

## RESEARCH PAPER

### EFFECT OF ULTRAFAST HEATING ON AISI 304 AUSTENITIC STAINLESS STEEL

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#### ABSTRACT

This study explores the effects of ultrafast heating on AISI 304 austenitic stainless steel. The research shows that ultrafast heating can lead to fine-grained mixed microstructures in steel, making it a potential alternative for modifying microstructure in stainless steel. The study demonstrates that a minimum temperature of 980 °C is required to achieve a fully recrystallized microstructure. The results also suggest that a lower temperature can result in a finer recrystallized grain size compared to higher temperature results. The study provides valuable insights into the impact of ultrafast heating on the microstructural constituents, recrystallization temperatures, and mechanical properties of investigated steel.

**Keywords:** ultrafast heating; heat treatment; stainless steels; AISI 304

#### INTRODUCTION

The drive towards greater energy efficiency in industrial processes has profoundly impacted various technologies, including heat treatments for steel. In recent years, there has been growing interest in the use of ultra-fast heating (UFH) - heating rates greater than 100°C/s - in cold-rolled steels due to its potential for faster cycle times and increased energy efficiency [1, 2]. This process utilizes induction heating, a non-contact technique that replaces resistive heating in heat treatment. The method involves inducing eddy currents on the surface of a ferromagnetic metal that is placed in an alternating magnetic field. This generates the Joule heating effect, resulting in rapid and efficient heat generation of the metal. Hence, UFH can be considered a promising alternative to traditional heating methods in the steel industry [3–6].

The cooling rate, applied to the steel immediately after heat treatment, plays a significant role in determining its final microstructure, potentially resulting in grain refinement and modification of the steel's strength [7–10]. The UFH process leads to the refinement of the austenitic grain and reduced material hardenability due to the increase in  $\alpha/\gamma$  transformation temperature, caused by the higher heating rate (HR). This is because a higher HR decreases the amount of carbon that can dissolve in austenite. The resulting microstructure is dependent on the HR and the maximum temperature achieved [11–13]. Stornelli et al. studied the effect of UFH on AISI 441, where an incomplete recrystallized microstructure was observed due to the use of an unsuitable maximum temperature and high heating rate [14].

The scope of efficiency in industrial processes requires materials that can meet this objective. Stainless steels used today are considered efficient materials in various applications where improved properties are required [15–18]. Austenitic stainless steels are a highly utilized material due to their excellent properties such as non-magnetic behavior, good formability, and

weldability, in addition to their remarkable resistance to corrosion and oxidation [19–20]. However, the yield strength of annealed plates is relatively low, which limits the use of austenitic stainless steel in engineering applications. Therefore, a challenge for scientists and engineers is to improve the yield strength while maintaining other favorable properties. Structural refinement is a widely used strengthening technique, which has been shown to be an effective approach in enhancing yield strength by refining the grain structure [21–27].

Liu et al. conducted a study of ultra-flash annealing on a commercial 316L austenitic stainless steel, resulting in a heterogeneous structure of recrystallized austenitic grains and non-recrystallized areas [28]. Sun et al. evaluated the effect of heating rate on the transformation of 304 steel and its relationship with mechanical properties. In addition, this type of treatment has enabled the generation of nanostructures and their subsequent application [29]. However, information in the literature regarding the use of UFH in austenitic stainless steels is scarce, making it feasible to study the microstructure and its effect on the mechanical properties of these materials.

The aim of this work is to evaluate the microstructural change and their relationship with the mechanical properties when a commercial AISI 304 steel undergoes a UFH process.

#### MATERIAL AND METHODS

AISI 304 austenitic stainless steel (X5CrNi18-10 / EN 1.4301) was studied. The chemical composition is shown in **Table 1**.

**Table 1** Chemical composition of AISI 304 (mass. %).

Material	Fe	C	Cr	Ni	Mn	Si
AISI 304	Bal.	0.07	17.5-19.5	8.0-10.5	2.0	1.0

120 x 700 mm sized samples of cold-rolled material with a 50% reduction were subjected to heating in an induction furnace with a maximum heating power of 100 kW (Pmax). Two different power settings were used (80% and 90% of Pmax) to achieve the HR between 200-260 °C/s and target peak temperatures (Tmax) of 950 °C, 975 °C, 1000 °C 1050 °C, 1100 °C and 1150 °C.

To determine and compare the average grain size of AISI 304 stainless steel as a function of heat treatment conditions, the specimens were prepared using conventional metallographic methods (according to ASTM E3). After heat treatment, the specimens were etched in an HNO3+H2O solution in an electrolytic cell using AISI 316L as the cathode. Microstructure was examined using an optical microscope (Eclipse LV150 NL, Nikon, Tokyo, Japan), and for fully recrystallized samples, image analysis was conducted with specialized software (AlexaSoft, X-Plus, serial number: 6308919690486393, Florence, Italy).

