Localized heat treatment to improve the formability of steel pipes for hydraulic applications: process design and mechanical characterization

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Abstract
In the present paper, authors have demonstrated how a localized induction heat treatment can be advantageously applied, controlled, and mechanically characterized on a specific part—i.e., on steel hose fittings for hydraulic applications. More specifically, the study shows how this specific type of heat treatment facilitates significant localization effects on mechanical properties, and how such a treatment could act as a powerful tool for material optimization in diverse applications. The instrumented micro-indentation test was adopted as the investigation method for mechanical characterization and, due to the reduced amount of material required for the test, has the double advantage of retrieving potential spatial gradients of the mechanical properties without causing permanent damage to the analyzed parts. A measurement of both Vickers hardness and plastic work are required in order to make the indentation necessary to quantify the strength and ductility capability of the parts’ materials. In addition, a customized tensile test, based on a strains measurement obtained through an optical full-field method—i.e., digital image correlation (DIC)—was developed with the aim of identifying and quantifying the correlation between the material properties attainable through a conventional tensile test and those measured by the instrumented micro-indentation test. Finally, it was demonstrated that the proposed customized tensile test, due to the localized heat treatment, is capable of retrieving potential spatial gradients of the material properties.

Keywords Localized heat treatment · Induction heat treatment · Micro-indentation test · Tensile test · Digital image correlation

1 Introduction
Heat treatments are powerful tools, used to improve the performance of materials in several industrial applications and attain specific mechanical properties without modifying the chemical composition of the materials [1]. One of the main drawbacks of such applications in industrial environments is their high cost, attributed to energy and time requirements. In its standard implementation, a heat treatment requires that the entire part to be treated fit into an oven, limiting the maximum volume. Furthermore, the application requires sufficient processing time, which increases according to the desired temperature to be reached (and maintained) and the thermal resistance of the system. In addition, the use of a standard heating chamber equipped with a single door renders the process discontinuous, implying an additional cost and time that can be avoided through the use of continuous oven. The solution of a continuous oven, however, does not resolve concerns related to the maximum processable volume or heating and cooling times. In addition, if the objective is to obtain only local properties, the fact that the whole part is contained in the oven implies an overall difficult process design, which cannot always provide for accurate results.

In this context, according to the different needs arising from a wide variety of industrial requirements, innovative localized heat treatments have been developed and proposed. Among these treatments, the induction-based heat treatments [2–4] has unique advantages in diverse applications,
seen in both industrial environments and research and development experiments.

Due to their high magnetic susceptibility, this type of heat treatment is most commonly applied to iron-based materials and steels, in particular. Several studies have demonstrated how the microstructure and mechanical properties can be significantly modified by induction-based heat treatments applied to a wide range of iron-based materials and applications. A number of research papers have further investigated the influence of operating parameters on mechanical properties, with a focus on bulk materials [5–7], superficial aspects [8, 9], and welded parts [10, 11]. Guo et al. [12] showed how a combination of induction heat and surface peening treatments improved yield strength without significantly impacting the ductility of pure iron. Bao et al. [13] designed a specific induction-based heat treatment for the automotive industry that was capable of conferring heterogeneous mechanical properties with the aim of optimizing the performance of the treated parts.

Microstructural and mechanical properties have been modified and improved on other types of materials, such as nickel-based coatings [14] and titanium alloys [15, 16]. Furthermore, induction heating can be used for several other applications, beyond heat treatments. These include the melting and casting of copper [17] and nickel alloys [18], technological processes implying large deformations [19, 20], and innovative welding processes [21, 22].

In the present paper, authors have proposed experimental methods that would quantify the impact of a localized induction-based heat treatment on the mechanical properties of steel hose fittings used in hydraulic applications. Specifically, the present research focuses on the production of pipes, obtained by machining a full cylindrical bar subsequently bent into a 90° angle. Two experimental methods were developed in order to quantify modifications to the mechanical properties: instrumented micro-indentation tests and tensile tests (supplied with optical equipment for the strain field measurement).

The proliferation of instrumented micro-indentation tests used for mechanical characterization is largely due to the work of Oliver and Pharr [23], whose numerical and experimental studies demonstrated, in the 1990s, how properties like stiffness, strength, and ductility can be retrieved by monitoring the load/displacement curve of an indentation test. Beyond the information obtained about the mechanical properties, a great benefit of this approach lies in the highly localized volume of the material involved in the test. This implies two important advantages: the single test provides the local mechanical properties and, therefore, the method can be used to retrieve spatial gradients of the properties; the indentation test can also be considered a semi-destructive or even non-destructive test, depending on how critically stressed the area is where the indentation is executed. These advantages have encouraged the use of this approach, prompting an establishment of standards [24, 25] and development of commercial devices [26, 27].

