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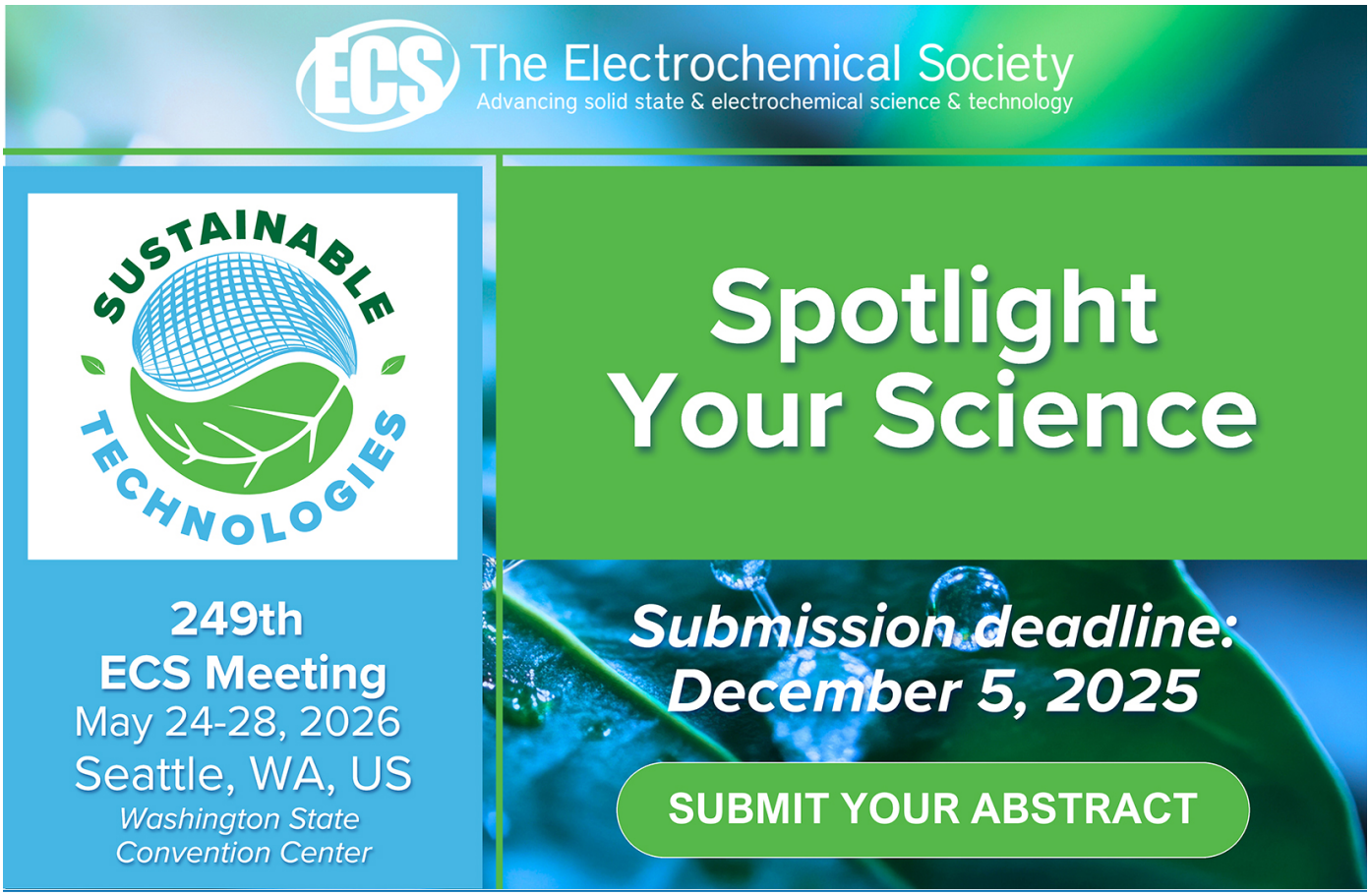
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Fracture failure analysis of metal materials by visual inspection and destructive testing

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Abstract. A methodology is presented to perform fault analysis in metal materials that have failed due to fracture. The proposed method was applied to the study of a fracture presented in the jaw supporting the test pieces in a universal machine used for mechanical tests on materials. The analysis was structured in two stages, initially a visual inspection of the failed element, followed by a series of destructive tests to identify the characteristics of the material and the occurrence of the failure. Visual inspection identified the morphology of the material in the fault zone with gloss and with a characteristic cleavage fracture shape corresponding to a fragile and brittle material. With arc and spark spectrometry the composition of the material was identified, Metallography showed the formation of martensite typical of medium-carbon steels subjected to thermal hardening and scanning electron microscopy identified the precipitation of carbides at the grain boundary, as well as the presence of gaps and other metallic and non-metallic inclusions in the microstructure. The proposed methodology allowed to characterize the fault and propose an appropriate solution by identifying possible hidden faults solving the root of the problem.

