Paraconsistent Logic applied in the metallography of welds classification through morphological characteristics and entropy of digital images

Mauricio Conceição Mario¹, João Inácio da Silva Filho, Maurício Fontoura Blos, Dorotéa Vilanova García, Natal de Jesus Gaspar, José Carlos Morilla, Carlos Alberto Amaral Moino and Maria Cristina Pereira Matos
Santa Cecília University – UNISANTA, Department of mechanical engineering, Osvaldo Cruz, 266 CEP-11045-000 Santos – SP – Brazil

¹ E-mail: cmario@unisanta.br

Abstract. In the study of weldability, the metallography digital image analysis has become a tool of wide application. The morphological analysis and particle counting applied in digital images to classify patterns can produce contradictory data. In order to increase the reliability index in the results, this paper describes a model able enough to do the analysis for the final classification supported in an evidential non-classical logic, called Paraconsistent Logic (PL). The model used morphological analysis and entropy filter in metallography digital pictures. In generating three types of information data, it was used metallographic samples of the traditional process, the process for tempering and weld samples repair after tempering process. The actions of the model showed satisfactory results getting the classification of samples inserted to test. These results showed that the architecture of the proposed paraconsistent model is feasible and can be adapted according to the peculiarity of the analysis of the weld type.

1. Introduction
This work of metallographic analysis in steel welds differs from the traditional approaches related to the subject since the proposal is to use techniques of Artificial Intelligence, notably the Paraconsistent Annotated Logic, to characterize the type of weld made, through the morphological analysis of digital images. Computational tools for the analysis of digital images allow to obtain parameters related to the characteristics of the same, which if properly treated can define their properties. In the case of welds in steel, the digital images of the same reveal properties such as granularity, which if they can be quantified, can identify the type of weld made and even its quality. The study developed in the paper proposes an unprecedented technique that can become relevant as steel is present in the infrastructure of constructions of the most varied types, such as metallic tubes used in the transport of oil by the sea, that is, in places where solder analysis without the need for further intervention represents less cost and risk. The processing and image analysis allows to identify and extract information from it and to obtain data related to structural features, facilitating automatic interpretation of characteristics by appropriate computer applications [1-3].
1.1. Morphological Analysis

In image processing, morphology is used to identify and extract image descriptors based on properties of shapes or contours. Morphological operations can be defined through the operators of dilation and erosion [4, 5].

A morphological operation of dilation is performed by positioning the center pixel of the structural element successively in each pixel of the background image. If one of the pixels next to it is foreground, the background pixel is transformed into foreground pixel [4-6].

One of the morphological operation of erosion application is the granulometry, which is the counting and measuring of sizes of granules or small particles. This process can be performed by computer image processing algorithm that initially makes the counting of objects present in a given image [4-6]. Following, the operation of erosion is repeated using always the same structural element, until there is no foreground object. Every step of this process records the total number of $F$ objects that were removed from the image as a function of the number of erosions $n$. The number of erosions necessary to remove an object is directly proportional to the size of the object. So if the object disappears in the $k$-th erosion, it can be said that their $X$ size is proportional to number $\alpha$ of erosions, where $k$ is a proportionality constant determined by the structural element used. This process allows forming $F(X)$ estimative which is the cumulative distribution function (CDF) of particle size, according to equation (1).

$$F(X)\int_{-\infty}^{x} p(x)dx$$

By elementary probability theory [5-8], the probability density function (PDF) is related by the equation (2):

$$p(x) = \frac{dF}{dx}$$

In (1) $p(x)$ it represents an estimate of the distribution of particle sizes [4-6].

1.2. Entropy applied to digital images

Considering the probability of a pixel of a digital image taking a value of intensity $i$ that varies from zero to a maximum value $-L_{\text{max}}$; then the distribution of intensity levels of the image $p_i$ can be given by the quantity of pixels of intensity $i = ni$ related to the total number of pixels in the image - $n$. This relation is described at equations 3 [1, 3, 8].

$$p_i = \frac{ni}{n}$$

where: $\sum_{i=0}^{L_{\text{max}}} p_i = 1$

The entropy of an image $H$ of a picture is given by equation (4), which provides a measure of the variation of the intensities of gray for the pixels that compose a digital image. The entropy value is zero when all the pixels that compose the image have the same intensity of gray and is maximum when an image contains the same amount of pixels for all the intensities [6-8].

$$H = -\sum_{i=0}^{L_{\text{max}}} p_i \log p_i$$

1.3. The Paraconsistent Annotated Logic – PAL

Classical Logic bases many current fields of modern science and, by analyzing the laws of valid reasoning, relates to a given proposition a logical state that qualifies it as true or false and is therefore considered a binary logic. But the real world is characterized by situations that, to be qualified, need to exceed the limit of two states, such as indefinite, ambiguous, or contradictory. To meet this demand were created Non-Classical Logics, which are characterized by extrapolate binary assumptions,
allowing logical states beyond true and false. One of the principles of Classical Logic is "the principle of the excluded third, \( p \lor \neg p \)" which means that "of two contradictory propositions, that is, one denies the other, one of them is true". Paraconsistent Logic is a Non-Classical Logic that repeals the principle of non-contradiction and admits the treatment of contradictory information in its theoretical structure [9-11].