On the other hand, in the present research, a combination of digital image correlation (DIC) methods [28] and standard tensile tests, performed on a portion of the pipes, facilitated a more accurate identification of some mechanical properties and their spatial gradients. Indeed, the full-field feature of this displacement measurement method allowed for a more accurate quantification of the strains placed on a large number of points, in theory equal to the number of pixels in the acquired images. In practice, due to noise of the acquisition chain and other sources of error, the number of points with strain that were accurately and successfully measured was smaller than the total number of pixels. The number was, however, still considerably higher than what would have been attainable by conventional method—e.g., strain gages and extensometers.

Finally, the authors demonstrated how to determine a relationship between the tensile test and micro-hardness properties. Specifically, authors demonstrate that stress and strain present at the necking limit are correlated to the plastic deformation work of indentation. The mathematical relationship, instead, can be assumed as linear, provided that the range of the values considered is not too wide. Evaluating this type of relationship has the advantage of providing important mechanical properties and their gradients, which are typically obtained by expensive and destructive tests—i.e., tensile test—through experimental procedures, such as the indentation test, that are considerably less invasive and costly, and easy to implement in an industrial environment without highly skilled operators.

Within this framework, and with the aforementioned considerations in mind, authors have successfully investigated and quantified the impact of induction-based heat treatments on the mechanical properties of steel hose fittings. The study has demonstrated how the developed methods allow the magnitude and gradient of the properties to be quantified and controlled, with the aim of advantageously placing the parts in the production cycle.

## 2 Materials and methods

The parts to be analyzed here are rectilinear steel pipes that will be curved permanently using a cold bending process, which should neither cause any damage or failure, nor should cause the strength of the original material to worsen. In this scenario, due to the large strains occurring on the portion to be bent, the ductility of the original material has to be increased, whereas the tensile strength and related properties should not be significantly impacted by the subsequent mechanical processes and heat treatments.
The original material is a cold drawn bar of 11SMnPb30 steel with a carbon average percentage of 0.07%. The main alloy elements are manganese (≈1.0%), sulfur (≈0.3%), phosphor (≈0.2%), and lead (≈0.3%). This composition confers good, high-speed machinability and limited weldability to the material. For bars whose diameter is less than 15 mm, the guaranteed minimum tensile strength and the Rockwell B hardness are 490 MPa and 79.5 HRB, respectively.

The bars to be curved in the cold process were machined in different sized pipe shapes and subjected to induction-based heat treatments. In order to quantify the variation in different sized pipe shapes and subjected to induction-based hardness are 490 MPa and 79.5 HRB, respectively.

2.1 The localized induction-based heat treatment

The induction machine used in the present research is an EIA model PowerCube 180/50 (absorbed power 12 kW, generated power 180 kVAR, maximum input current 17 A), formed by two main parts: the generator controlled by a microcomputer and the heating head. This machine can be used to apply either induction heating or induction welding. The generator provides and accurately controls the current and voltage necessary to obtain the desired magnetic field, which is set by the microcomputer and sensors that can be introduced into the processing system. The heating head used in the present application is the HH13, which is designed to work with a middle-low frequency (50 Hz), although different heads can be used to work at a medium-high frequency (200 Hz). Both the generator and the head are properly refrigerated with internal piping connected to a refrigerated hydraulic circuit.

An inductor, designed according to the specific needs, is connected to the heating head and generates a magnetic field whose intensity and spatial distribution depends on its shape, dimensions, and constituting material. In the specific case of the present application, the inductor consists of four identical coils connected in series (whose axes were 65 mm apart). Each coil is formed by three loops with the following geometrical dimensions: axial pitch 12 mm, internal diameter 44 mm, external diameter 56 mm, and wire diameter 6 mm.

The temperature setpoint and processing time were the operative parameters that were assumed to optimize the effect of the heat treatment on the mechanical properties. The temperature of the pipes was measured by an infrared sensor connected to the microcomputer controlling the generator. The temperature was measured in real-time and was used as a feedback signal to control the magnetic field generated by the coil.

The temperature range used in the present study was 700–850 °C, which falls between two intervals provided in the material datasheet described as soft annealing (650–700 °C) and hot forging deformation (950–1250 °C). Indeed, under 700 °C no significant improvements in ductility were observed. On the other hand, over 950 °C the reduction of hardness (and hence strength) would make the material too weak for the applications it was designed for. Once the temperature setpoint was achieved, a further safety factor was required as the temperature measurement could not guarantee the identification of the actual maximum temperature of the pipes. As a result, the authors decided not to pass 850 °C. Improving the total processing time, which is a current constraint imposed on the production process, was one of the main motivations of this study.

