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RESEARCH PAPER

EFFECT OF ULTRAFAST HEATING ON AISI 441 FERRITIC STAINLESS STEEL

Giulia Stornelli[1,], Luciano Albini[2], Paolo Emilio Di Nunzio[2], Giulia Tiracorrendo[2], Bryan Ramiro Rodriguez Vargas[1], Andrea Di Schino[1]*

[1] Università degli Studi di Perugia, Dipartimento di Ingegneria, Perugia, Italy
[2] RINA Consulting—Centro Sviluppo Materiali SpA, Via Castel Romano 100, 00128 Roma, Italy

*Corresponding author: giulia.stornelli@unipg.it, Università degli Studi di Perugia, Dipartimento di Ingegneria, Via Goffredo Duranti, 93, 06125 Perugia, Italy

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ABSTRACT

The use of the ultrafast heating (UFH) heat treatment process attracted great attention in the last few years, following the requirements for CO2 emissions reduction. The effect of ultrafast heating (UFH) treatment on AISI 441 ferritic stainless steels is reported in this paper. Results show that a minimum temperature of 975 °C is required to achieve a fully recrystallized microstructure. The study highlights the effect of ultrarapid annealing on grain size evolution as a function of different adopted process parameters. The obtained microstructure is related to mechanical properties in terms of ultimate tensile stress and hardness. The tensile properties fit well with the measured average grain size, thus allowing to target the tensile properties.

Keywords: ultrafast heating; heat treatment; stainless steels; microstructure

INTRODUCTION

In last years, the adoption of ultra-fast heating (UFH) heat treatment reached large attention from both scientific and industrial points of view [1]. The above heat treatment is favored by the possibility to heat metals by means of an induction magnetic process consisting in transferring heat to the metal by an induction coil which generates an electromagnetic field. The alternating magnetic field generated by the induction coil penetrates the metallic component and creates the well-known eddy currents inside the metallic object. Such currents heat the metal by the Joule effect. Based on the above description UFH represents a way to optimize industrial processes by a reduction of heating time. This will consequently increase productivity [2–5]. Promising results were reported concerning the application of the process to carbon steels [6,7]. Such results anyway also outlined the most important limitations of UFH process with respect to conventional steel-processing lines [8]. As a matter of fact, the increase in terms of heating rate strongly affects the phase transformation kinetics and as consequence steel mechanical properties: results reported in literature clearly show that an increase in terms of heating rate enhances the α/γ transformation temperature, with a refinement of the austenitic grain size [9-12]. At the same time, an increase in α/γ transformation temperature [13] reduces the available carbon amount which can be dissolved in γ phase and this implies a reduction of the hardenability [14]. Moreover, during UFH, the carbo-nitrides is reported to strongly depends also on heating time and not just temperature: this is to be considered as quite unusual with respect to what commonly happens in conventional annealing processes [15, 16]. As far as carbon steels are concerned, UFH is therefore reported to be promising in the austenitization step of the process (before quenching and tempering) [17–26]. It is also successfully applied after cold rolling to promote grain refinement [27, 28], leading to an increase in tensile properties [29–31]. It is reported that the application of UFH inhibits the dislocation re-organization which is typical of recovery [32–35]. Hence recrystallization process occurs in direct competition with austenitization [36–38]. The final microstructure of steel which underwent a rapid heating process is therefore strongly related to the heating rate and the peak temperature reached during the treatment [39, 40]. In the case of a high heating rate and not adequate peak temperature, a completely recrystallized microstructure is not achieved [41]. Very little information is available about the effect of UFH on stainless steel.

Stainless steels are nowadays used in almost every application field. In fact, thanks to their peculiar combination of properties (strength and corrosion resistance) since their first development in the early 19th century, they have been adopted in automotive, construction and building, energy, aeronautical, medical and food applications [42]. Among those, ferritic stainless steels are widely used in the automotive industry especially following their ability to be formed and welded [43, 47]. Such ability is strongly affected by the microstructure in terms of average grain size: therefore, the possibility to increase productivity by innovative heat treatment without significantly modifying the microstructure is an important goal to be targeted.