The Paraconsistent Annotated Logic (PAL) is a class of Paraconsistent Evidential Logic, which makes signal treatments represented by annotations allowing a description and equalization through algorithms [9]. In Paraconsistent Annotated Logic - PAL, the propositional formulas are accompanied by annotations. Each annotation belonging to a finite lattice assigns values to its corresponding propositional formula [10, 11].

1.4. The Paraconsistent Annotated Logic with annotation of two values - PAL2v

Considering the annotation consisting of two evidential values it is possible to obtain paraconsistent logical states and equations capable of providing levels of certainty and contradiction necessary for decision making [10, 11]. A representation of PAL2v can be given as follows: in the Annotated Paraconsistent Logic of annotation with two values, for each proposition two values of degrees are associated. The first value contained in the annotation represents the evidence favorable to the proposition \( p \) (belief - \( \mu_1 \)), and the second value of the annotation represents the evidence contrary to the proposition \( p \) (disbelief - \( \mu_2 \)). Figure 1 shows the representation of Hasse Reticulate with two values. For Hasse's lattice with two values, it has been:

\[
\tau = \{(\mu_1, \mu_2) \mid \mu_1, \mu_2 \in [0,1] \subseteq \mathbb{R}\},
\]

and if \( p \) is a basic formula, the \( \sim : \tau \to \tau \) is defined as:

\[
\sim ([\mu_1, \mu_2]) = (\mu_2, \mu_1),
\]

where \( \mu_1, \mu_2 \in \{x \in \mathbb{R} \mid 0 \leq x \leq 1\}\) and \( \mu_1, \mu_2 \) are an annotation of \( p \). The four-vertex grid for LPA2v is shown below [10, 11]:

\[\text{Figure 1. Hasse's lattice.}\]

One can relate the extreme logical states represented in the four corners of the lattice with the values of degrees of belief and disbelief:

\( p_T = p (1,1) \Rightarrow \) The annotation composed by the degree of belief and disbelief attributes to the proposition \( p \) an intuitive reading that \( p \) is inconsistent.

\( p_1 = p (1,0) \Rightarrow \) The annotation composed by the degree of belief and disbelief attributes to the proposition \( p \) an intuitive reading that \( p \) is true.

\( p_0 = p (0,1) \Rightarrow \) the annotation composed by the degree of belief and disbelief attributes to the proposition \( p \) an intuitive reading that \( p \) is false.

\( p_{\perp} = p (0,0) \Rightarrow \) the annotation composed by the degree of belief and disbelief attributes to the proposition \( p \) an intuitive reading that \( p \) is paracomplete [10, 11].

The Paraconsistent Annotated Logic of bi-valued annotation - PAL2v proved to be adequate when using the knowledge of evidence to help resolving conflicts when multiple inconsistent inferences occur. The PAL2v is able to treat contradictions by analyzing favorable evidence and contrary evidence to a particular proposition. As can be seen in [10], [11] and [12] through these analyzes, PAL2v can modify the behavior of a system so that the "intensity" of contradictions decrease.
1.5. Paraconsistent Artificial Neural Cell of Analytics Logical Connection – PANCa
Paraconsistent Artificial Neural Cell of Analytics Logical Connection - PANCa [13-15] is a group of interconnected paraconsistent algorithms and it can receive evidence degrees from different points in an Artificial Paraconsistent Neural Network. The PANCa treats the evidence resulting from these points, presenting, in the output, a value resulting from a paraconsistent analysis of points that converge to this cell [13-15]. Figure 2 depicts the structure of a PANCa.

\[
\mu_{E} = \frac{1}{2} \left[ (\mu A - \lambda A) + 1 \right]
\]

(7)

When the TCF is set to 0, \( \mu_{E} \) is restricted so it cannot be considered as evidence resulting from the evidence of input [13-15].

2. Experimental methods
In the works [16] and [17] the authors aimed to testify the feasibility of using the tempering pass applied to repairs performed on pipes. Based in these works we made the analysis of hardness mapping [18] performed in three welded test samples, which are called: test sample of the original weld, test sample of weld with tempering pass and test sample of repair weld with tempering pass.

In the first test sample it was made the welding and thermal treatment for stress relief, according to the recommendations of ASME B31.3 – 2012 norm; in the second test sample it was applied weld fillets using the technique of tempering and in third test sample was done a repair using the same technique. In the three test samples were performed hardness mappings in an area that involves the base metal, the heat affected zone and the fusion zone.