In order to take advantage of conventional process procedures applied in the factory, which would make pipe production more convenient, it was estimated that a single pipe could not be inside the coil for more than 15 s. This time would take into account that four parts are simultaneously treated during the induction heating and would include the increasing temperature ramp and time interval during which the temperature was maintained at its setpoint. Obviously, the shorter the total time, the better the attained production result would be.

Figure 1 shows three moments from the induction heat treatment performed on the pipes. In particular, Fig. 1a represents the moment before the coils are engaged on the first group of four pipes. Figure 1b captures the final part of the heating process, indicated by the rising steam and the hot portion of the pipes, seen in red. Finally, Fig. 1c depicts the moment immediately after the coils are lifted up to engage the subsequent group of pipes. A video showing the entire heating process applied to the 4×4 matrix of pipes is included as supplementary material with the manuscript. The video shows both the heating and part of the cooling phase. The latter consists in a first cooling step using air at room temperature (the duration is 30 s for the last group of pipes, with an increase equal to the total process time for each of the following groups) and a second cooling step in a tunnel with forced air at −2 °C for an additional duration of 270 s. For the sake of brevity, the second cooling step is not shown in the video. Only the moment when the matrix of pipes enters in the tunnel can be observed.

2.2 The micro-indentation test

The first type of mechanical test carried out on the specimens was a micro-indentation test performed by a Anthon-Parr instrumented hardness station, available at the Mech-LAB of the Department of Mechanical, Energy and Management Engineering (DIMEG) at the University of Calabria. This specific equipment is configured into four modules: the nano-indenter, the micro-indenter, the optical profilometer,
and the optical microscope. In the present study, only the micro-indentener and optical microscope modules were used.

The specimens analyzed by this type of test consisted of a piece of pipe (full cylinder in the case of the original material) whose surface had been prepared to achieve high precision geometrical properties. Such features, in turn, allowed for high accuracy and repeatability when the micro-indentation test was performed. More specifically, after obtaining an axial section, the specimen is mounted in a cylindrical thermoset resin using the Struers mounting press, model CitoPress-1. In this way, the exposed surface allows for the testing of possible mechanical property gradients in both the radial and axial directions.

Once mounted, the specimens were ground and polished in order to achieve the surface roughness necessary to attain accurate results through an instrumented micro-indentation test characterized by a rather small penetration depth (few micrometers). These final operations were carried out by a Struers grinding and polishing equipment, model Tegramin-25, using the grinding/polishing protocol prescribed for that specific steel. It is a five-step protocol, the main features of which are schematically reported in Fig. 2. Under each image of a disk-shaped abrasive tool, the following is indicated: the type of tool (SiC foil, disk, or cloth); the fineness of the abrasive surface (grit number for the foil, size of the suspension particle for disk and clothes); and the processing time.

After a series of tests, a protocol that guided execution of the instrumented micro-indentation test was established. This type of test measures the loading and unloading portions of the load/displacement curve when a specific indenter is applied to the surface under investigation. Generally, the test is carried out in load control (Fig. 3a), with fixed increasing and decreasing speeds ($v_i$ and $v_d$) and a pause in between ($t_p$). The consequent displacements are measured by a sensor mounted on the head (Fig. 3b) and the final load/displacement is obtained by eliminating the temporal coordinate (Fig. 3c). The choice of the maximum load

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**Fig. 1** Three moments during the induction heat treatment: a) the beginning of the treatment, the pipes were machined and placed in proper holders arranged on a 4 x 4 pattern fixed on a plate; b) the coils begin heating the first four pipes; c) the coils just raised up before moving on the second line formed by four other pipes, the cooling (in air) just started for the first four pipes. A video of the whole process, including both heating and the first step of cooling (in air), is available in the supplementary material of the manuscript.

**Fig. 2** Abrasive tools and main process parameters for surface treatment

| GRINDING | POLISHING |
|---------|-----------|
| PRE     | POL1      |
| FINE    | POL2      |

- SiC foil
grit 320 9 μm
cloth
- disc
grit 320 9 μm
cloth
- cloth
grit 320 9 μm
- cloth
grit 320 9 μm
cloth
- cloth
grit 320 9 μm
- cloth
grit 320 9 μm
$F_{\text{max}}$ is crucial due to the non-linearity of the entire experiment, whereas the resulting maximum displacement $\delta_{\text{max}}$ is simply measured by the equipment. Another parameter to be chosen is the indenter type, the most common being spheres, corner cube, Vickers, and Berkovich. In the present study, the parameters for $v_i$, $v_d$, and $t_p$ were chosen within the usual ranges used for steels: 50 mN/s, 50 mN/s, and 10 s, respectively. The selected indenter was the Vickers, and $F_{\text{max}}$ was fixed to 1.5 N. The value of 1.5 N represents the tradeoff between two opposite needs: the higher, the more accurate the measurements of load and displacement will be; the lower, the smaller the indent dimension on the surface will be, implying a more reliable retrieval of the properties’ gradients.