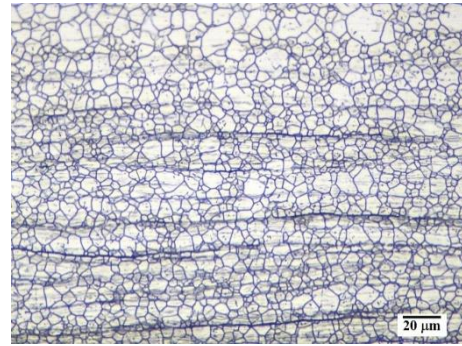
The hardness of the specimens was measured using a Vickers durometer (HV-50, Remet, Bologna, Italy) with a 10 kg load applied at 1/4 of the thickness. Ten indentations were made on each specimen, and the average value was calculated. Tensile tests were performed on two ISO 50 specimens, and the average of the two tests was used for each condition.

### RESULTS AND DISCUSSION

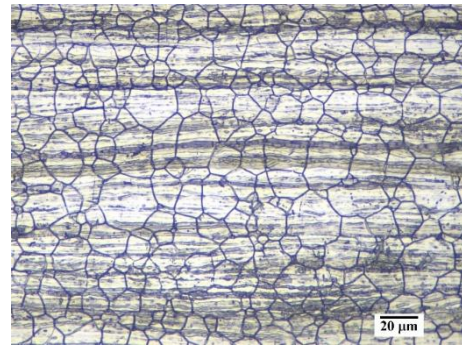
The data from **Table 2** shows that as the temperature increases from 984 °C (HR = 240 °C/s) to 1180 °C (HR = 207 °C/s), the microstructure in the material exhibits growth of the austenitic grain size (**Fig. 1**). This phenomenon could be attributed to the heating and cooling rates, as an increase in the heating rate also corresponds to similar behavior in the cooling rate, which is influenced by the thermal gradient between the material and the environment. A higher cooling rate tends to favor the formation of finer grain size, just as the solidification with rapid cooling promotes the nucleation and growth of smaller grains.

**Table 2.** Maximum reached temperature with heating rates (HR) and average grain size of heat-treated specimens.

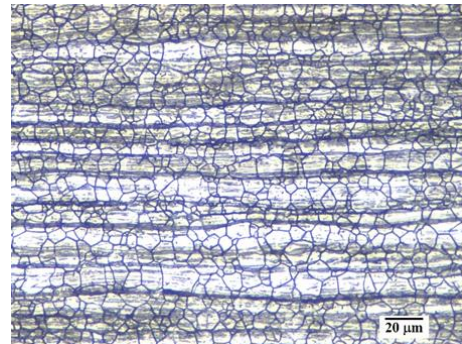
T <sub>max</sub> (°C)	Average grain size (µm)
984	4.11 ± 0.4
1018	4.65 ± 0.5
1053	6.64 ± 0.6
1062	5.95 ± 0.6
1063	10.85 ± 1.0
1079	6.82 ± 0.7
1086	8.71 ± 0.9
1109	9.93 ± 1.0
1117	9.98 ± 1.0
1135	15.23 ± 1.9
1180	12.73 ± 1.5



