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Thermite Welding

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Abstract

Paper contains some experimental results on quantitative metallographic analysis of welded structures through aluminothermic process. Paper presents the measurements performed to determine the proportion of pores and inclusions, the proportion of pearlite and ferrite, established by phase quantitative analysis. It also presents the results of quantitative analysis of grain size, assessed in accordance with standard ASTM E 112:96.

Key words: *thermite welding, metallographic analysis.*

Introduction

Thermite welding or aluminothermic welding is an effective, highly mobile method of joining heavy section steel structures such as rails. It is a fusion welding process in which heat source is the heat released by the exothermic chemical reaction from thermite burning.

Thermite is a pyrotechnic composition of a metal powder and a metal oxide that produces an exothermic oxidation-reduction reaction known as a thermite reaction. If aluminum is the reducing agent it is called an aluminothermic reaction.

The most common composition is the iron thermite. The oxidizer used is usually either iron (III) oxide or iron (II,III) oxide. The latter is easier to ignite, likely due to the crystal structure of the oxide.

After ignition of the mixture, combustion is extremely violent spreading into entire mass of thermite [1]. The thermite reaction can be described by the chemical equation below [1]:

$$3\,FeO + 2\,Al \Rightarrow Al_2O_3 + 3\,Fe + 741{,}4 \text{ kcal/kg thermite;}$$
$$Fe_2O_3 + 2\,Al \Rightarrow Al_2O_3 + 2\,Fe + 944{,}4 \text{ kcal/kg thermite ;}$$
$$3\,Fe_3O_4 + 8\,Al \Rightarrow 4\,Al_2O_3 + 9\,Fe + 879{,}7 \text{ kcal/kg thermite.}$$

The products are aluminum oxide, free elemental iron, and a large amount of heat. The reactants are commonly powdered and mixed with a binder to keep the material solid and prevent separation. Commonly the reacting composition is 5 parts iron oxide red (rust) powder and 3 parts aluminum powder by weight, ignited at high temperatures. A strongly exothermic (heat-generating) reaction occurs that via reduction and oxidation produces a white hot mass of molten iron and a slag of refractory aluminum oxide. The molten iron is the actual welding material; the aluminum oxide is much less dense than the liquid iron and so floats to the top of the reaction, so the set-up for welding must take into account that the actual molten metal is at the bottom of the crucible and covered by floating slag.

The principle of the thermite welding is illustrated in figure 1 [2]:

Fig. 1. Thermite welding [2]

For welding, the area around the joint is inserted into crucible, made from refractory material. When the crucible is made up, it is considered to have sufficient space for the melted metal and slag, respectively for the gas evaporation. Melted products are introduced through a special channel, built in the bottom of the form, where they lift gradually, filling the entire space of the crucible.

The thermite burning is done in crucible, the mixture ignition can be achieved with an electric arc or a special primer. When the ignition occurs, the thermite must be dry, because water can cause splashing or explosion.

Thermite welding is widely used to weld railway rails [3]. The weld formed has higher mechanical strength than other forms of weld, and excellent corrosion resistance. It is also highly stable when subject to repeated short-circuit pulses, and does not suffer from increased electrical resistance over the lifetime of the installation. However, the process is costly relative to other welding processes, requires a supply of replaceable moulds, suffers from a lack of repeatability, and can be impeded by wet conditions or bad weather (when performed outdoors).

Experimental Determinations

Quantitative metallographic analysis of a joint welded through aluminothermic process

Metallography is the study of metals by optical and electron microscopes and it serves both, research and industrial practice. With optical microscopy, the light microscope is used to study the microstructure; optical illumination systems are its basic elements. For materials that are opaque to visible light (all metals, many ceramics and polymers) only the surface is subject to observation, and the light microscope must be used in a reflective mode. Contrasts in the image produced result from differences in reflectivity of the various regions of the microstructure [4].

Microscopy can give information concerning a material’s composition, previous treatment and properties. Particular features of interest are:
- grain size

- phases present
- chemical homogeneity
- distribution of phases
- elongated structures formed by plastic deformation

The microscopic metallographic analysis conducted in this paper, aimed towards the characterization of the thermite-steel prototype as a distinct entity and the tramway aluminothermic welds.

