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Effect of thermo-mechanical processes on microstructure evolution in austenitic stainless steels

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Abstract

The mechanical properties of steels are strictly connected to chemical composition as well as to microstructural features obtained after thermo-mechanical processing. As a consequence, recrystallization and grain growth are relevant to the mechanical properties of steels, thus suggesting the necessity of mathematical models able to predict the microstructural evolution after thermo-mechanical cycles. In particular, in stainless steel grades, mechanical characteristics, and a proper microstructure with an adequate grain size distribution, are very important in order to achieve the required formability and deep drawing properties for many applications. This paper deals with the study of microstructural changes, such as grain size variations and recrystallized volume fraction in stainless steels during isothermal treatments through the application of a mathematical model, able in general to describe the primary recrystallization and grain growth in metals. The developed model takes into account the recrystallization phenomenon and Zener drag effect. A general continuity equation is proposed describing in continuous way recrystallization and grain growth phenomena without taking into account textures effect. The influence of input parameters is analyzed.

Keywords: Stainless steel; recrystallization, grain growth

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1. Introduction

Stainless Steels are nowadays used in almost every application field. In fact, thanks to their peculiar combination of properties - namely, strength and corrosion resistance– that made its fortune since its discovery in the early 19th century by Nilsson (2014) they are adopted in automotive as reported by Rufini et al. (2018) construction and building by Saha et al (2013)., energy by Di Schino et al. (2017), aeronautical by Di Schino et al. (2019), medical by Talha et al. (2013) and food applications by Boulanè et al. (1996). Additive manufacturing is also an emerging technology (in the spotlight for its unique capability to produce near-net-shape components, even geometrically complex, without part-specific tooling needed) able now to process also stainless steels by Zitelli et al. (2019). In order to achieve their own target, not only mechanical properties, but also an adequate microstructure of the product is needed. In particular a well recrystallized microstructure with a homogeneous grain size distribution is at the basis of an easier and more uniform formation process during the production of the final good. This is the reason why there is the need for quantitative models that accurately predict the effect of the processing parameters on the final product in order to control the microstructure and properties of steels during a thermo-mechanical treatment. The empirical approach, which has long been used, is now recognized as being of limited value. Moreover, in many cases, the cost of industrial-scale parametric experimental investigations is prohibitively expensive. The modelling, which has been carried out to date, may be divided into two general groups by Humphreys et al (1996). There are the micro models such as Monte Carlo simulation, cellular automata, molecular dynamics, vertex models and phase field models which aim to deal with individual processes such as deformation or annealing, or perhaps only part of them, i.e. recovery, recrystallization or grain growth by Anderson et al. (1992). Then there are the coupled models which can involve two models (e.g. combining a deformation and an annealing model) or can use many models in the attempt to simulate a large-scale industrial process.

2. Results and discussion

2.1 Description of the model

In this paper a quantitative coupled model which is able to predict some of the most important microstructural features for a stainless steel is described and applied: mean grain size, grain size distribution and the recrystallized volume fraction are the model outputs, taking into account the steel grade, the heating curve and the deformation history of the strip. This model combines a recrystallization model that works simultaneously with a grain growth model (based on the Hillert equation that was previously developed by Abbruzzese and Lücke) by Abbruzzese et al. (1992).
It is well known that the driving force of primary recrystallization is mainly related to the system tendency to eliminate the deformed energy introduced by cold working. During the heat treatment, a release of the deformation energy that activates the movement of dislocations and sub-grain boundaries (thus restoring a dislocation free microstructure) occurs. Once that all the dislocations are eliminated and a complete recrystallized, structure is created in the material, the larger grains begin to grow at the expenses of the smaller ones (secondary recrystallization).
Concerning grain growth, the statistical model is based on the assumption of Edward (1970):

- Super-position of average grain curvatures in individual grain boundaries;
- Homogeneous surroundings of the grains. As a first approximation, it is assumed that a surrounding matrix, identical for all the grains with the same radius, can replace the individual neighborhood of any grain. Following this assumption all the grains of the same size will grow with the same rate. Then, they can be collected in classes characterized by their size Ri and frequency n_i and the analysis can be scaled up to study the behavior of grain classes, instead of single grains.
- A random array of the grains, namely the probability of contact among the grains, is only depending on their relative surface in the system.

