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Proceeding Paper

Exploring the Correlation between Thermal Diffusivity and Ultimate Tensile Strength in Usibor® 1500 through Laser Thermography †

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Abstract: This paper presents a non-destructive laser thermography (LT) procedure for estimating Usibor® 1500 ultimate tensile strength (*UTS*) based on thermal diffusivity measurements. The key innovation lies in the revealed inverse relationship between thermal diffusivity (α) and *UTS*, highlighting its potential for estimating mechanical properties in a non-destructive way. The experimental phase involved analyzing fifteen specimens using a 960 nm CW laser source and a thermal camera to measure thermal diffusivity. The results demonstrate a clear correlation between α and *UTS*, providing valuable material characterization insights and demonstrating promising applications in mechanical design.

Keywords: thermal diffusivity; laser thermography; Usibor®1500; ultimate tensile strength; hardness; hardening; mechanical properties; non-destructive test (NDT)

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1. Introduction

One of the critical requirements in mechanical design is the modification of the mechanical properties of steels according to several operating conditions. In this regard, heat treatments play a crucial role in altering the microstructure of steels to achieve desired mechanical strength characteristics. However, assessing the success of these treatments on components typically requires destructive or semi-destructive testing, which significantly compromises the integrity of the component itself.

Active thermography, which is already widely employed for process monitoring [1,2], non-destructive testing (NDT) [3–5] and material characterization [6–9], could offer an alternative to current inspection methods to overcome their limitations. In fact, considering the inverse correlation between hardness and thermal diffusivity, thermal measurements of α can provide an assessment of the mechanical properties of steels.

This study represents a further advance compared to previous work [10], aiming to develop a preliminary LT experimental procedure for estimating the *UTS* in boron steels based on α measurements.

2. Materials and Methods

As reported in other research works [8,10,11], α is closely related to the microstructure of steels and, therefore, to their hardness. Hence, it can be used as an index to detect variations in hardness. Thermal diffusivity measurement is typically performed using the transient plane source (TPS) method [12], but this method is unsuitable for rapid application for components. On the contrary, various thermographic methods offer great potential for industrial applications due to their rapid measurement times and versatile setups [6,7,13].

Among the different methods available in the literature [6,7,13], this study focused on laser spot thermography [9,14]. This method has the significant advantage of enabling the measurement of α along the thickness or on the surface of the component. It involves heating the component's surface with a thermal pulse and evaluating the temporal temperature response of the circular laser spot using a thermal camera. Laser spot thermography was chosen for this study due to its reflection setup and the analysis's simplicity, making it more suitable for industrial applications.

2.1. Specimens

Fifteen specimens, obtained through the Gleeble® 3180 physical simulator, were analyzed to replicate the thermo-mechanical process occurring during hot forming [15]. By optimizing the specimen [16], five different levels of bainite and martensite percentages were obtained, summarized in Table 1. Only the nominal percentage in an ~10 mm area at the center of the specimen, as highlighted in Figure 1, was investigated. For each level, three specimens were produced to evaluate process reproducibility. According to the manufacturer's data, the Usibor® 1500 has an Al-Si coating of a ~30 µm, which was not removed during the heat treatment and therefore present on all analyzed specimens.

Table 1. Description of the percentages of martensite and bainite present in specimens.

	A	D	B	E	C
Bainite	0%	18%	44%	85%	100%
Martensite	100%	82%	56%	15%	0%

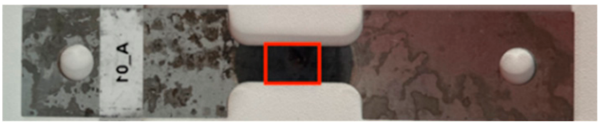

Figure 1. One of the tested specimens. The red square indicates the area with the nominal phase.

2.2. Experimental Setup and Data Analysis

The central region of each specimen was heated using a 1064 nm NdYag laser source with a circular top-hat spot ~6 mm in diameter. The laser operates in CW during the pump lamp ignition period of 300 µs, which could be approximated as a pulse for the considered model without significantly affecting the measurement. Heating and cooling were recorded using a FLIR 6000sc MW thermal camera calibrated from −10 °C to 55 °C, with a framerate of 1 kHz and spatial resolution of 0.26 mm/pxl, for 2 s.