1. Introduction

The main objectives of maintenance are to always provide reliable and safe operation of equipment and machines, reduce costs, minimize downtime, and have comprehensive planning and execution of work to ensure operation [1]. To achieve this objective, the functions and possible functional failures should be clearly defined the inability of an equipment to fulfill its function, in order to adopt a policy for the management there of [2]. Reliability engineering and predictive maintenance have two main objectives. Firstly, prevent catastrophic failures of critical production systems in a plant. Secondly, avoid deviations from acceptable performance levels that result in physical injuries, environmental impact, loss of capacity, or poor product quality [3].

One of the tools used for this purpose is failure analysis focused on the characterization of the materials, defined as the process of making observations and collecting analytical data to determine how a component failed, and then applying engineering principles to define why the failure occurred and what should be done in order to prevent future failures [4-5]. In failure analysis are involved branches of engineering as varied as material science, manufacturing processes, thermodynamics, and heat transfer, among others [6]. As a result, this analysis is used in the solution of different engineering problems, to mention just a few: failure of diesel-engine crankshafts [7], analysis of natural gas pipeline [8], and it is even applicable to smaller elements such as steel cables.

When performing a failure analysis, the Equipment Maintenance Log Sheet, maintenance plants, failure rate record of the machine, the data sheet, to know the conditions under which the failure occurred and so forth, should be considered. The more data and elements are available, the more accurate is the

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analysis [9]. The availability of satisfactory methods for the evaluation of equipment that fails unexpectedly is of paramount importance. Failure studies provide valuable information to meet future design needs [10]. Metallurgical failure analysis can be defined as the process by which the mechanisms responsible for the failure of metal components are determined [11].

This work presents the identification of the root cause of a fracture failure in one of the jaws in a universal testing machine used to perform material strength testing in the mechanical engineering laboratory of Francisco de Paula Santander University in the municipality of Ocaña, Colombia. The strength of materials laboratory of Francisco de Paula Santander University located in the municipality of Ocaña, Norte de Santander, Colombia, has a universal testing machine model PU-300 M manufactured by the company Pinzuar Ltda, to perform mechanical strength tests on materials. One of the pieces that make up the jaws system presented a fracture in the upper part. This piece allows the operator to open or close the jaws to introduce or extract the sample. It is not known what caused the failure of the piece since the machine is mainly used for teaching and scientific research. As a result, the machine is not constantly subjected to high loads that could have generated mechanical fatigue failure.

The failure in the piece that composes the jaws system of the PU-300 M universal testing machine prevents the sample from being secured in the correct way for the test, preventing the tests from being carried out. The problem associated with this failure is that this element is not considered susceptible to this type of failure. Therefore, its appearance caused the complete stop of the equipment. Additionally, the manufacturer does not have this part in stock. As a result, it is not available for purchase by the user. The failure generated the need to perform a root cause analysis focused on the characterization of the materials to determine the cause of failure, as well as the material required for manufacturing the part so that the machine can be put back into operation.

2. Materials and methods

To characterize the material that presented the fracture, this work was carried out following the methodology proposed in Figure 1, which is based on failure analysis. The methodology consists of two stages. Firstly, a description of the failure was developed through visual inspection. This was done by analyzing the operating conditions of the machine, taking measurements and pictures, and inspecting the part. Subsequently, the type of failure was compared with theoretical studies. Secondly, the characterization of the part was carried out using hardness tests, metallography, Arc/Spark Optical Emission Spectrometry, and scanning electron microscopy (SEM) with energy-dispersive X-ray spectrometry (EDS).

Finally, the methodology proposed in the characterization stage, based on the analyses carried out in the two stages, allows the identification of the root cause of the failure and the evaluation of a solution to avoid future failures and, if possible, to solve potential hidden failures found during the characterization process.

