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# Experimental Study of Mechanical Behavior and Microstructural Benchmarking Between the Rail and The Thermite Weld

Fatima Sidki[1], Ilias Mouallif[1], Abdelhamid El Amri[1], Mustapha Boudlal[2] and Abdelkader Benali[1]

[1]Laboratory of Control and Mechanical Characterization of Materials and of Structures, National School of electrical and mechanical, Hassan II University, El Jadida road, BP 8118 Oasis Casablanca, Morocco.

[2]Higher Institute of Maritime Studies, Hassan II University, El Jadida road, BP 8118 Oasis Casablanca, Morocco.

**Abstract:** - The kingdom of Morocco has become the first African country to adopt a high-tech rail infrastructure, for the mega (giant) project “Morocco High Speed Train” (TGVM). Reducing the noise levels of rail traffic is an extremely important issue for the environment and for rolling stock as well. Therefore, research and development in this field in Morocco is very important. The elimination of rail joints is a crucial factor in the reduction of rail noise. The junctions of rails in the railways should be designed in a way to obtain a great continuity of the raceway. Currently, the rails connections are made by two methods: (1- Resistance welding) and (2- aluminothermic welding). The second method is considered the most reliable in Morocco’s railways. For this purpose, this paper aims to present a set of experimental studies of mechanical behaviour, where various samples are recorded from base metal zones and areas of thermite weld. These samples are taken from broken rails that have been used in service. After the benchmarking a microstructural differences have been identified by the optical microscope and the scanning electron microscope between the area of the base metal and the rail thermite weld.

**Keywords: -** Rail, thermite weld, mechanical behavior, microstructure, base metal, melted zone.

## I. INTRODUCTION

Historically it is known that thermite welds contain substantial micro porosity and inclusions and this is a contributing cause to their poor ductility and impact toughness [1]. Myers [1] published values for thermite weld sample tensile test percent elongation (1% to 5.6%), tensile test percent reduction in area (1.8% to 3.5%). Since the weld is actually a casting, large columnar grains are found in the microstructure and this is also a major cause of thermite welds being so brittle and tending to fracture in a cleavage mode [2]. Hauser [3] stated that the most common reasons for thermite weld failure in service are due to porosity, voids and inclusions in the weld metal, or gouges and local areas transformed to martensite during post weld finish grinding.

Currently, the rail is the most important and powerful ground transportation of passengers and goods. This evolution has occurred over more than a century, and the rail speed has increased throughout the years. However, this development of rails faces so many challenges such as the augmentation of speed, and the massive loads which should be supported by the railways.

Rail of railways is inevitably the seat of defects, these last can be initiated in their three parts: head, soul and foot, and more specifically in the welded joints [4]-[7]. However, growth may cause degradation of the material and thus lowering the comfort, resulting in more noise and increase dynamic load. They can lead to fracture of the rail [8], and it may result in derailment in some cases if it is not remedied. For this purpose, the objective of this work is to study and understand of the phenomenon of embrittlement of thermite welds, through the identification of the grain size and the presence of inclusions that promote the initiation of this phenomenon.

To complete this objective, mechanical and microstructural characterizations were carried out on the base metal zones and the areas of thermite weld. Facies control of the base metal and the weld zone are characterized by measuring their hardness and metallographic analysis using optical microscope (OM) and scanning electron microscope (SEM).

## II. THERMITE WELDING PROCESSES

The chemical reactions associated with the thermite process are highly exothermic and therefore release tremendous amounts of heat which can be used for welding. The reactions used for today's rail welding processes are between fine aluminum and iron oxide powders which are ignited in a crucible.

The most commonly used reactions are as follows [9]:

$$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 + 181.5\,kcal \quad (1)$$

$$3Fe_3O_4 + 8Al \rightarrow 9Fe + 4Al_2O_3 + 719.3\,kcal \quad (2)$$

The theoretical temperature created by the second reaction is about 5.600°F [10], but heat loss is due to non-reacting alloy additions, radiation from the crucible, etc., bring the melt temperature down to 3.500°F [9]. When the exothermic reaction in the crucible (see in Fig.1) is completed, about 20 to 25 seconds is required for separation of the slag from the molten steel. After the slag (mostly aluminum oxide) has floated to the top of the crucible, molten steel is released from the bottom of the crucible. Liquid steel pours down into the hardened sand mold which has been packed with luting sand and special paste around the two rail ends to be joined. The rail ends, which have been preheated with gas torches, are partially melted by the liquid steel as the mold fills and the weld then is allowed to cool and solidify. When the weld is solid the molds, head riser and base risers are removed and the rail head is finish ground to the proper contour for train traffic.