Generally, a tram or railway rail consists of three parts [5]:
- upper-called head, which contains about 45% of rail material;
- bottom-called foot, which contains about 35% of rail material;
- the intermediate-called web, with about 20% of the material.

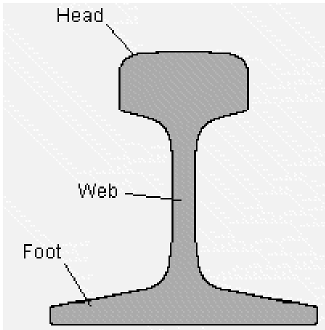


Fig. 2. Rail parts

Studies and experimental research on aluminothermic welds of some tram rails, focused on:
- Quantitative analysis of pores and inclusions
- Quantitative phase analysis
- Grain size measure.

To create contrast between the elements of the metal's microstructure, chemical solutions known as etchants are used to selectively corrode some of those elements, which show up as darker regions.

This is possible because differences in the composition, structure or phase of a metal will create electrochemical potentials that alter the relative rates of corrosion when exposed to an etchant [6].

In our studies we have used as metallographic etching a solution of nital (2 ml HNO_3 in 98 ml methanol), knowing as nital reveals austenite grain boundaries and other phases in plain iron and most steels.

We have highlighted three areas, well defined in the welded material, they standing out after the attack with metallographic agent, as follows:
- Weld Bead (WB)
- Heat-affected zone (HAZ)
- Parent/base metal (BM)

To perform a more accurate metallographic analysis, were taken samples in cross-section of each distinct area.

After microscopic analysis accomplishment, were issued analysis reports for each of the three areas (WB; HAZ; PM). The results of these reports were correlated, interpreted to obtain a variation of the inclusions, phase and grain size in head, web and foot.

Analyses were performed in the Laboratory of Optical & Electronic Microscopy of the Polytechnic University of Bucharest.

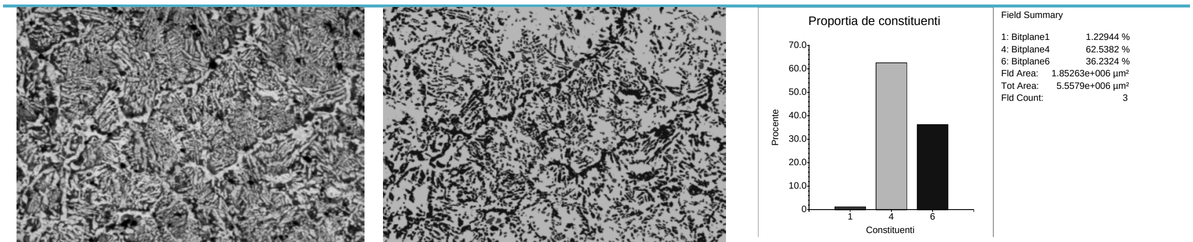
Quantitative phase analysis

Quantitative phase analysis was performed on three areas: head, web and foot, in weld, heat-affected zone and parent/base material.

Parameters considered in the analysis achievement were following:

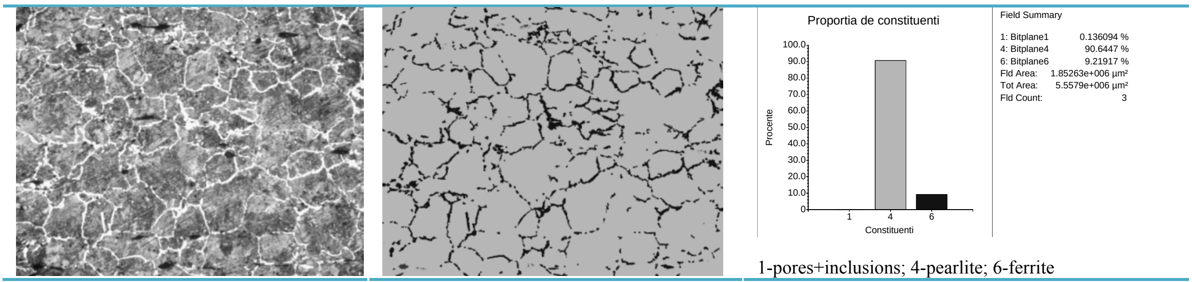
- pore & inclusions proportion
- pearlite proportion
- ferrite proportion.