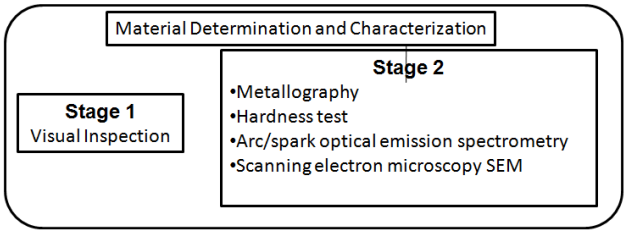


Figure 1. Two-stage methodology used to characterize the universal machine jaw material.

2.1. Visual inspection

This stage allowed understanding the operation of the universal testing machine used to carry out tensile and compression tests on materials. Figure 2(a) shows the Universal Testing Machine model PU-300M manufactured by Pinzuar Ltda. This machine is used to perform tensile, compression, and bending tests on different metallic and non-metallic materials to determine their maximum stress and deformation coefficients. The jaws system (Figure 2(b), Figure 2(c)) is responsible for holding the sample during the

tensile test. The force vs. time data is recorded in software. This software provides the deformation graph of the material, as well as the maximum load the material can withstand. The test ends when the sample breaks.

During the tensile test on a standardized steel sample, one of the parts of the jaws system presented a fracture in its upper part. This part allows the operator to open or close the jaws to introduce or extract the sample. It is not known what caused the failure of the part. As a result, measurements and pictures of the part were taken. Then, a comparative analysis was made, based on the types of failures found in the literature review [12].



(a) (b) (c)

Figure 2. (a) universal testing machine; (b) upper jaw; (c) lower jaw.

2.2. Destructive testing

The piece was physically and chemically characterized. Arc/spark optical emission spectrometry tests were carried out to determine the percentage of each chemical element that makes up the piece. Also, metallography analysis and hardness tests were performed to observe the surface microstructure and the hardness of the material to deformation. Finally, SEM with EDS was used to observe the microstructure and morphology of the material. The data obtained was analyzed to determine the cause of failure [13].

Hardness tests and spectrometry results can be used to determine the material from which the part was originally manufactured [14]. Metallography and SEM can be used to determine whether the material was subjected to any heat treatment to change its properties [15]. Based on the analysis of the results obtained, possible design or manufacturing errors can be detailed, which can be critical points in the appearance of the failure [16].

To carry out the tests, 1cm × 1cm × 1cm samples were selected from the material under study. For the metallography, the surface of the test sample was polished to a mirror-like appearance. Then, the surface was chemically etched in Nital and Kalling solutions. For the SEM, the sample was gold-coated to obtain better conductivity and, therefore, better micrographs. This allowed detailing what happened to the material, as well as determining if the material was subjected to heat treatments after its manufacture.

The metallographic analysis was carried out with an Optika microscope, model B-157ALC, following the specifications of the ASTM E3-11 standard [17]. The sample was prepared in Bakelite for its later polishing. Then, it was sanded and polished until it acquired a mirror-like appearance. Finally, it was etched with a solution of Nital and Picral. Each sample was observed at 50X, 100X, 200X, and 400X magnifications. The hardness test was carried out in a Mitutoyo HR-300 hardness tester, under the guidelines of ASTM E18-19 standard [18]. Ten (10) hardness values were taken at different points of the piece. Figure 3 shows the sample with the points where the hardness measurements were taken. The chemical composition analysis of the sample was carried out using a Bruker Q4 TASMAN spectrometer. The SEM images were obtained using a piece of equipment JCM-6000PLUS.



Figure 3. Sample with hardness test points.

3. Results and discussions

Figure 4 shows the part where the failure occurred. The part was visually inspected and measured. A photographic report was prepared to make a comparison that allowed the classification of the type of failure presented. Toughness is the term used to define a material's ability to plastically deform and absorb energy. Terms such as ductile or brittle are commonly used to define high-toughness (ductile) or low-toughness (brittle) materials. In this context, cleavage fracture is the most brittle fracture mechanism that can originate in crystalline materials. Cleavage fracture can be defined as an extraordinarily rapid propagation of a crack, by the simple separation of the atomic bonds, along a given crystallographic plane [19].

The visual inspection seeks to detail the physical nature of the object inspected. Among these are the size, shape, surface texture, and condition in which it is found, as well as the detail of the defects that allow an assessment of the state in which the material under study is found [20]. Figure 5 shows a fracture of the piece without plastic deformation with a granular appearance on the surface generated by normal stress applied at approximately 90° in the direction of the load. This leads to contemplating the hypothesis of brittle fracture [21].