Considering the limited inspection area and the confirmed material isotropy throughout the central volume of the specimen, only the measurement of α in the thickness direction was considered. Five repetitions were performed for each specimen to ensure statistical significance for individual test measurements. To compare the results, a fixed time window and ROI (Region of Interest) were established for all tests. This approach allows for calculating uncertainty bands for each inspected level, considering not only the replicates across different specimens but also the repetitions within each specimen. The results were compared with the mechanical test results obtained in a previous study [15,16], wherein specimens were obtained using the same process and subsequently subjected to uniaxial tensile tests.

3. Results

In Figure 2, the graphs display the α values obtained for each inspected nominal phase percentage. It can be observed that an increase in the bainitic phase corresponds to an increase in α. The uncertainty bands (95%) for each measurement are sometimes extensive and partially overlap with the diffusivity measurement for the next level. However, when examining individual measurements and their respective uncertainties for each specimen, differences between the specimens resulting in this dispersion are noticeable. The summarized table also presents values of hardness for each phase percentage obtained from a previous study using specimens derived from the same process and laboratory, but only three values for *UTS* [15,16].

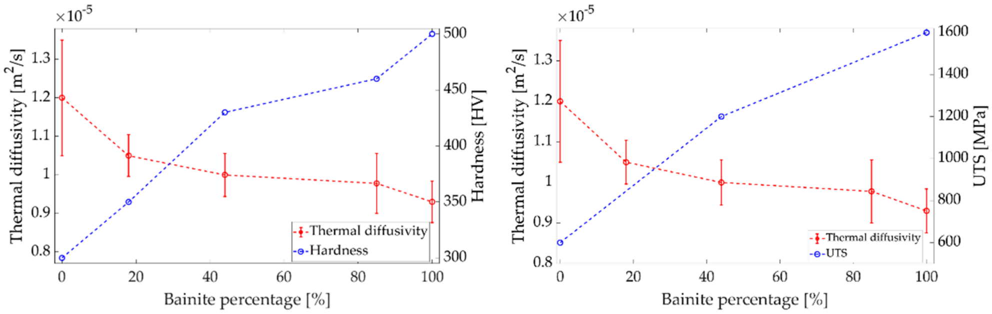

Figure 2. Behavior of α, hardness Vickers and *UTS* as a function of bainite percentages.

4. Discussion

The first aspect that must be discussed is the extension of the uncertainty for thermal diffusivity measurements for each percentage. Considering that the percentage value being considered is the predicted nominal value for the process, this dispersion could also be attributed to the imperfect repeatability of the production process, which can only be verified through metallographic analyses of the phase percentages present.

Figure 2 shows the correlation among the hardness, the *UTS* obtained from previous works [15,16] and the α values. It can be observed that there is an inverse correlation between the α values and the derived *UTS* values. Therefore, a preliminary empirical relationship can be established to estimate the *UTS* of boron steel based on α measurements. However, this relationship is considered preliminary as it is necessary to perform tensile tests directly on the inspected specimens to evaluate this relationship and verify the phase percentages present in the inspection area through traditional controls.

Another aspect that should be considered is that all measurements were obtained considering the presence of the Al-Si coating, which is usually present for Usibor® 1500 sheets. In the case where the derived relationship is applied to the material without a coating, it should be adjusted accordingly, although the respective differences between the different phases should remain constant.

5. Conclusions

In conclusion, an NDT preliminary procedure based on LT to estimate the *UTS* of boron steels was proposed in the presented work.

The analysis of α measurements revealed a clear relationship between the phase percentages and α. An increase in the bainitic phase resulted in higher α. These findings highlight the possibility of estimating the phase percentage in boron steel through LT.

However, it is essential to note the presence of uncertainty bands in the measurements, indicating possible variation among specimens. This dispersion could be attributed to the imperfect repeatability of the production process, which should be further investigated through metallographic analyses.

The correlation between α and *UTS* revealed an inverse relationship. A preliminary empirical relationship was proposed, which suggests the potential of estimating the *UTS* of steel based on α measurements. However, further validation through traditional controls is required to assess the accuracy of this relationship and verify the phase percentages within the inspection area.

Considering the presence of Al-Si coating on Usibor® 1500 sheets, it is important to note that adjustments may be necessary when applying the derived relationship to materials without a coating. Additionally, the relative differences between the different phases should remain consistent even without the coating.

In summary, these findings contribute to the understanding of phase composition's effects on α and its correlation with *UTS*, paving the way for further research and applications in material mechanical characterization.

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