These results are shown in the optical micrographs in the figures, below. In Figures 3, 4 and 5 the optical micrographs of the active area of the rail, respectively the head, are shown.



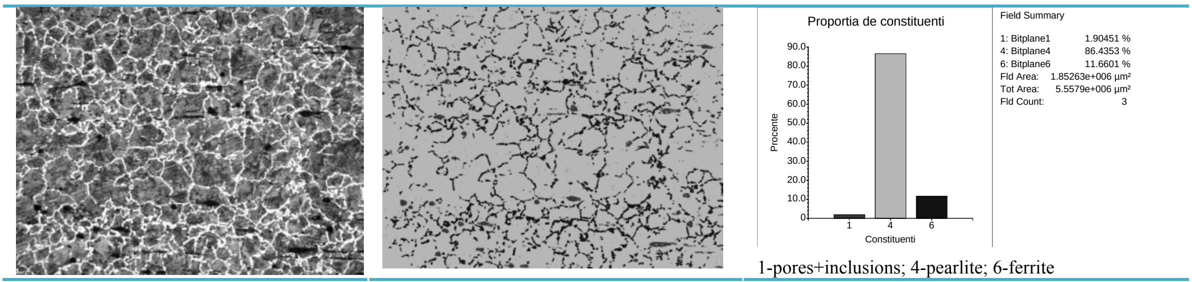
1-pores+inclusions; 4-pearlite; 6-ferrite

Fig. 3. Optical micrographs head-WB (10X)



1-pores+inclusions; 4-pearlite; 6-ferrite

Fig. 4. Optical micrographs head-BM (10X)



1-pores+inclusions; 4-pearlite; 6-ferrite

Fig. 5. Optical micrographs head-HAZ (10X)

In Figures 6, 7 and 8 the optical micrographs of the middle area of rails, so called web, are presented. The following figures show the captured images and the ones processed of the optical micrographs, made in the foot rail, as well the proportion of constituents.

By examining the optical micrographs carried out in our studies and research on the thermite welding, the followings have been found:

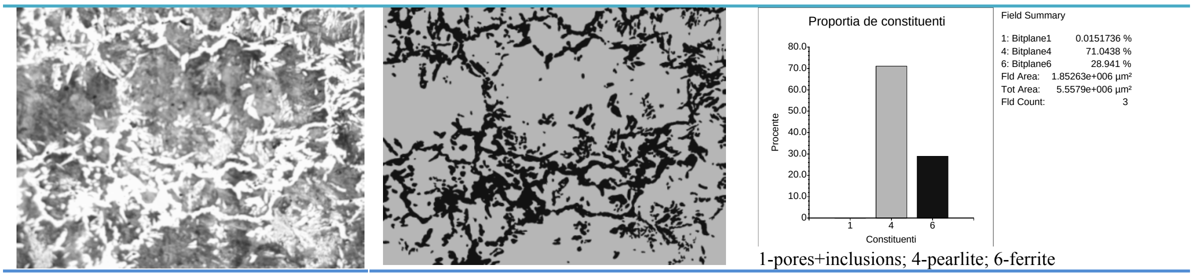


Fig. 6. Optical micrographs web-WB (10X)