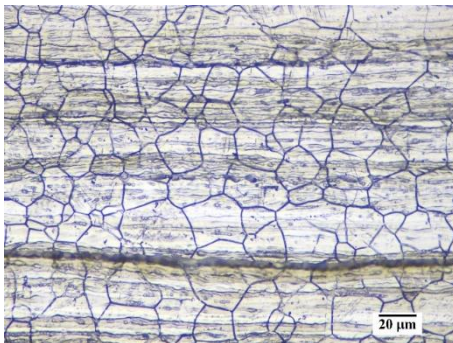
T<sub>max</sub> = 1018 °C



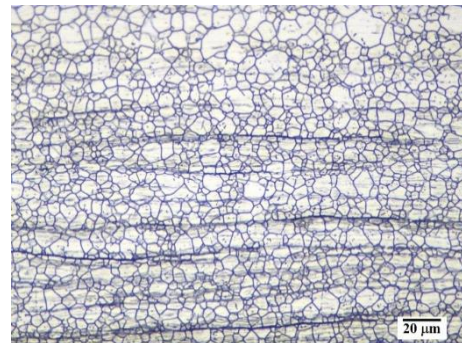
T<sub>max</sub> = 1109 °C



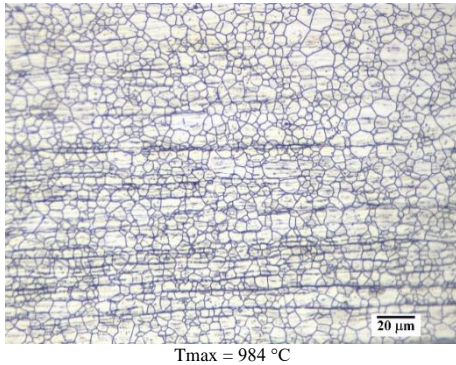
T<sub>max</sub> = 1053 °C



T<sub>max</sub> = 1180 °C



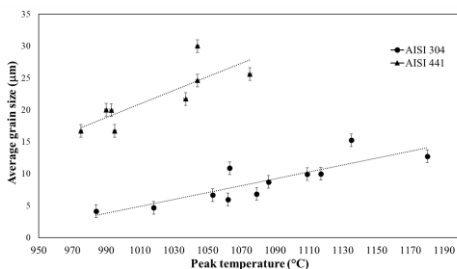
T<sub>max</sub> = 1018 °C



**Fig. 1** Microstructural variations with different peak temperatures

The graph in **Fig. 22** illustrates the average grain size as a function of the heat treatment temperature for the considered material (AISI 304), in comparison with the results from a previous study employing AISI 441 [13]. The purpose of this comparison is to assess the effect of this type of treatment on both stainless steels. It is evident that in both cases, the grain growth exhibits a linear increase as the temperature increases. However, for AISI 304, the influence of temperature on grain growth appears to be less pronounced compared to AISI 441, as indicated by a linear trend with a steeper slope. It is worth mentioning that complete recrystallisation occurs under suitable heating and velocity conditions, leading to a microstructure displaying morphology resulting from plastic deformation. Conversely, when high heating rates are employed without reaching an appropriate peak temperature, partially recrystallized microstructures can be obtained. This means that certain areas of the material may retain the original crystalline structure while recrystallization occurs in other regions.

Previous studies have demonstrated that in the case of austenitic stainless steels, the process of removing deformations and internal stresses within the material, known as recovery, is considered negligible. As a result, the immediate onset of recrystallization during UFH does not imply significant changes in the transformation mechanism of the material [30–32].

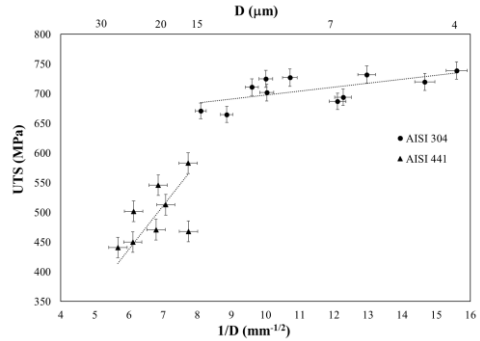


**Fig. 2** Variation in grain size with peak temperature (AISI 304 vs AISI 441)

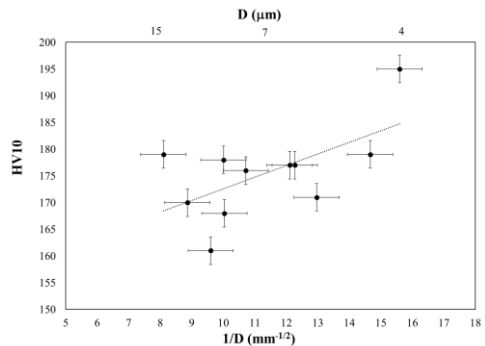
The tensile behavior of a material can be described by its relationship with the average grain size. This relationship is described by the Hall-Petch relationship (**Eq. 1**), which states that as the grain size decreases, the material's tensile strength increases. In other words, a material with smaller grains tends to exhibit greater resistance to deformation under tensile loading. This correlation is because grain boundaries act as barriers to

dislocation movement, thereby increasing the material's strength. Therefore, it is well known that controlling and optimizing the grain size in a material can be crucial for improving its mechanical properties and tensile behaviour.

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



**Fig. 3** Variation in UTS with grain size (AISI 304 vs AISI 441)



**Fig. 4** Variation HV with grain size

The results demonstrate a more pronounced change in the maximum tensile stress in relation to the variation in grain size of ferritic stainless steel 441 (**Fig. 3**). However, in both cases, a Hall-Petch type dependency of the material's strengthening is observed, which increases linearly with the  $\sqrt{D}$ . **Fig. 4** illustrates the variation of hardness values in AISI 304 steel. Results confirm a Hall-Petch behavior also in terms of hardness, as expected based on UTS results.

## CONCLUSIONS

In this study, an induction annealing process allowing ultrafast heating was conducted on an austenitic stainless steel AISI 304, and the results revealed that an increase in the temperature of the heat treatment led to the growth of the austenitic grain size. At a temperature of 984 °C, a grain size of  $4.11 \pm 0.4 \mu\text{m}$  was obtained. A comparison was also made with previous research on UFH conducted on AISI 441, demonstrating that the UFH process has a greater influence on grain growth and strengthening for ferritic stainless steel compared to the results obtained on AISI 304.

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