness measured on the BM have values in the range 78-117 HV1, the average value being ~95 HV1;
- when using the threaded cylindrical pin, the average hardness value in the processed area was ~59HV1, representing ~62% of the BM hardness;
- the maximum hardness value of the processed area was 72 HV1, for Exp.1;
- when using the conical pin tool with four bevels, similar phenomena to the previous case were recorded, the average hardness being ~62 HV1, which represent ~65.2% of the BM hardness.

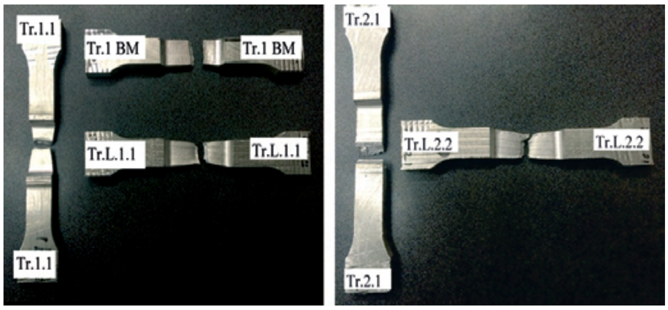
Test specimens were taken from the base material to perform the mechanical tensile test (Tr.1BM specimen) and from the processed area, respectively, perpendicular to the processing direction (Tr.1.1 and Tr.2.1 specimens) and longitudinally along the processing direction Tr.L.1.1 and Tr.2.2.2). The appearance of the samples after the mechanical tensile test is shown in Figure 8.

After the mechanical tensile tests of the specimens, the following values for mechanical strength have been obtained:

- base material - AlSi12 cast aluminum alloy - Rm = 180N/mm^2
- for samples taken in cross-section of processed material - $Rm_{1.1}$ = 166N/mm^2, $Rm_{2.1}$ = 181N/mm^2
- for samples taken on the longitudinal direction of the processed material - $Rm_{L1.1}$ = 171N/mm^2, $Rm_{L.2.1}$ = 187N/mm^2

It was found that the tensile strength values are higher by ~3% on the longitudinal samples taken on the processing direction, compared to those taken transversely to the processing direction.

When using the tool with pin having four bevels, Rm tensile strength values are higher than when the threaded cylindrical tool was used, both for Rm comparisons for cross-sectional specimens and for specimens taken in the longitudinal direction. Better resistance obtained for Exp. 2 may be due to the much lower process temperature developed in this case (the process temperature for Exp. 2 was on average by ~ 100°C lower than for Exp.1).



a) Exp.1 b) Exp. 2

Figure 8. Aspect of samples after mechanical tensile tests - EN AW 4047 processed material and BM (Exp.1, Exp.2).

The bending test pursued the determination of the plastic deformation capacity of the material after FSP processing, compared to the base material BM. It has been found that the plasticity of the cast base material is very low, the bending angle at which the breakage occurs is only 12-14 °. In the case of FSP processed surfaces, the results of the bending test showed an increase in the bending angle to break up to 180 °, resulting in a complete bending (Figure 9).

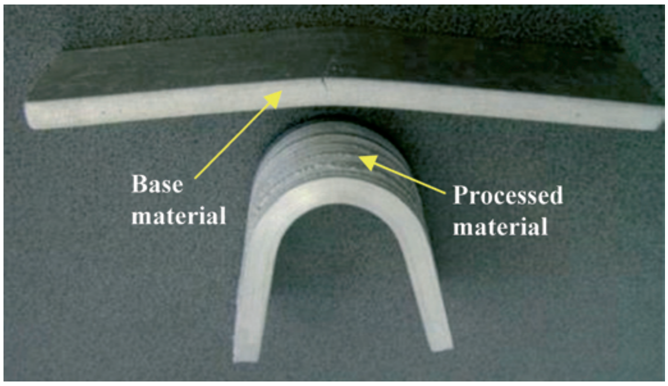


Figure 9. Bending test for BM and for the processed material - EN AW 4047 cast alloy.

The experimental results have demonstrated that by applying FSP processing to the cast aluminum alloy EN AW 4047 (AlSi12), local changes in the characteristics of the base material can be obtained and these can be exploited in concrete applications according to specific requirements (degree of deformability, hardness).

5. Conclusions

The experimental program consisted in the successive FSP processing, in multiple passes, of the cast aluminum alloy EN AW 4047 (AlSi12) in order to obtain extensive processed areas with well-defined properties in relation to the base material.

Good results were obtained when using the M6 threaded cylindrical processing tool, the process stabilizing at ~100mm from the beginning of the tool action on the BM.

When using a conical pin tool with four flat bevels, obtaining a defect-free area is dependent by the pressing force of the tool's shoulder on the base material BM and is reflected by its depth of penetration into the base material. The experiments demonstrated that at a penetration of the tool shoulder in BM at depth h≥0,7mm, no defects were formed in the processed area.

In all experiments, process temperature records were made using the infrared thermographic technique. Due to the geometric characteristics, the lowest average process temperatures were recorded when use the conical pin tool with four bevels (in this case the friction phenomenon was also accompanied by the cutting phenomenon).

Macro and microstructural analysis, sclerometric analyzes were performed. In all cases, it was observed that under the action of the FSP tool and the process dynamics there was a "burst" of the coarse grains specific to the cast alloys and much more homogeneous microstructures made of fine grains have been obtained.

By applying the FSP processing to the cast aluminum alloy EN AW 4047, a degree of maximum deformability was obtained (when the base material at the bending test breaks at an angle of ~12-15°), as well as an increase in break elongation (tensile) on the processing direction, as appropriate, with maximum 25%.

Depending on the nature and requirements of the application, experiments have demonstrated that the FSP processing can be successfully applied to the cast aluminum alloy EN AW 4047 (AlSi12). Spectacular changes in the properties of the base material can be achieved particularly in terms of improving the degree of deformability.

Acknowledgements

The paper was elaborated on the basis of the results obtained within the project PN 18.33.02.01 entitled "Research on the development of innovative and ecological technologies for the processing of cast metallic materials from the category of aluminum alloys used in industrial applications, using friction stir processing", financed by the Ministry of Research and Innovation, in the frame of Nucleu Program of ISIM Timisoara (contract 17N / 2018).

References

[1]. Mishra, R.S., Mahoney, M.W – „Friction Stir Welding and Processing", ASM International, The Materials Information Society, Ohio, USA, 2007

[2]. Chun Yip Chan – "Friction stir processing of Aluminum-Silicon Alloys", PhD Thesis, The University of Manchester, UK, 2011

[3]. Weglowski, M.S. – "Friction stir processing - State of the art", Archives of Civil and Mechanical Engineering, Vol.18, Issue 1, pp114-129, January 2018

[4]. Adrian Alexandru – „Metalurgie fizică 2", ISBN 973-702-180-0 Editura Tehnopress, Iaşi, 2005.

[5]. Elliot, R.–"Eutectic Solidification Processing Crystalline and Glassy Alloys", London, Butterworth, 1983

[6]. Barnes, S.J., Lades, K. – "The evolution of aluminium based piston alloys for direct injection diesel engines", Federal-Mogul Power Cylinder Systems Company, 2001

[7]. Edwards, W.M. – "Microstructural and mechanical property modelling for the processing of Al-Si alloys", PhD thesis, Institute of Polymer Technology and Materials Engineering, Loughborough University, 2002