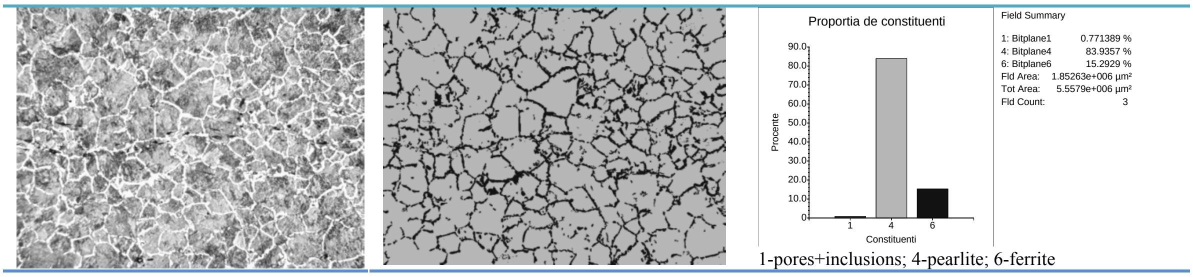


Fig. 7. Optical micrographs web-BM (10X)

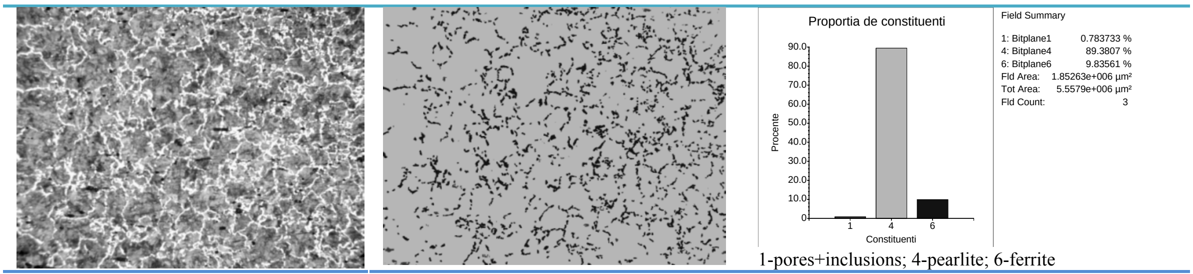


Fig. 8. Optical micrographs web-HAZ (10X)

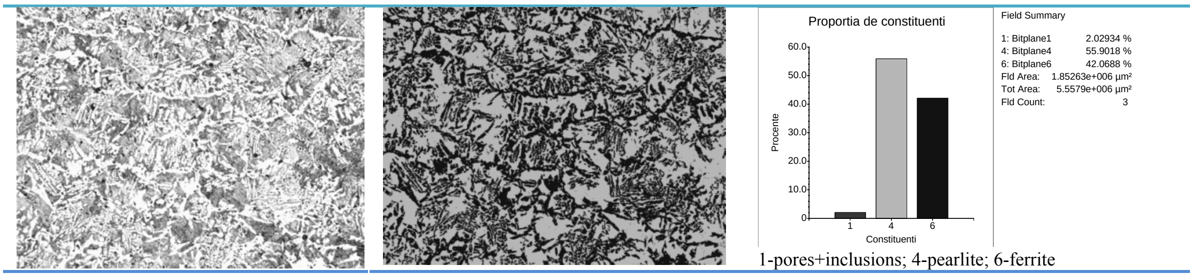


Fig. 9. Optical micrographs foot-WB (10X)