In its standard implementation, the mechanical properties attainable from this type of test are as follows:

- The Vickers hardness $H_{\text{V}}$, equal to the $F_{\text{max}}$ divided by the surface area of the resulting indentation;
- The plastic work $W_{\text{pl}}$, equal to the area between the loading and unloading curves;
- The Young’s modulus $E$, related to the initial slope of the unloading curve $S$.

Considering that the Young’s modulus is not significantly affected by thermal or mechanical treatments, properties $W_{\text{pl}}$ and $H_{\text{V}}$ were chosen to compare the effects of the localized heat treatment on material performance. These properties provide an estimation of the induced ductility and strength variations, respectively.

### 2.3 The tensile test

When possible, the use of a hardness test is particularly convenient for the mechanical characterization of a material. The highly localized volume of the material involved in the test means that the preparation of specific specimen according to standard protocols can be avoided. This offers advantages when evaluating the gradients of possible mechanical properties and in the ability to directly apply the test to prototypes or even real components. On the other hand, the findings obtained by an instrumented micro-indentation test cannot be easily applied to design procedures, which are generally based on mechanical properties determined by a tensile test (i.e., yield strength, tensile strength, plastic flow parameters, tensile ductility).

In this scenario, the correlation between the properties measured by the two types of test would be particularly useful, in order to identify the parameters meaningful for design (i.e., the ones measured by the tensile test) through an easier, cheaper, and less invasive experimental procedure (i.e., instrumented micro-indentation test). Unfortunately, determining this sort of correlation is strongly material-dependent and it is, therefore, not possible to define general relationships that would apply to any material. Ad hoc studies tailored to a specific material (or class of materials) must be carried out.

With this goal, a rectilinear tube-shaped specimen, whose geometry was chosen according to the ASTM standard E8/E8M-16a, was analyzed through a tensile test. Due to the localized heat treatment applied to the specimen, it was possible that the mechanical response could be heterogeneous and, therefore, it was not possible to assume the typical strain field occurring on a homogeneous specimen subjected to a uniaxial stress state. As discussed in the results sections, no significant radial or circumferential gradients were observed in terms of material properties. The only spatial variable affecting the mechanical response, as a result, is the axial direction. In this hypothesis, the variation of mechanical properties can be measured by evaluating the longitudinal strain gradients induced by the uniaxial stress state, which instead, for a homogeneous material, would have induced a uniform distribution of this strain component.

DIC methods were used to retrieve the longitudinal strain gradient. A schematic of the experimental setup is shown in Fig. 4. The tensile test was applied to a tubular specimen by a universal testing machine (MTS, model Criterion 45). According to ASTM standard prescriptions, two snug-fitting metal plugs were inserted in the ends of the specimen, to allow the machine jaws to properly grip the specimen. The test was carried out in displacement...
control by applying a load speed to the crosshead equal to 0.25 mm/min. Voltages proportional to the load and displacement values were used as reference signals to synchronize the images acquired by the camera, a Prosilica model ATV-GT2450 (resolution $2448 \times 2050$ pixel, pixel dimension $3.45 \mu m \times 3.45 \mu m$, maximum frame rate 15 Hz). The image illumination was optimized by two diode light sources placed symmetrically around the camera. All the signals (voltages and images) were acquired by a workstation interfaced with all devices by way of the data acquisition system, ISI-SYS model DAQ-STD-8D.

Figure 5 shows some images used in the DIC analysis. Figure 5a shows in more detail the image used for the metric calibration, while Figs. 5b and c depict the first and the last images acquired during the tensile test. Assuming that the only spatial coordinate affecting the mechanical response is the axial direction ($z$-axis), 11 zones (the alternated yellow and red rectangles in Fig. 5b), where material properties are assumed to be constant due to the reduced extension, were defined and analyzed separately. The dimensions of each zone are 2 mm and 1 mm, along the $x$- and $z$-directions, respectively. The existing stress state for the whole specimen is uniaxial, hence, unchanged in the highlighted zones, whereas the strain state changes according to the mechanical properties.

2.4 The specimens

Different types of specimens were analyzed with the aim of evaluating the impact of the localized heat treatment on the mechanical properties of the different process parameters, as well as the effectiveness of the proposed testing methods.

Table 1 summarizes the main features of the investigated specimens. The base material was initially tested (specimen #0), which consists of a full bar with a 15 mm outer diameter. Specimen #1 is a lathe-machined tube with inner and outer diameters equal to 7 and 11 mm, respectively. All other specimens were subjected to heat treatments after being machined. In addition, specimen #2 was annealed in order to evaluate the maximum ductility attainable from the material, whereas all the others (specimens #3 to #8) were treated by localized induction heating using different process parameters (temperature and time treatment) and different pipe geometry (inner and outer diameters).