The metallography images of weld are in the first stage manipulated by the image editor so that the dimensions can be patterned in the size of 120 x 80 pixels for morphological analysis and for the characteristics of entropy.

2.1. Operation of erosion applied to the image of the original weld metallography
Figure 3a shows the image of metallography of test sample in which was applied the original weld, base metal region; figure 3b shows the image of the original weld, base metal zone [18], after morphological operation of erosion:
Figures 3. Image of original weld metallography, base metal zone and image of original weld metallography, base metal region, after operation of erosion.

The results for base metal, heat affected zone and fusion zone, original weld, are showed on tables 1, 2 and 3.

| Table 1. Base metal, original weld. |
|-----------------------------------|
| size  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
| number of particles | 94  | 107 | 109 | 111 | 112 | 112 | 112 | 112 | 111 | 111 | 113 |

| Table 2. Heat affected zone - original weld. |
|--------------------------------------------|
| size  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
| number of particles | 64  | 66  | 68  | 68  | 69  | 69  | 69  | 69  | 69  | 69  | 69 |
| size  | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| number of particles | 69  | 69  | 69  | 69  | 69  | 69  | 69  | 70 |

| Table 3. Fusion zone, original weld. |
|------------------------------------|
| size  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
| number of particles | 165 | 171 | 173 | 174 | 174 | 173 | 173 | 174 | 174 | 174 | 175 |

The operation of erosion is applied to the metallography image of weld using tempering pass and repair weld, which respectively results obtained after morphological operation of erosion.

2.2. Entropy applied to metallography images
The entropy operation [4] and [19] was applied to each one of the digital images relating to the respective regions base metal, heat affected zone and fusion zone of the original weld, tempering and repair. Table 4 shows the results by region.

| Table 4. Normalized values of mean intensity of pixels for each type of weld by region. |
|-----------------------------------------------|
| kind of weld/region | base metal | heat affected zone | fusion zone |
| original            | 0.547      | 0.486               | 0.576       |
| tempering           | 0.717      | 0.526               | 0.563       |
| repair              | 0.678      | 0.685               | 0.605       |

2.3. Characterization of base metal, heat affected zone and fusion zone by Paraconsistent Annotated Logic
The characterization of base metal, heat affected zone and fusion zone for the types of original weld, tempering and repair will be made from Paraconsistent Artificial Neural Cell of Analytics Logical Connection - PANCa [13-15] who receive evidence of morphological analysis and from the digital entropy image of metallography welds. The values obtained through morphological and entropy analysis with sample tests, are the references values. Figure 4 depicts the architecture of the
Paraconsistent Network Analysis. The values obtained from morphological analysis and from the entropy are normalized according to equation 7. The normalization equation (8) provides output values within the interval [0, 1], where values close to one mean that the test values inserted approach the reference values. The normalization of values for morphological analysis and entropy is:

\[
\text{Normalization } \mu = \frac{1}{e^{\left[\text{reference value} - \text{test value}\right]}} \tag{8}
\]

In the first stage of the network, the inputs \( \mu \) and \( \lambda \) of Paraconsistent Artificial Neural Cell of Analytics Logical Connection - PANCa will receive respectively the values related to morphological analysis and the values related to entropy, which were normalized from Equation (9). Equation (10) is referring to paraconsistent analysis by the PANCa.

\[
evidence = \frac{\left[\left(\mu \lambda - \lambda^2\right) + 1\right]}{2} \tag{9}
\]

\[
\lambda 2 = 1 - \mu E_{pr} \tag{10}
\]

\( \mu E_{pr} \) is the value of the degree of evidence of previous iteration. The \( \lambda \) input, normally used as contrary evidence input in PANCa, is complemented as shown in equation (8), for that to start representing a favorable evidence degree. The morphological analysis represents the amount of particles related to its dimensions which are proportional to the amount of operations of erosion performed. The values related to the entropy represents the mean intensity of gray level in pixels related to a given image region of metallography. The first PANCa, through the \( \mu \) and \( \lambda \) inputs, analyses the evidence relating to morphological analysis - respectively the amount of particle sizes and the mean value of dimensions of these particles. The output of this first cell is connected to the \( \mu \) input of the second cell, while \( \lambda \) input receives the value related to entropy.

This second cell presents in the output an evidence of morphological analysis and entropy. So the first three pairs of PANCa in architecture of figure 4 make the paraconsistent analysis of morphology and entropy respectively for base metal, heat affected zone and fusion zone weld regions. The architecture connects the analysis of base metal and heat affected zones, connects the resultant analysis base metal and heat affected zones with the fusion zone analysis, thereby completing the resulting analysis related to the three regions of one type of weld.