The integration of all the above assumptions in the model leads to the following final form of the grain growth rate equation:

$$\frac{dR_i}{dt} = M\sum_j \left(\frac{1}{R_j} - \frac{1}{R_i}\right)\frac{n_j 4\pi R_j^2}{\sum_j n_j 4\pi R_j^2} \quad (1)$$

Where R_i [cm] and R_j [cm] are the radius of grain belonging to class i and j and n_j and n_j are the total numbers of grains in class i and j.
In the above formula $M = 2m\gamma$ is the grain boundary diffusivity and in our case study, m has been evaluated according to the Stokes-Einstein relationship by Valentini et al. (2002) and Di Schino et al. (2002) is the surface energy of the freely growing grains in the deformed matrix. To describe the recrystallization process integrated with the grain growth, it is necessary to propose an extended growth equation that allows to contemporarily and continuously analyse the evolution of free nuclei in the matrix. This can be done passing through partially impinged grains up to full contact. An "influence mean radius" was introduced in order to allow to evaluate the fraction of surface in contact between different grains by Di Schino et al. (2002).
The final equation for recrystallization and grain growth can therefore be written as:

$$\frac{dR_i}{dt} = m[(\frac{Gb^2}{3}\Delta\rho - \frac{2\gamma}{R_I})\sum_j^{i^*} p_j + m\gamma\sum_{j=i^*}^{n_c} p_j(\frac{1}{R_j} - \frac{1}{R_i}) \quad (2)$$

Where G [dyne/cm^2] is the shear modulus, b [cm] is the Burger's vector and $\Delta\rho$ [cm^{-2}] is the difference of dislocation density for the deformed material and the recrystallized material. At last: $p_j = (n_j R_j^2)/\sum_j n_j R_j^2$.
Thanks to the previous equations a calculus program, that can predict the evolution over time of the grain size distribution, has been developed.
Once the equations have been simplified and the calculus program developed, the model has been calibrated for some steel grades (austenitic steel grades such as AISI 304 and 316). As a result, the model is able to give interesting responses in terms of mean grain size, grain size distribution and the recrystallized volume fraction as a function of the cold reduction rate prior to the annealing and the annealing heat curve. In the following, the influence of such parameters is established.

2.2 Validation of the model

The model has been validated for two different grades of austenitic stainless steel: AISI 304 and AISI 316. The validation process has been based on the calibration of m parameter that was multiplied for a specific pre-factor (that is different for each steel grade and depend on the chemical composition of the steel), in order to gain the congruence between the results of the model, in terms of grain size at different recrystallization times, with the corresponding experimental data reported in literature [28-29]. In figure 1 one example of the validation process is shown (for a typical austenitic stainless steel).

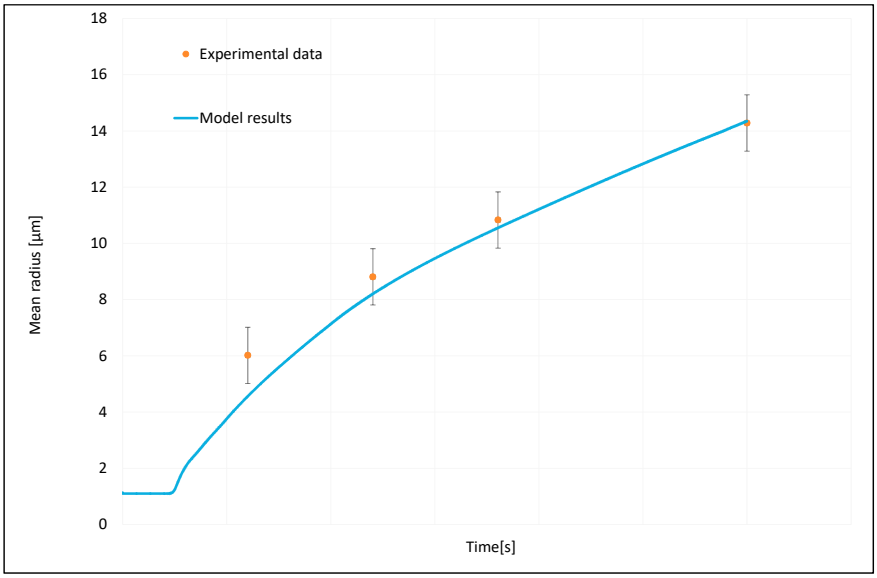

Figure 1. Comparison between the model results, in terms of grain size, and the experimental data found in literature.