This paper aims to investigate the effect of UFH on commercial ferritic stainless steel in terms of microstructure and mechanical properties.

MATERIAL AND METHODS

The material studied in this paper is an AISI 441 stainless steel (X2CrTiNb18 – EN 1.4509). Its chemical analysis is reported in **Table 1**.

Table 1 Chemical analysis of AISI 441 (main elements, mass %).

Steel grade	C	Cr	Ni	Mo	Others
AISI 441	0.02	17.5-18.5	-	-	Ti+Nb=0.55%

Specimens with size 120 x 700 mm in the state of cold rolled material (cold reduction= 50%) were heated in an induction furnace allowing a maximum heating power P_{max} of 100 kW. Two different powers set were tested (80% and 90% of P_{max}), allowing heating rates ranging 210-260 °C/s and targeting different peak temperatures: 750 °C, 900 °C, 950 °C, 975 °C, 1000 °C, 1050 °C.

After heat treatment the specimens were etched with Vilella's reagent. Microstructure was then analyzed by a light microscope (Eclipse LV150 NL, Nikon, Tokyo, Japan) and, in the case of fully recrystallized samples, image analysis was performed using a dedicated software (AlexaSoft, X–Plus, serial number: 6308919690486393, Florence, Italy). From the image analysis it was possible to determine and compare the average grain size of AISI 441 steel as a function of heat treatment conditions.

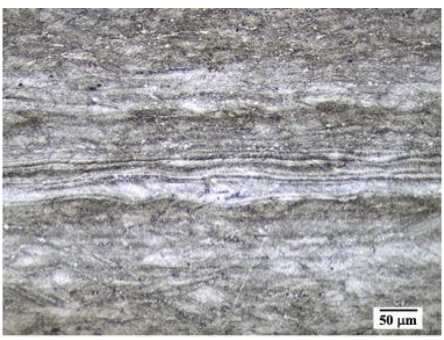
Hardness was measured by a Vickers durometer (HV–50, Remet, Bologna, Italy) with 10 kg load at ¼ of the thickness. Three indentations were carried out for each specimen and the average value was considered. Tensile tests were carried out on two ISO 50 specimens; the average of two test was considered for each condition.

RESULTS AND DISCUSSION

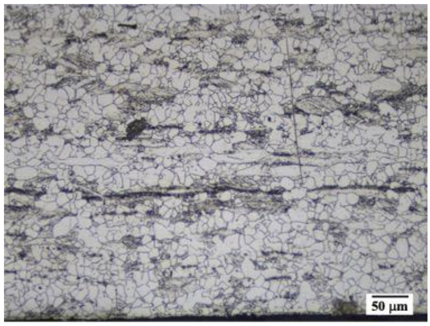
Performed test results in process conditions and microstructures are summarized in **Table 2**. Results show that a minimum temperature of 975 °C is required in order to achieve a fully recrystallized microstructure with a fine average grain size of 16.7 ± 0.8 μm. Just as an example the obtained microstructure corresponding to 750 °C, 960 °C, 975 °C, 1075 °C peak temperatures are reported in **Fig. 1**.

Table 2 Heat treated specimens: maximum reached temperature and microstructure

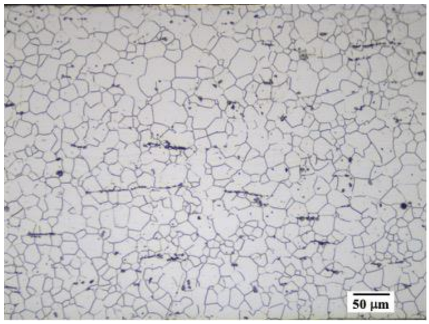
T_{max} (°C)	Average grain size (mm)
750	Not recrystallized
880	Partially recrystallized
890	Partially recrystallized
925	Partially recrystallized
960	Partially recrystallized
975	16.7 ± 0.8
990	20.0 ± 1.0
995	16.7 ± 0.8
1037	21.7 ± 1.1
1044	26.8 ± 1.3
1045	31.1 ± 1.5
1075	25.6 ± 1.3