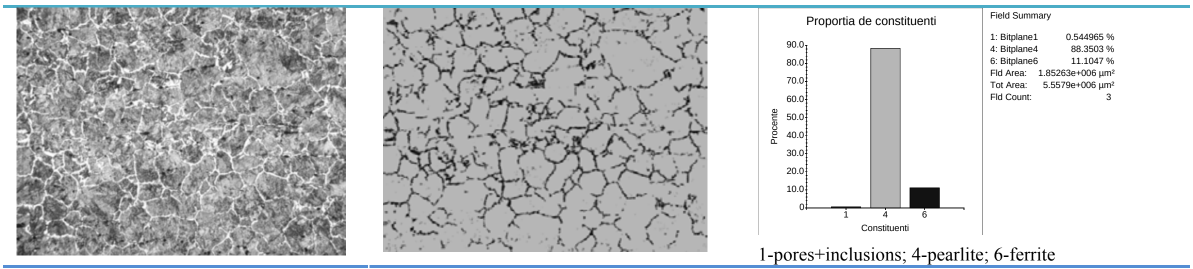
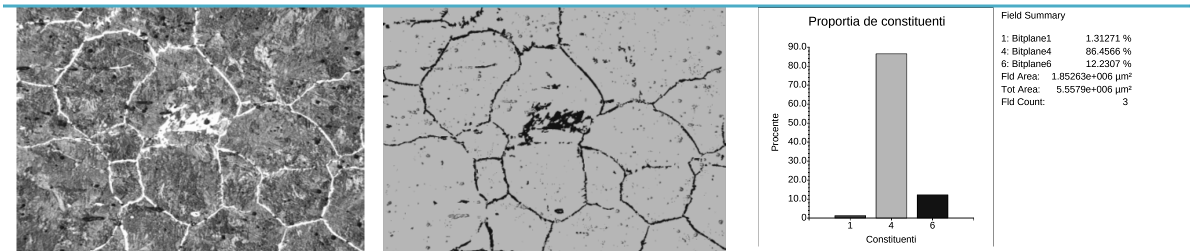


Fig. 10. Optical micrographs foot-BM (10X)

In the bead weld, the ferrite proportion is at a maximum level, compared to heat-affected zone and base material; the value recorded varies between 36% and 55%. The ferrite distribution on the section of the weld bead is irregular and random, depending on how the ferrite plates have grown among the pearlite grains during solidification.



1-pores+inclusions; 4-pearlite; 6-ferrite

Fig. 11. Optical micrographs foot-HAZ (10X)

In the transition area the proportion of the ferrite drops considerably, placing around the value of 11 %. Its distribution is more uniform and a low tendency to form acicular ferrite. In the metal base, the proportion of the ferrite is stabilized at approximately 9 %.

The high proportion of ferrite in the weld bead, as well as its irregular distribution is due to inhomogenity of the melt before solidification. Structural heterogeneity both on section and height is due to inhomogeneity of the thermite-steel.

We have also observed an orientation in bands of acicular ferrite and pearlite by the advancing direction of the solidification front, respectively oblique in head and foot and horizontal predominately in the web. Decreasing the proportion of ferrite on vertical flange from foot area to head and the great variation of the wall section between foot, web and head, which induces considerable variation in the solidification rate, it may be due to direct strong carbon segregation and inverse segregation of manganese.

Concerning pores and inclusions, they recorded very low values up to 1%. Pores and inclusions are considered weld defects, pores being much more serious defects because they develop internal fatigue cracks and offer easy crack propagation path. Source of porosity in thermite welds are dissolved gases in molten metal.

Quantitative analysis of grain size

In the metallographic laboratory, analyzing grains in metallic and alloy samples is important for quality-control. Most metals are crystalline in nature and contain internal boundaries, commonly known as "grain boundaries". When a metal or alloy is processed, the atoms within each growing grain are lined up in a specific pattern, depending on the crystal structure of sample. With growth, each grain will eventually impact others and form an interface where the atomic orientations differ. It has been established that the mechanical properties of the sample improve as the grain size decreases. Therefore, alloy composition and processing must be carefully controlled to obtain the desired grain size [7].

Highlighting methods and determination of grain size in steels are provided by ASTM E112-96, this method being used in the measurements carried out in our studies, which followed [8]:

- tendency to grains growth and its kinetics at heating, steel susceptibility to overheating and hot plastic deformation respectively;
- real grain size after deformation and heat treatment knowing that a real fine grit determine good mechanical resistance to cold, plasticity, toughness, fatigue resistance, while, a coarse grained favors a hot strength [5].

The images obtained by the image-contrast analysis for the three parts of the rail (head, web, foot) are shown in Figures 12-20.