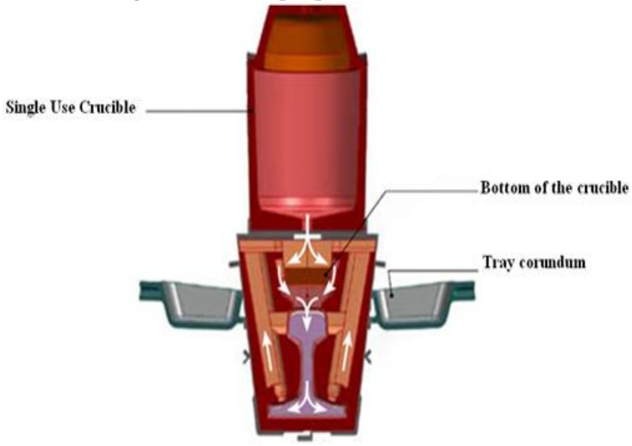


**Fig.1. :** Schema of the crucible.

Steam railroads around the world began to see the benefits of rail welding. From 1924 to 1930 the German State Railway tested thermite welded rail sections of various lengths and the Krefeld Railway in Germany made 7.000 meters of continuously welded rail [11]. Thermite welding also played an important role in the reconstruction of the German railway network after World War II. In the United States, the Central of Georgia Railroad used welded rail for tunnel trackage in 1930 and the Delaware and Hudson Railroad is credited with the first open-track installation of thermite rail welds in 1933 [11]–[13]. By 1980, it was estimated that continuous welded rail installations represented more than 80.000 miles of main track in the United States [13]. Although not all of these welds were made with the thermite process, the aluminothermic method certainly "paved the way" for rail welding. Today there are three major thermite weld manufacturers active in North America.

In Morocco, the assembly rail of railway is the thermite welding process with limited preheating (LP) (Fig.2); it is similar to the welding process SKV-F which is used in England and Australia [14]-[17]. This process is characterized by a key parameter, which is the preheating time.

This is performed for a well determined duration (five minutes), without control of the temperature obtained at the end of the sequence; it is carried out using the following equipment: a propane tank, a burner air and a pressure regulator Mano

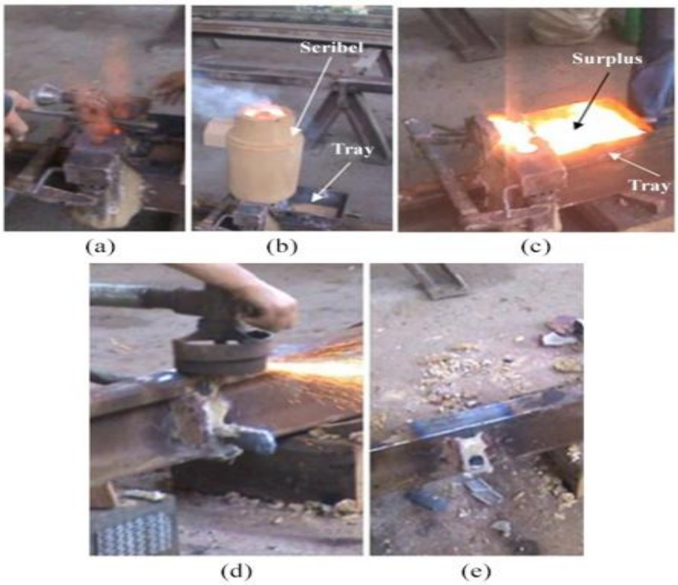


**Fig.2.** : Steps to execute a thermite weld: (a) preheating, (b) outbreak of thermite reaction, (c) solidification, (d) grinding and (e) finishing [17],[19].