Table 1 shows the hardness test results of the sample. The material has a uniform hardness with an average value of 20.86 Rockwell C. Table 2 shows the spectroscopy test results for each of the elements that make up the sample with their respective percentages.

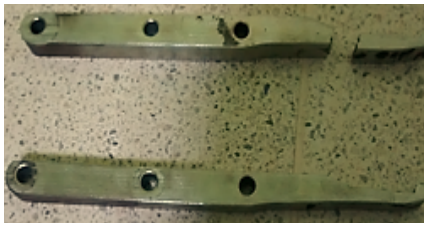


Figure 4. Fractured piece.



(a) (b)

Figure 5. Fracture in the clamping piece of the jaw; (a) exterior view; (b) interior view.

Table 1. Sample hardness test.

Rockwell C hardness										
P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	Ø
21.20	20.60	21.20	21.10	20.60	20.60	21.30	20.10	21.00	20.90	20.86

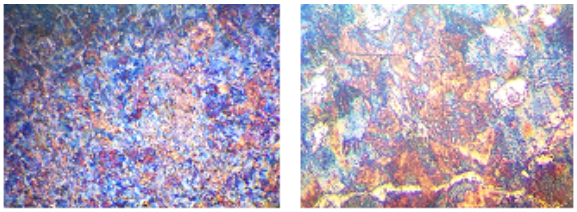
*Ø: Average. *P: Test point.

Table 2. Chemical composition of the sample, Arc/spark optical emission spectrometry results.

	Arc/spark optical emission spectrometry results									
	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Cu%	Fe%
1	0.5840	0.9630	0.9500	0.0870	0.0560	0.0320	0.0050	0.0180	0.0360	97.0800
2	0.5650	0.9200	0.9320	0.0810	0.0410	0.0320	0.0043	0.0200	0.0350	97.1900
3	0.5660	0.9020	0.9280	0.0770	0.0350	0.0330	0.0060	0.0220	0.0370	97.2000
4	0.5630	0.9040	0.9380	0.0720	0.0380	0.0310	0.0042	0.0220	0.0360	97.2100
5	0.5600	0.9410	0.9180	0.0730	0.0340	0.0290	0.0039	0.0180	0.0370	97.2100
Ø	0.5680	0.9260	0.9330	0.0780	0.0410	0.0310	0.0047	0.0200	0.0360	97.1800

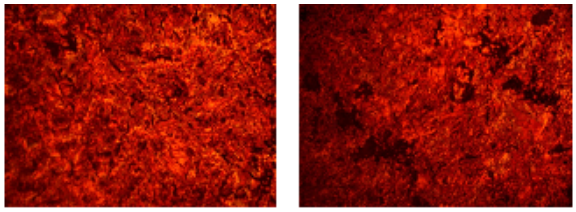
*Ø: Average.

Figure 6 shows the optical micrograph of the sample etched with Nital at different magnifications. Figure 7 shows the sample etched with picral. The metallography reveals the formation of martensite obtained by the rapid cooling of austenite. This is a mixture of lath and plate morphologies with a typical formation of medium-carbon steels [22]. Martensite is a single-phase metastable state. In steel, martensite is a tetragonal crystal structure that occurs when steel is rapidly cooled from the austenite phase [23].



(a) (b)

Figure 6. Metallography of the sample etched with Nital at different magnifications. (a) 100X; (b) 400X.



(a) (b)

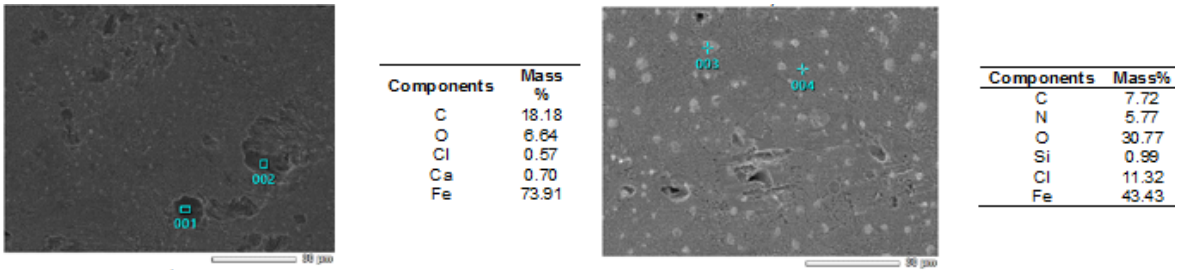
Figure 7. Metallography of the sample etched with Picral at different magnifications. (a) 50X; (b) 400X.