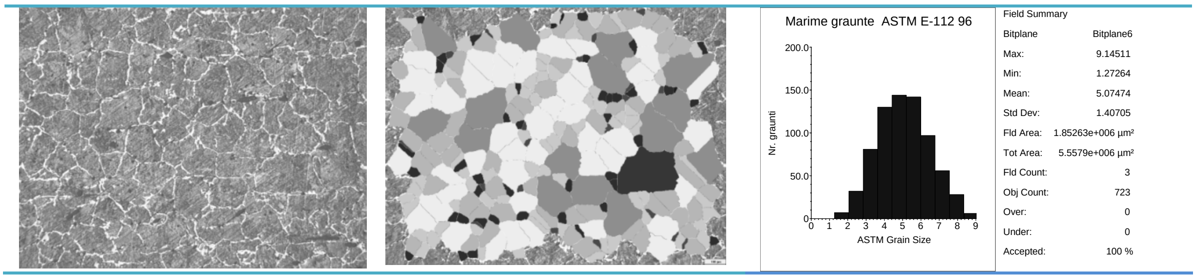


Fig. 12. Grain-size head-WB (10X)

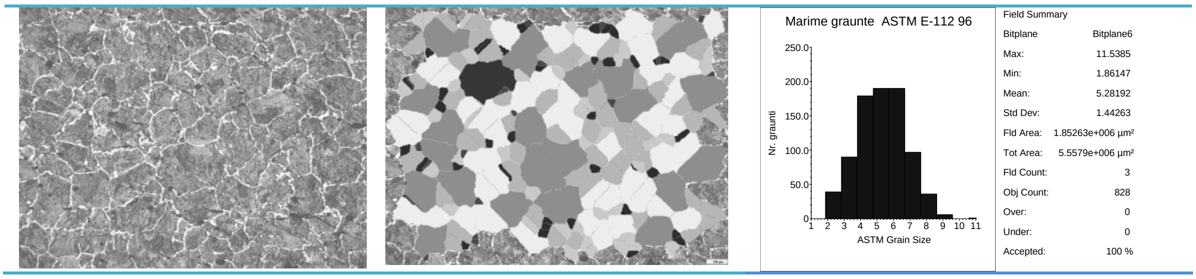


Fig. 13. Grain-size head-BM (10X)

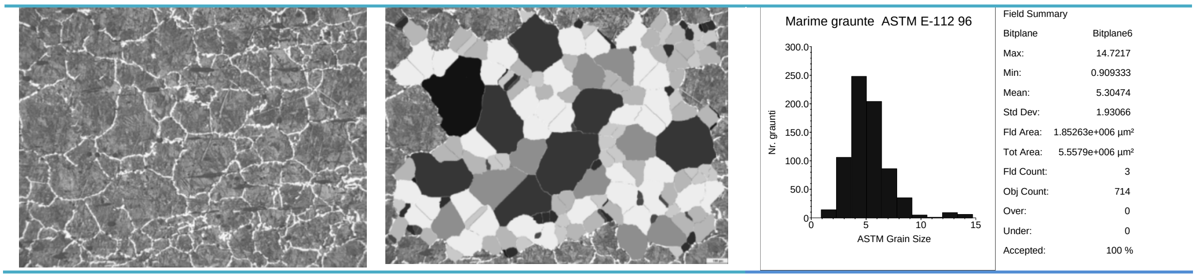


Fig. 14. Grain-size head-HAZ (10X)

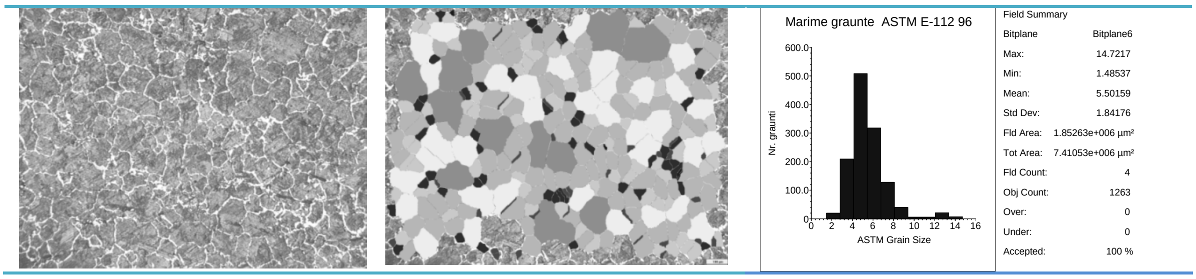


Fig. 15. Grain-size web-WB (10X)