## III. EXPERIMENTAL PROCEDURES AND RESULTS

**A.** Materials and chemical compositions

The materials of the rail and the thermite weld are pearlitic steel standardized by UIC (International Union of Railways). Its mass chemical compositions are presented in table 1. The samples used for the hardness test as well as those used for observation under the optical microscope are cut from a piece of rail with a weld at the central area between the soul and the rail foot.

The melted zone has a content of manganese and sulfur slightly greater than that of the base metal (1.01% and 0.049%, respectively). This difference could be the cause of the variation in hardness between the melted zone and the base metal (see Table 1).

**Table I:** Chemical composition (wt %) of the base metal (BM) and the melted zone (MZ).

| **CE*** | **C** | **Si** | **S** | **P** | **Mn** | **Ni** | **Cr** | **Al** | **Ti** |
|---|---|---|---|---|---|---|---|---|---|
| **BM** | 0.7 | 0.31 | 0.043 | 0.003 | 0.98 | 0.02 | 0.01 | 0.005 | 0.001 |
| **MZ** | 0.7 | 0.31 | 0.049 | 0.002 | 1.01 | 0.02 | 0.01 | 0.004 | 0.002 |

*: Chemical Element.

**B.** Mechanical testing of Brinell hardness

In these tests, a mechanical characterization of materials used in this study is performed using a durometre Brinell type Controlab. The diameter of the ball is in the order of 2.5 mm. The tests were carried out in the Laboratory of Public Tests and Studies (LPEE) according to EN 14 730 - 1 [18].

Hardness measurements are taken along a specimen outlet on a rail containing a weld (see Fig.3).

Figure 4 shows the results of hardness tests carried out on a line in the longitudinal direction of the rail [17].

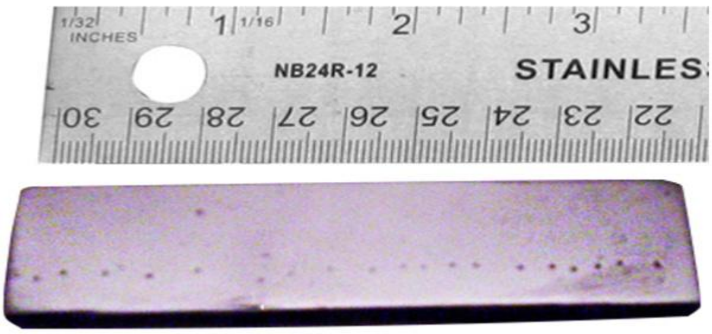


**Fig.3.** : Hardness test specimen.

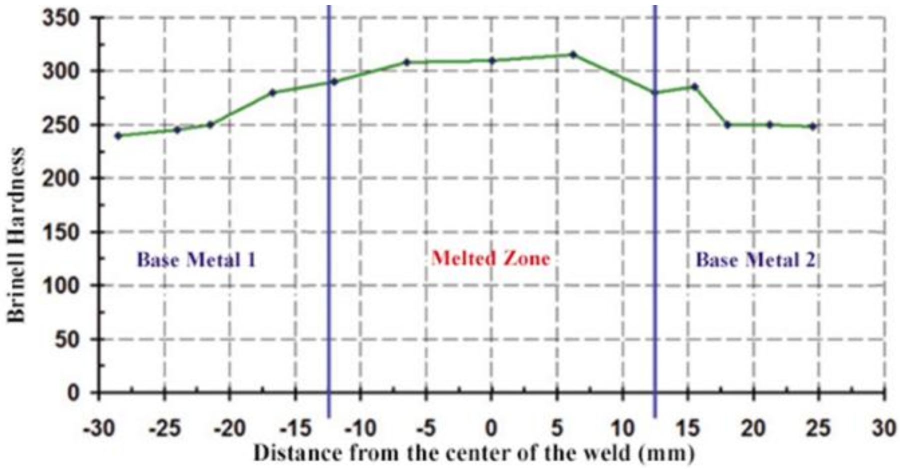


**Fig.4.** : Result of Brinell hardness test according to EN 14730-1[17].

**C.** Analysis of microstructure with optical

After polishing, the surface of the samples is subject to an acid attack with a chemical reagent which is the Nital (96% solution of ethanol and 4% nitric acid). This attack reveals the various constituents of the metal structure. These are grains having dimensions of the order of few tens of micrometers visible by optical microscopic observation, as shown in Fig. 5**.**