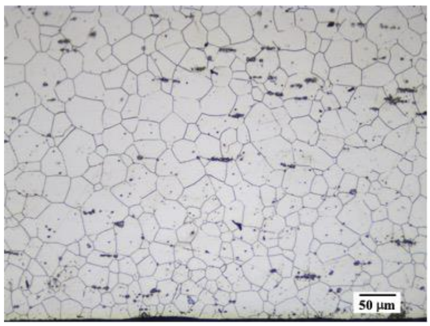
T_{max}=750 °C



T_{max}=960 °C



T_{max}=975 °C



T_{max}=1075 °C

Fig. 1 Microstructures obtained at different temperature peaks

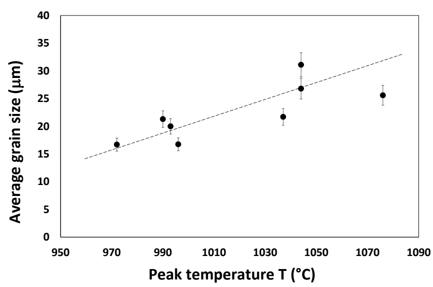


Fig. 2 Grain size dependence as a function of peak temperature

Thus, the average grain size increases as T_{max} increases (**Fig. 2**) following a linear behavior, as expected since no abnormal

growth is observed. The limited grain growth and the small values of grain size obtained by the considered process, even in the case of high temperatures (about 1050 °C), is due the high heating rate which activates the nucleation of all the recrystallization nuclei in a very short time. Furthermore, the short treatment time limits the extent of coarsening of the microstructure by grain growth.
The tensile behavior has been related to the average grain size according to the following Hall-Petch relation:

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}} \quad (1.)$$

where σ_y is the ultimate tensile strength, σ_0 is the intrinsic strength of the material (corresponding to single crystal structure) and k_y is a constant depending on the alloy (**Fig. 3**). Considering a σ_0 value of 100 MPa, as commonly accepted in the case of steels [35] a k_y value of about 60 MPa/mm$^{1/2}$ is found. Such value is in good agreement with respect to what is found in ferritic steels carbon steels [48]. Similar behavior is reported in terms of hardness (**Fig. 4**).

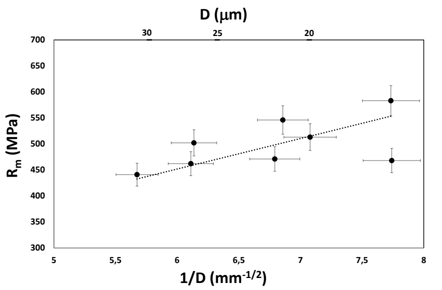


Fig. 3 Ultimate tensile strength dependence on average grain size

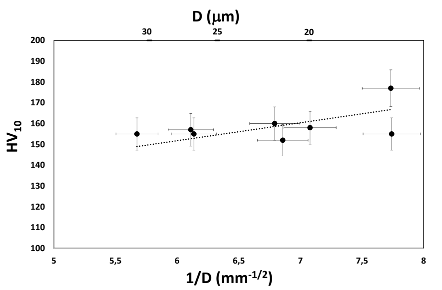


Fig. 4 Hardness dependence on average grain size

The above result allows to determine the average grain size required to achieve a given target tensile stress, hence the peak temperature needed according to **Fig. 2**.

CONCLUSIONS

Induction annealing process allowing ultrafast heating has been applied to AISI 441 stainless steel. Results show that a minimum average grain size of 16.7 ± 0.8 µm can be achieved with a minimum peak temperature of 975 °C and that the final grain size slowly increases with increasing the peak temperature. The tensile properties fit well with the measured average grain size, thus allowing to target the tensile properties.

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