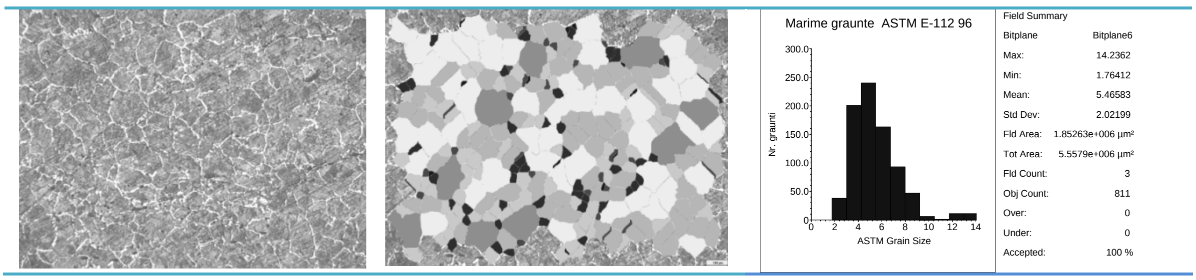


Fig. 16. Grain-size web-BM (10X)

Studies achieved to measure the grain size showed that average grain size, according to ASTM-112:96, is approx. 5.5, what for a casting is a normal size.

In the head area there is a relatively uniform distribution of the grain size, where the solidification conditions are close to one homogeneous (at the top and bottom of the head).

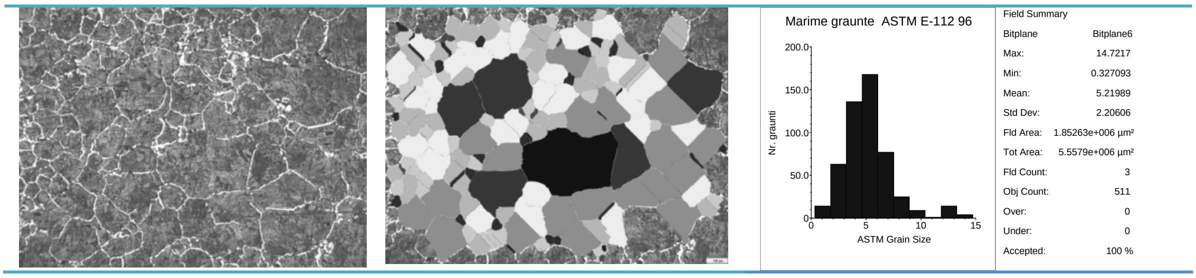


Fig. 17. Grain-size web-HAZ (10X)

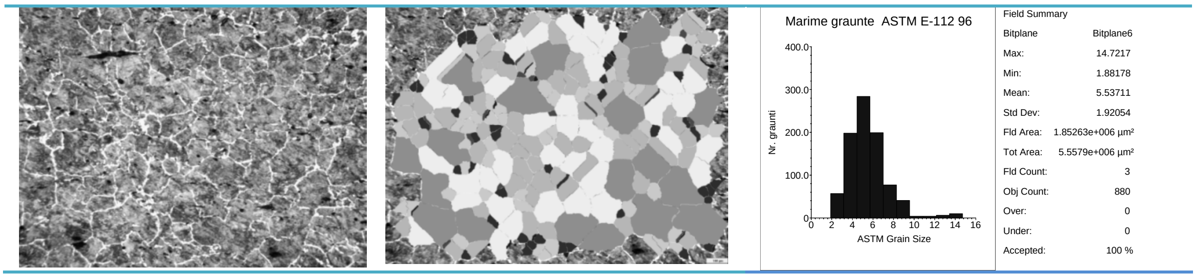


Fig. 18. Grain-size foot-WB (10X)