3 Experimental results

Before investigating the effect of the localized induction heat treatment on the material’s mechanical response, three conditions were analyzed in order to establish reference values for the mechanical properties. Initially, specimens #0, #1, and #2 were tested by microindentation tests, and the reference values for the $W_c$ and $H_d$ were evaluated. Subsequently, the same properties were measured on specimens from #3 to #8 with the goal of identifying the effects of the localized induction heating. Several tests were also carried out to evaluate possible spatial gradients of the mechanical properties. Finally, a uniaxial test was performed on specimen #5 in order to
evaluate the correlation between the properties obtained by the two experimental approaches.

### 3.1 Reference specimens subjected to instrumented micro-indentation test

Specimens #0, #1, and #2 were initially tested to establish reference values for the mechanical properties and to understand the potential existence of their spatial gradients. The geometric axial symmetric shape of the specimen and the type of (mechanical and thermal) treatments applied to the material meant that circumferential gradients could be excluded, whereas the axial and radial directions were considered potential spatial variables for these gradients. In this hypothesis, different areas were investigated by performing the micro-indentation tests at several known coordinate points. In particular, the three areas highlighted by red boxes in Fig. 6a were considered for the base material (specimen #0), while the two red boxes in Fig. 6b were analyzed for specimens #1 and #2. In all the cases, no significant spatial gradients were observed.

The material properties obtained for these three reference specimens through the instrumented micro-indentation tests are shown in Fig. 7. In particular, Fig. 7a and b show the Vickers hardness ($H_{\text{it}}$) and the plastic work ($W_{\text{pl}}$) for the base material (specimen #0), while Figs. 7c and d show the same for the lathe-machined material (specimen #1), and Fig. 7e, f for the machined and annealed material (specimen #2). The continuous red lines represent the mean value $\mu$, while the dashed lines show double the standard deviation $\sigma$ added and subtracted from the mean value.

Three matrices of tests were carried out on the aforementioned highlighted areas: on Fig. 7a—for the base material ($11 \times 11, 17 \times 11, 21 \times 25$, total 833 tests) and the two same matrices—Fig. 7b—on the other two specimens ($2 \times 19 \times 17$, total 646 tests). Due to the highly localized material volume involved in the single test, the results that fell far from the average value were discarded. By calculating average values for $H_{\text{it}}$ and $W_{\text{pl}}$, it is possible to conclude that the machining does not imply substantial changes in the mechanical response, while the annealing deeply modifies the material, significantly increasing its ductility and decreasing its hardness.

Table 2 shows the statistical parameters $\mu$ and $\sigma$ of $H_{\text{it}}$ and $W_{\text{pl}}$ for the three reference specimens. The mean values of

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**Table 1** Specimens and the (mechanical and heat) treatments applied to them. $M$, machined; $A$, annealed; $LI$, localized induction heating; $D_i$ and $D_o$, inner and outer diameters

| ID | Mechanical and heat treatments | Dimensions |
|----|--------------------------------|------------|
|    | Type                          | $T$ (°C)   | $t$ (s) | $D_i$ (mm) | $D_o$ (mm) |
| #0 | None                          | NA         | NA      | –       | 15.0       |
| #1 | M                             | NA         | NA      | 7.0     | 11.0       |
| #2 | M+A                           | 935        | 468     | 7.0     | 11.0       |
| #3 | M+LI                          | 700        | 10      | 7.0     | 11.0       |
| #4 | M+LI                          | 800        | 5       | 7.0     | 11.0       |
| #5 | M+LI                          | 850        | 1       | 7.0     | 11.0       |
| #6 | M+LI                          | 780        | 1       | 4.0     | 8.0        |
| #7 | M+LI                          | 850        | 1       | 5.0     | 11.0       |
| #8 | M+LI                          | 850        | 6       | 9.5     | 14.0       |
specimen #1 were assumed as reference values used to compare and quantify the mechanical properties obtained on the induction heat-treated materials, reported in the following section.

3.2 Localized induction heat treated specimens subjected to instrumented micro-indentation test

The next three specimens (#3, #4, #5) tested by the micro-indentener are characterized by the same size ($D_i = 7$ mm, $D_o = 11$ mm) but by different process parameters ($T$ and $t$). The aim of these tests was to understand if different combinations of processing temperature/time could generate similar mechanical properties. Lower process temperatures were applied for a longer time, in order to allow less energetic configurations more time to re-arrange the crystalline structures. Similarly, for these specimens, the areas shown in Fig. 6b were tested to identify the potential spatial gradients of the properties. In this case, the axial direction ($x$-axis) clearly displayed a gradient, whereas along the radial direction ($y$-axis) no significant mechanical property variations were observed. The lack of gradients along the radial
direction leads us to consider the heat treatment as volumetric, implying that the entire volume of the treated component undergoes the same mechanical property variations.