2.4. Architecture Classifier System of identifying the type of weld
The network architecture for characterization of base metal, heat affected zone and fusion zone (figure 4) is tripled so it is possible to examine the values of the regions for classification of three types of weld, "original", "tempering" and "repair". Figure 5 shows the architecture of complete network, where the output of each module of characterization of regions converges to the last module, called “Expert System for identification of the weld type”. The Expert System receives the evidence of modules related to each type of weld and through the algorithm 1, described below, provides a proposition of output that can be the type of weld and the positive evidence related to the proposition. There is the possibility of indeterminacy as output information, in the case of conflicting data entered in input or values in which it is not possible to establish a substantial difference of evidence for different types of weld.

Verify which module presents the biggest evidence, if the original, tempering or repair welds
Present in the output the identification of the type of weld with bigger evidence and the respective evidence
If two modules have equal evidence and bigger evidence than a third one
Present at the output the identification of two kinds of weld of these modules and the evidence is 50% of corresponding evidence to the two selected types of weld
If the three modules have the same evidence
Present in the output the type of weld as undefined and no evidence
Algorithm 1: Algorithm of Classifier System of weld type identification.
Figure 5 shows the complete architecture of the network identification of the type of weld.

**Figure 4.** Network Architecture of Paraconsistent Analysis for characterization of base metal, heat affected zone and fusion zone, through the entropy values and morphological analysis of digital images of metallography.

**Figure 5.** Complete architecture of Paraconsistent Analysis Network to identify types of weld: "original", "tempering" and "repair".
3. Results and discussion

To evaluate the paraconsistent analysis network of weld types it will be inserted values resulting from morphological analysis and entropy of digital images of metallography.

The first test sample is the analysis of metallography image resulting in repair of weld by tempering - steel ASTM A148 Gr 80 50 [20], for base metal, heat affected zone and fusion zone.

The second test sample is the analysis of metallography image resulting from tempering weld - pipes API 5L Gr B [21], for heat affected zone. There are two samples in this case, sample 1 and 2.

The third test sample is the analysis of metallography image resulting from tempering weld - steel X10CrMOVnB9-1 [22], for base metal, heat affected zone and fusion zone.

Tables 5, 6 and 7 respectively present the results related to the analysis of the type of weld made in metallography digital figures extracted from works of [20], [20] and [21] (first, second and third examples mentioned above). These works have in common the tempering weld. In the works with steel ASTM A148 Gr. 80 50 and API 5L Gr B pipes, the focus is the result obtained in repair situations, while for steel X10CrMOVnB9-1 the focus is the heat treatment.

| Table 5. Result of the tempering weld analysis - steel ASTM A148 Gr 80 50 [19]. |
|---------------------------------------------------------------|
| base metal + heat affected zone + fusion zone evidence |
| original | 0.408 |
| tempering | 0.452 |
| repair | 0.497 |

| Table 6. result of the tempering weld analysis - pipes API 5L Gr B [20]. |
|---------------------------------------------------------------|
| base metal + heat affected zone + fusion zone evidence |
| original | 0.117 |
| tempering | 0.119 |
| repair | 0.121 |

| Table 7. result of the tempering weld analysis - steel X10CrMOVnB9-1 [21]. |
|---------------------------------------------------------------|
| base metal + heat affected zone + fusion zone evidence |
| original | 0.462 |
| tempering | 0.494 |
| repair | 0.698 |

The analysis of characterization of the type of weld performed by the Paraconsistent Analysis Network resulted in the three types of weld being characterized as repair weld after the tempering pass, with evidence 0.497 to the steel ASTM A148 Gr. 80 50, 0.121 to the tubes API 5L Gr B and 0.698 for the steel X10CrMOVnB9-1.

4. Conclusions

The works used to test the Paraconsistent Analysis Network of characterization of weld types have variations in weld processes, pre-welding heat treatment and characteristics of digital images of metallography. The characterization model of weld type proposed in this paper showed satisfactory results regarding the classification of samples inserted for the test, even with the variation mentioned in the welding process and the characteristics of metallography images. The computational model of Paraconsistent Analysis Network of weld type characterization can be adapted to characterize welds made at similar or distinct processes, and for that it is required parameter changes described in item 2.4. The classification can be also performed by different analysis criteria of base metal, heat affected zone and fusion zone; the network architecture proposed in item 2.3 may be altered to cover a different number of regions. The use of a network architecture based on Paraconsistent Annotated Logic allows the proposed model to be adapted according to the peculiarity of type weld analysis. Even when there are no measurements related to base metal and fusion zone, the network made the
analysis with two measures related to heat affected zone, demonstrating that the lack of information regarding measures can be treated by the proposed architecture. The result of this analysis in particular is that the result was correct, but with a smaller value of evidence degree in relation to the other two analyzes. Considering the need of validating weld procedures, particularly in steel tubes located in offshore environment, the presented proposed model for weld characterization can be adapted and refined for applications related to this area.

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