Figure 8 shows the SEM micrograph using EDS. Chemical elements are present in the section analyzed. Also, non-metallic inclusions are present, particularly hard, and non-deformable inclusions.

Figure 9 corresponds to the SEM images of the sample that was chemically etched with Nital. Figure 10 shows the sample that was chemically etched with Picral. The micrographs show a matrix with certain porosity that shows irregularities and voids, as well as separation and precipitation of carbides at the grain boundary.

Through the SEM study it is possible to appreciate in detail how the microstructure of the material is, which makes it possible to have reasons of consideration that determine what happened in the failure through the root cause analysis, Therefore, at microscopic size, the fissure and the grain size limits are observed, leaving in evidence incomplete tempering processes that generate structural micro-cracks that cause sudden failure due to fatigue.

Using the online database MatWeb with the percentages of components described in Table 1, AISI 1040 water quenched steel was selected [24], with the characteristics described in Table 3 and Table 4.

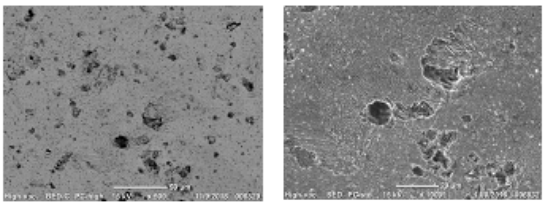


Components	Mass %
C	18.18
O	6.64
Cl	0.57
Ca	0.70
Fe	73.91

Components	Mass%
C	7.72
N	5.77
O	30.77
Si	0.99
Cl	11.32
Fe	43.43

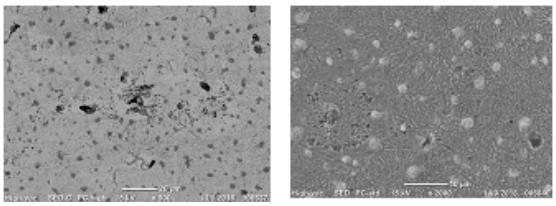
(a) (b)

Figure 8. Scanning electron microscopy; (a) Sample etched with Nital; (b) Sample etched with Picral.



(a) (b)

Figure 9. Scanning electron microscopy, sample etched with Nital. (a) 500X; (b) 1000X.



(a) (b)

Figure 10. Scanning electron microscopy, sample etched with Picral. (a) 800X; (b) 2000X.

Table 3. Chemical composition of AISI 1040 water quenched steel (MatWeb).

Components	%
Carbon (C)	0.37– 0.44
Iron (Fe)	98.6– 99
Manganese (Mn)	0.60– 0.90

Table 4. Mechanical properties of AISI 1040 water quenched steel (MatWeb).

Mechanical properties	Metric system
Hardness, Brinell	223
Hardness, Rockwell B	96
Hardness, Rockwell C	18

4. Conclusions

The proposed methodology allowed a systematic analysis of the root cause of the failure presented in the fracture of one of the jaws of the universal test machine model PU-300M. The process carried out in the stage of visual inspection allowed to establish characteristics of the fault presented and in the same way with the destructive and non-destructive tests the due characterization of the material of which the part presenting the fault was composed was carried out.

In the second stage of the process, destructive testing allowed an understanding of the hardness, composition, and microstructure of the material. The material studied has an average hardness of 20.86 Rockwell C, practically homogeneous on the surface of the part. Arc/spark optical emission spectrometry revealed that the material has an average carbon content of 0.568%. The material has high concentrations of Silicon Si (0.9260%), which forms a hard, slightly deformable non-metallic inclusion, and Manganese (0.933%), with a body-centered crystal structure, making it less ductile.

Metallography indicated the formation of martensite by the transformation of austenite in the quenching process of the medium-carbon steel. The results of the scanning electron microscopy and energy-dispersive X-ray spectrometry allowed observing the presence of elements such as silica, and manganese, as hard and non-deformable inclusions, which due to their crystal structure decrease the number of sliding systems and affect the ductility of the material. There was evidence of grain boundary segregation, and the presence of irregularities, cracks, and voids, indicating a cleavage fracture.

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