Figure 8 shows the results for this group of specimens. In this case, the graphs are displayed according to the local abscissa $x$ (spanning an interval of 20 mm length), while the $y$ information is not considered. The continuous (mean value) and dashed (double the standard deviation distance from the mean value) curves have the same meaning as the straight lines in Fig. 7. The gray bands in the graphs emphasize minimum and maximum values obtained in reference conditions (Table 2, specimens #1 and #2) for the $H_{\text{it}}$ and $W_{\text{pl}}$.

The shape of the gradient is quite clear, consisting of a single concavity variation with a maximum occurring around the center of the warming coil (having a length of 40 mm). The identification of the center, however, is not straightforward due to both the uncertainty arising during the positioning of the pipe pieces inside the specimen holder and the machining of the pipes themselves, done in order to obtain the specimen.

The results of Fig. 8 clearly demonstrate that the timing of heat application is not particularly relevant, whereas the processing temperature is what significantly impacts the mechanical properties. Results show a clear increase (decrease) of ductility (hardness) with an increase in temperature. Hence, if a localized induction treatment is performed on a pipe with the aim of increasing the formability of the portion to be subjected to high plastic deformations, a quite short process (merely 1 s) applied at 850 °C produces a level of ductility not far from that which is attainable in the annealing process, which instead requires a 468-s treatment. Indeed, in this case, the maximum $W_{\text{pl}}$ value is equal to 3149 nJ, not far from 3331 nJ obtained by the conventional annealing process.

Subsequently, an additional group of three specimens was tested (#6, #7, #8) with the aim of evaluating the combined effects of the process parameters ($T$ and $t$) and pipe sizes ($D_i$ and $D_o$). Similarly, for this group of specimens the possibility of gradient formation of the mechanical properties was evaluated by performing a matrix of tests, as shown in Fig. 6b. Again here, only the axial gradients were observed and the treatment could be considered volumetric, with further tests being carried out along the line shown in Fig. 6c.

![Specimen II3](image1)

![Specimen II4](image2)

![Specimen II5](image3)

![Specimen II3](image4)

![Specimen II4](image5)

![Specimen II5](image6)

**Fig. 8** Vickers hardness ($H_{\text{it}}$) and plastic work ($W_{\text{pl}}$) obtained for the second group of three specimens, characterized by the same geometrical dimensions but different processing temperatures and times: **a** and **b** specimen #3; **c** and **d** specimen #4; **e** and **f** specimen #5. The gray bands in the graphs emphasize minimum and maximum values obtained in reference conditions (Table 2, specimens #1 and #2) for $H_{\text{it}}$ and $W_{\text{pl}}$. 

| Specimen | Hardness ($H_{\text{it}}$) [Vickers] | Plastic work ($W_{\text{pl}}$) [nJ] |
|----------|-------------------------------------|-------------------------------------|
|          | $\mu$ | $\sigma$ | $\mu$ | $\sigma$ |
| #0       | 235.1 | 6.8     | 2530  | 59      |
| #1       | 227.2 | 4.9     | 2543  | 47      |
| #2       | 138.9 | 3.8     | 3331  | 69      |

### Table 2 Mean value $\mu$ and standard deviation $\sigma$ of $H_{\text{it}}$ and $W_{\text{pl}}$ for the three reference specimens
This was done by decreasing the step between two consecutive indentations with the goal of increasing the spatial resolution used to retrieve the axial gradients. The results are shown in Fig. 9. By comparing specimens #6 and #7, it is possible to conclude that, regardless of the different dimensions of the two specimens, temperature is still the dominant parameter. But when the overall dimension of the specimen grows significantly, as in the case of specimen #8, size begins to be an influencing parameter as well. Indeed, the comparison of specimens #7 and #8 shows that the increase (decrease) of ductility (hardness) obtained for the bigger specimen (#8) is smaller, even if the process is applied at the same temperature (850 °C) for a much longer time (6 s instead of 1 s). In addition, it is worth mentioning that specimen #8 has not only bigger diameters, but is also longer (the investigated length is 30 mm instead of 20 mm), which required that the specimen be broken into two pieces due to limitations of the mounting system. The ends of the two facing surfaces had to be machined and some local alterations occurred, which explains the experimental data missing over a length of about 5 mm.