2.3 Reduction rate effect

One of the free input parameters of the model is the cold reduction rate of the strip prior to the annealing process that it is linked to the quantity of stored deformation energy via the dislocation density. The effect of reduction rate has been exploited maintaining the temperature constant at 1100°C and varying the cold reduction rate jointly to the dislocation density ($\Delta\rho$) and the initial numbers of deformation nuclei (N) measured by means of X ray diffraction analysis.

Results show that, if cold reduction is varied in the range from 30% to 90%, the final mean radius is slightly higher in the 30% case and this can be explained because the recrystallized grain size depends primarily on the amount of deformation, being smaller for large amounts of deformation. Therefore, a higher strain will provide more nuclei per unit volume (N) and hence a smaller final grain size.

Moreover, it can be concluded that a reduction ratio higher than at least 60% gives a reproducible microstructure with the same mean grain radius, being all other parameters equal.

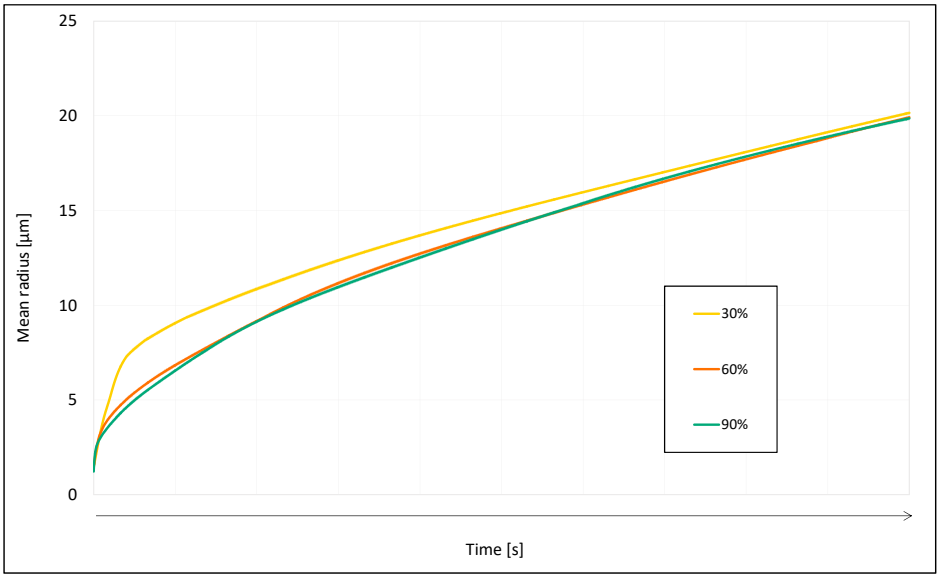

Figure 2. Mean radius over time for three different reduction rates.