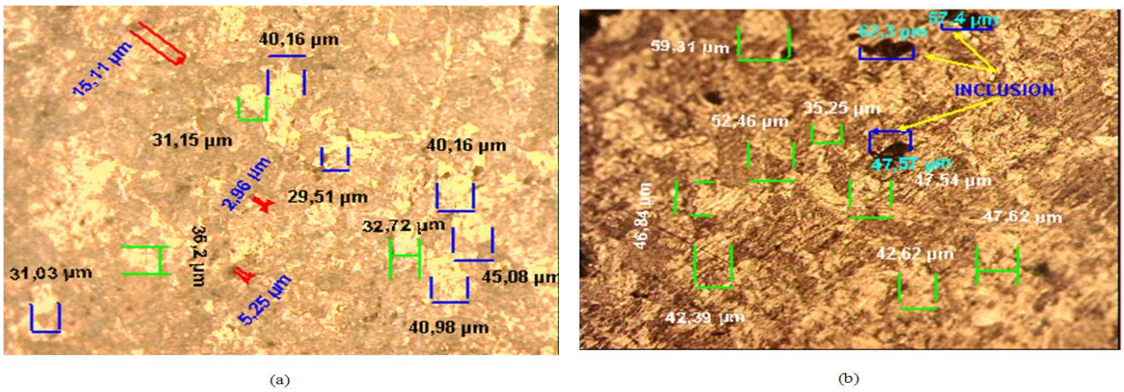


**Fig.5.** : Microstructure of: (a) the base metal. Ferrite grains are observed and (b) the melted zone with precipitated inclusions in the whole matrix (magnification: 200×)

**D.** Inspection of the microstructure with SEM

After microstructural analysis by optical microscope, other observations in the scanning electron microscope were performed on the same samples to confirm the presence of inclusions and grain coarsening in the melted zone compared to the base metal.

Figure 5 illustrates microscopic observations of the order of 100 µm for two samples one of the base metal (Figure. 6a) and the other of the melted zone (Figure. 6b).

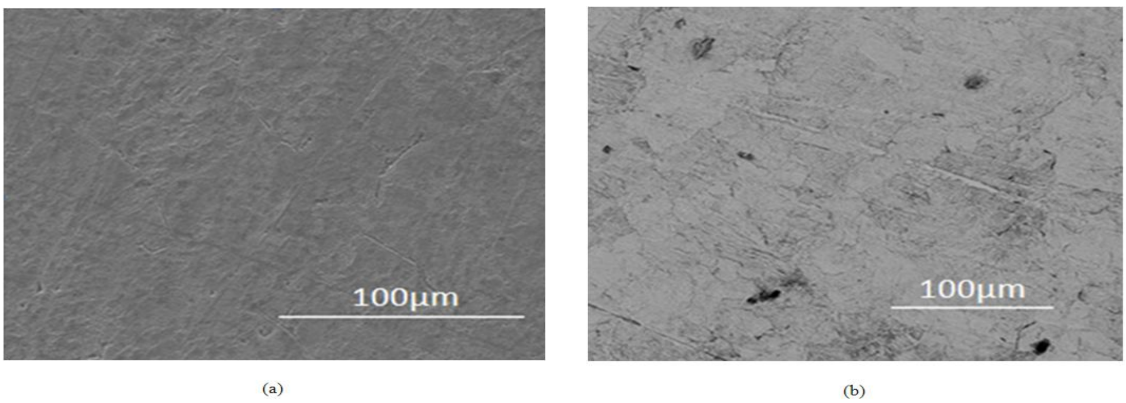


**Fig.6.** : Scanning electron microphotograph analysis of: (a) the base metal and (b) the melted zone.

## IV. DISCUSSION

**A.** Mechanical properties

The results of the hardness tests carried out on the specimen of rail longitudinally (see Figure 4) shows maximum values of Brinell hardness in the weld zone and a gradual decrease of these values in the HAZ (Heat Affected Zone) in order to stabilize in the base metal. This is caused by the sudden cooling of the aluminothermic welding during execution of the welding process. This can be explained by the quenching effect, wherever the hardness values are not similar on the rail and the weld. Indeed, the surface of the weld cools faster than its heart, which favors a formation of martensite concentrated on the surface of the weld, generating a hard weld at the bottom but brittle at the surface due to the phenomenon of grain coarsening. The hardness gradient between the melted zone and the base metal characterizes the hardenability of the thermite weld [17].