3.3 Specimen subjected to tensile test and correlation with micro-indentation test

Specimen #5 was selected to undergo a tensile test instrumented by DIC equipment for the elongation measurement, according to the procedure described in “Sect. 2.3.” The data obtained would be subsequently correlated with those obtained through the micro-indentation test. More specifically, a pipe-shaped specimen was fixed in the universal testing machine jaws using two snug-fitting metal plugs, as shown in Fig. 4. An internal trigger signal, generated by the experimental apparatus, allowed the applied load, crosshead displacement, and an image of the specimen at a specific time to be saved. The trigger signal was generated for every 10 µm of crosshead displacement or 250 ms, whichever occurred first. An analysis of the images done through correlation algorithms allowed for an evaluation of the local normal strain in the 11 areas highlighted in Fig. 5. The local stress, by comparison, was assumed to be uniform until the necking onset, which implies a highly localized overload of the specimen at the weakest section, rendering the assumption of uniform stress and strain no longer valid. The local true stress \( \sigma \) and true strain \( \varepsilon \) values were calculated by the following equations:

\[
\sigma = \frac{P}{A_0} \left( 1 + \frac{\partial w}{\partial z} \right) \\
\varepsilon = \log \left( 1 + \frac{\partial w}{\partial z} \right)
\]  

The stress/strain curves shown in Fig. 10 were evaluated at the different abscissas \( z \). In Eq. (1), \( P \) is the applied load, \( A_0 \) the initial cross section, and \( w \) the displacement component along the \( z \)-direction. The derivative with respect to \( z \) represents the nominal (or engineering) deformation used to calculate the true values. Figure 10 clearly shows how the ductility increases in the center of the specimen (around \( z = 0 \)), where the curves extend up to considerably...
higher strain levels. These curves cannot be considered as representative of the complete mechanical behavior up to the failure of the material, because a fracture of the specimen occurred where the necking began, due to the stress concentration. From that instant, the stress in no longer uniform, and the fracture that took place in this section does not allow for an evaluation of the stress/strain response evolution as a consequence of the localized heat treatment applied to the material.

Nevertheless, some further considerations arise when analyzing the data of Fig. 10. In fact, according to theory of plasticity [29], the condition revealing the necking onset is given by the following equation:

\[ \frac{\partial \sigma}{\partial \varepsilon} = \sigma, \quad (2) \]

which can be easily imposed to the curves shown in Fig. 10. Figure 11 shows the plot of the functions \( \frac{\partial \sigma}{\partial \varepsilon} \) at different abscissas \( z \), whereas the red points represent the coordinates \((\varepsilon_N, \sigma_N)\) that satisfy Eq. (2), representing the necking onset. These parameters \((\varepsilon_N, \sigma_N)\) can be considered as the material’s properties and they can be put in a graph as a function of abscissa \( z \), shown in Fig. 12, where the gradients of both \( \varepsilon_N(z) \) in Fig. 12a and \( \sigma_N(z) \) in Fig. 12b are reported. It is possible to notice the same trend of parameter \( W_{pl} \), with its maximum value occurring at the midplane.

By using the fitting curves of parameters \( \varepsilon_N(z) \), \( \sigma_N(z) \), and \( W_{pl}(z) \), an empirical correlation law can be easily obtained. Before identifying this law, it is necessary to “align” the different curves, which implies translating them horizontally in order to set the same abscissa \( z \) as that of the maximum values. The coincidence of the maxima is a reasonable assumption, considering the difficulties in the practical identification of such a point and the fact that the material characterized by the highest ductility (maximum \( W_{pl} \)) should also show the latest possible necking onset condition (maximum \( \varepsilon_N \) and \( \sigma_N \)).

Subsequently, by matching the second-degree polynomials, the following two equations can be obtained:

\[ \varepsilon_N = 0.8531 \times 10^{-3} W_{pl} - 2.515, \]
\[ \sigma_N = 0.4834 W_{pl} - 952.8, \]

which define the empirical relation existing between the mechanical properties obtained by a tensile test \((\varepsilon_N, \sigma_N)\) and an instrumented micro-indentation test \( W_{pl} \). Obviously, these correlations do not contain the entire range of properties involved, but have proven to be consistent on the considered intervals and, therefore, reasonable to slightly extrapolate these equations beyond the studied range.

4 Discussion and conclusions

The study described in the present paper aims to identify experimental tools capable of evaluating the mechanical response of materials subjected to heat treatment, implying significant modifications and potential gradients of the material’s properties—i.e., induction heating.
For this purpose, the instrumented micro-indentation test resulted as quick, reliable, and economical. In addition, two quantities—i.e., the Vickers hardness $H_v$ and plastic work $W_{pl}$—achieved through the simple post-processing of the loading/unloading curves, proved to be a good comparative estimation of strength and ductility when a specific material, subjected to different treatments, is analyzed. Due to the complex stress state induced by this type of test, mechanical properties directly usable for design purposes and typically obtained by a standard tensile test—i.e., yield and tensile strength, ductility, and plastic flow parameters—cannot be measured in a straightforward manner. As such, authors have demonstrated how, for a fixed material, simple empirical mathematical laws can be estimated by correlating the experimental results of the micro-indentation tests with the mechanical properties measured on the same material. This is done through a standard tensile test on a material whose strain distribution is characterized by non-negligible spatial gradients retrieved by a full-field optical method—i.e., digital image correlation (DIC).