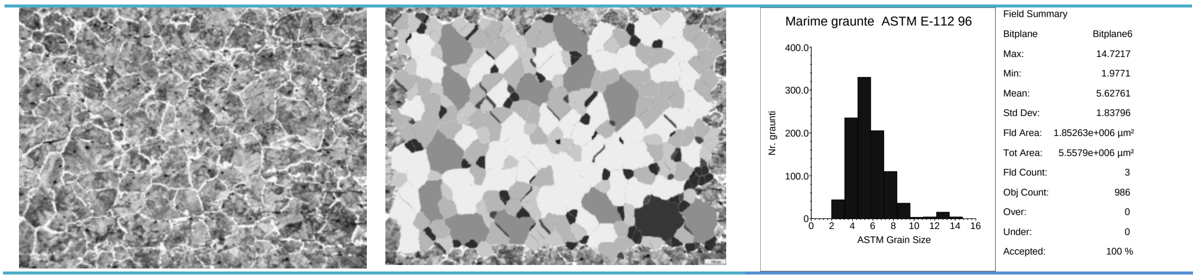


Fig.19. Grain-size foot-BM (10X)

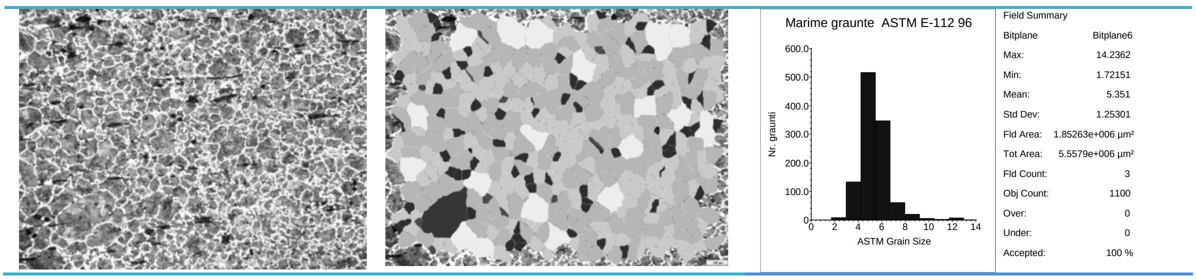


Fig. 20. Grain-size foot-HAZ (10X)

In the area where the solidification rate is very small and it is not guided, the structure consists of non-uniform grain. In the area with guided solidification both grain size and grain distribution have values close to the base metal. Most unevenness of the grain size is recorded in the area with thin walls (web) and respectively, in transition zone.It is estimated that less resistant material that will be in the transition area, from heart, where is the maximum degree of unevenness.

Conclusions

The studies and experimental research on aluminothermic welds, accomplished in this paper, focused on general characterization of the thermite-steel prototype, as a distinct entity and characterization of the thermite welding by metallographic analysis. Metallographic analysis has been performed in three points of welding material: weld bead, base metal and heat affected zone and in three areas of welded rail: head, web and foot.

The methods used for the study were the following:
Quantitative Phase Analysis applied to determine the proportion of pores and inclusions as well as the proportion of ferrite and pearlite;

- Optical micrographs show that the largest proportion of ferrite is found in the weld bead compared to base metal and transition zone.
- The high proportion of ferrite in the weld bead, as well as its uneven distribution is due to insufficient homogeneity of the melted metal before solidification.
- Structural heterogeneity both on section and height is due to inhomogeneity of the thermite-steel.

Quantitative analysis of grain size, according to ASTM E112:96

- Grain size is within normal limits specific for a casting.
- Optical micrographs reveal that the grain size distribution is uniform, where solidification condition is close to one homogeneous; maximum degree of unevenness is found in the transition zone of the web, where the material is the least resistant.

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Sudarea aluminotermică

Rezumat

Lucrarea conține unele rezultate experimentale privind analiza metalografică cantitativă a structurilor sudate prin procesul aluminotermic. Sunt evidentiate măsurătorile efectuate pentru determinarea proporției de pori si incluziuni, a proporției de perlită şi ferită, prin analiză cantitativă de fază. Lucrarea prezintă, de asemenea, rezultatele analizei mărimii de grăunte, evaluate în conformitate cu standardul ASTME 112:96.