**B.** Observation with optical microscopique

Fig.4a shows the metallography of the base metal of the rail where the phase pearlite and inclusions are observed. In Figure 5b one metallography of the melted zone of the weld shows microstructural characteristics different from those of the base metal.

According to the comparative study between the microstructural base metal and the melted zone, a grain refinement was observed in the granular structure of the base metal as shown in Figure 5a, which gives a short explanation of the method of preparation rail according to UIC standards. Indeed, as it is known that the grain refinement has a very advantageous effect on the hardness of making the material harder but not fragile. For microstructural analysis, the thermite weld indicates that the melted zone brings up a clear grain coarsening (see Figure 5b), attributing to the formation of brittle phases. This is confirmed by the hardness profile in Figure 4, which shows a maximum hardness in the melted zone and a gradual decrease of this hardness in the heat affected zone (HAZ) to stabilize in the base metal. This is due to a sudden cooling of the weld during the process of execution of thermite welding that can simulate the phenomenon of hardenability.

The second reason for this fragility in the melted zone can be justified by the presence of various inclusions developed in the weld, as shown in Figures 5a and 5b. They consist mainly of sulfides, oxides, silicates, aluminates, iron nitrides and other elements. They are formed by a chemical reaction in the liquid phase or during the solidification of the weld. Among these inclusions, there is the iron sulfide (FeS), which finally solidifies in the grain boundaries. Through metallographic analyzes, FeS can be recognized by its brown color, its elongated shape and its location in the grain boundaries. In addition, inclusions of manganese sulfide (MnS) are always formed in the liquid phase, so they can grow freely to polyhedral crystals observable outside the primary grain boundaries. They are microscopically identifiable by their polyhedral shape and their blue-grey color.

**C.** SEM examination of specimens

Microstructural observations were carried out in a scanning electron microscope on two specimens of rail [base metal (Figure 6a) and melted zone (Figure 6b)]. These specimens are attacked by Nital to facilitate comparison of observation results of the grain size.

According to observations by SEM, shown in Figures 6a and 6b, two successive zones were distinguished: a zone with a large grain structure (Figure 6b) and one structured by small grains (Figure 6a). Indeed, during the casting of the filler metal into the joint to be welded, the solidification begins quickly by germination of the solid metal in the central zone between the soul and the rail foot. This rapid solidification can also generate inclusions and maintain a large grain structure (Figure 6b) compared to that of the base metal. Therefore, the solder becomes more brittle in the central zone between the soul and the rail foot which is the area most highly stressed by traction exerted by the passage of trains. This embrittlement can cause brittle fracture of thermite welds but less important than that fracture of the welds affected by the adhesion defect (or poor bonding) [17].

## V. CONCLUSIONS

The microstructural and mechanical properties of base metal and melted zone of railway have been evaluated with special attention to the effect of process variable settings on weld fragility, hardness, and microstructure. The integration of maintenance methods and careful control of the welding sequence are important in ensuring high quality steel welds that are free of defects and discontinuities. Through testing and analysis, the following conclusions have been drawn:

- The results of the testing hardness show clearly an embrittlement of the thermite weld that can be explained by the hardenability of the weld on account of its sudden cooling during execution of the welding process.
- The microstructural analyses (on OM and SEM) have confirmed this embrittlement by the presence of various inclusions and the grain coarsening which has been shown in the metallographic structure of the thermite weld.

All these phenomena (hardenability, grain coarsening and embrittlement) may facilitate the crack propagation and eventually can lead to brittle fracture at the rail/weld interface.

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