A comparison of the results attained through these two experimental methods demonstrate how, for the analyzed material in a limited range, the ductility (quantified as the stress or strain at the necking onset, measured by the tensile test) is directly proportional to the plastic work (quantified as the area between the loading and unloading curves, measured by the micro-indentation test). If the range is extended, the correlation law (still monotonic) becomes non-linear and can be evaluated by points or by a piecewise linear function.

The material investigated in the present study is a cold drawn bar of 11SMnPb30 steel, characterized by good,
high-speed machinability and limited weldability. Bars made from this material were used to build pipes for different hydraulic applications. A short portion (about 40 mm) of the pipes, machined out of the base material, was subjected to an induction heat treatment by changing the two main process parameters—i.e., temperature and processing time. The effect on the pipe size was also investigated.

The experimental campaign carried out by micro-indentation tests was divided into three steps, each of which involved three different specimens.

The tests performed on the first set of specimens were initially intended to determine reference values for the mechanical properties of the material in its virgin form (without any kind of heat treatment performed on it or just machining), and then again when a conventional annealing was applied. In the first case (specimens #0 and #1), the material exhibits its maximum strength and minimum ductility, with a consequent maximum hardness (227.2 Vickers) and minimum plastic work (2543 nJ) that represents the best configuration to carry the highest load in normal working conditions. On the contrary, in the second case (specimen #2) the material is characterized by minimum strength (minimum hardness, 138.9 Vickers) and maximum ductility (maximum plastic work, 3331 nJ), which represents the best configuration when the material must be processed by plastic deformation—e.g., bending operations. The potential effect of the machining operation (specimen #0 vs specimen #1) resulted as negligible.

Subsequently, for the second group of specimens (#3, #4, and #5), the geometry of the pipes was fixed (inner and outer diameters equal to 7 and 11 mm, respectively), and three processing temperatures were applied (700 °C, 800 °C, and 850 °C) for a corresponding, decreasing amount of time (10 s, 5 s, and 1 s). Appreciable spatial gradients for all specimens were observed along the axial direction, whereas along the radial direction no significant variation was observed. For this group of specimens, the best results in terms of ductility were observed for specimen #5 (850 °C, 1 s), with a maximum plastic work of 3149 nJ, a value quite close to that obtained for the annealed specimen (3331 nJ). Temperature resulted as the most influential parameter. Indeed, an increased processing time at lower temperature did not imply any improvement of ductility.

Finally, in the third and last group of specimens (#6, #7, and #8), the combined effect of the processing parameters (temperature and time) and geometric dimensions was investigated. A comparison of specimens #6 and #7 showed that the bigger thickness (3 mm vs 2 mm) and bigger outer diameter (11 mm vs 8 mm) of specimen #7 does not affect the radial gradients, whereas the higher processing temperature used for #7 (850 °C vs 780 °C), again, allowed for a higher maximum plastic work value (3082 nJ vs 2789 nJ). On the other hand, the longer processing time of specimen #8, if compared with specimen #7 (6 s vs 1 s) at the same temperature (850 °C), was not sufficient to attain the same maximum value of plastic work (2948 nJ vs 3082 nJ), suggesting that a bigger outer diameter (14 mm vs 11 mm) implies a reduced effectiveness of the induction equipment used in the present work.

In conclusion, the authors demonstrated how a localized induction heat treatment can be successfully performed on pipe-shaped specimens in order to attain a significant local increase of the material ductility (and consequently its formability) without impacting the mechanical properties of the entire treated part. For the specific type of steel considered and the equipment employed, an induction heat treatment performed at 850 °C and applied for 1 s provided a local ductility value quite close to that attainable with a conventional annealing treatment with a duration of several minutes, provided that the outer diameter does not exceed 11 mm. The process also demonstrated the existence of a clear correlation between stress and strain at the onset of necking (measured through a conventional tensile test) and plastic work (measured by a micro-indentation). The latter measurement method can be adopted as a quick, reliable, and cheap characterization method for materials processed through innovative treatments.

In the future, further investigations could be carried out in order to better understand the mechanics underlying the mechanical properties’ variation induced by the localized induction heat treatment. In particular, residual stress measurement methods (e.g., X-ray diffraction, Barkhausen noise analysis, hole drilling) could reveal the presence of stress states arising from the heat treatment that could impact the mechanical properties or the results of the measurement methods applied to the treated material.

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**Declarations**

**Ethics approval** The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.
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