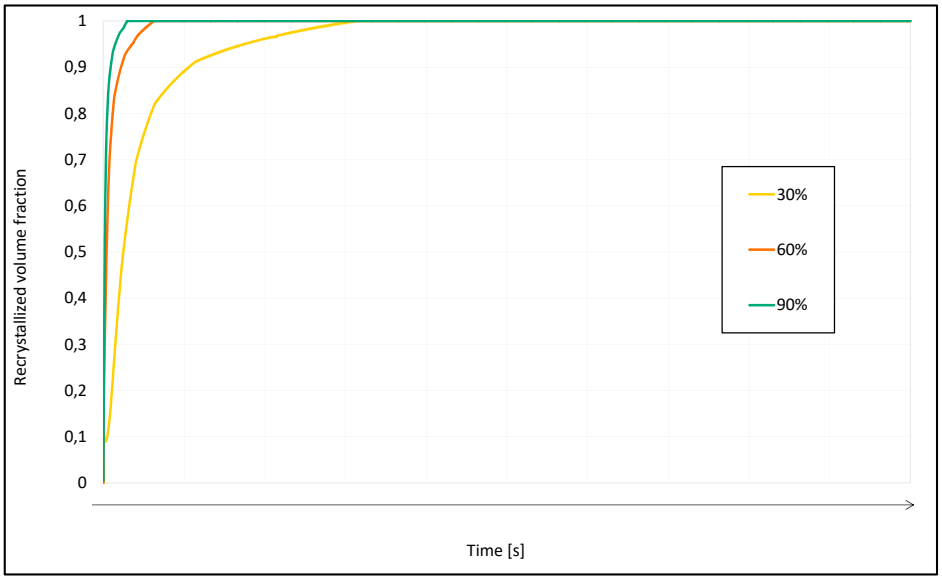

Figure 3. Recrystallized volume fraction over time for three values of cold reduction rate.

The amount of strain affects also the recrystallization rate because the strain modifies the amount of stored energy and the number of effective nuclei. The model shows that, for the two higher values of 60% and 90% of cold reduction rate, the recrystallized volume fraction reaches the unitary value respectively 5 times and 12 times earlier with respect to the 30% case.

2.4 Annealing temperature effect

Another of the free input parameter of the model is the annealing temperature that has a profound effect both on recrystallization kinetics and grain growth. It is well known that it deeply influences the mobility parameter *m*. Four

temperatures, ranging from 700°C to 1100°C, have been simulated for AISI 304 steel grade while, at the same time, cold reduction rate (90%), dislocation density $\Delta\rho$ and the number of nuclei N were maintained constant.
The effect of annealing temperature on grain size is reported in Figure 4. Results show, as expected, that the mean radius size increases with increasing annealing temperature. In terms of the model, can be explained by the variation of the mobility parameters (according to the Stokes-Einstein equation) which ranges from 10^{-14} erg/cm^2 (at 800°C) to 10^{-11} erg/cm^2 (at 1100°C).
From a metallurgical point of view ,this result confirms that temperatures below 1000°C are not able to activate a significant recrystallization effect in the strip, with grain size growing very slowly and never reaching a final grain size value higher than 5 μm. At higher temperatures (1050°C) recrystallization and grain growth occur correctly, and a significant difference on the final radius is found between the 1050°C and 1100°C treatments.
The same result is confirmed also by the evaluation of the recrystallized volume fraction shown in Figure 5.

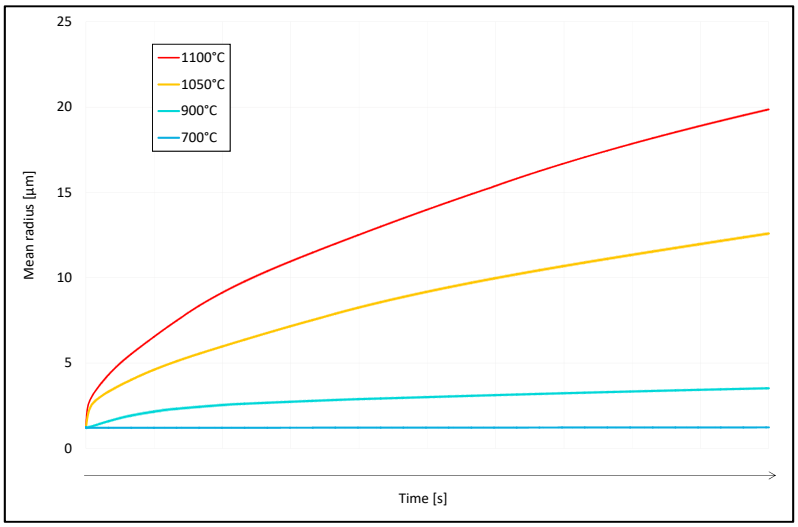

Figure 4. Mean radius over time for four different annealing temperatures.

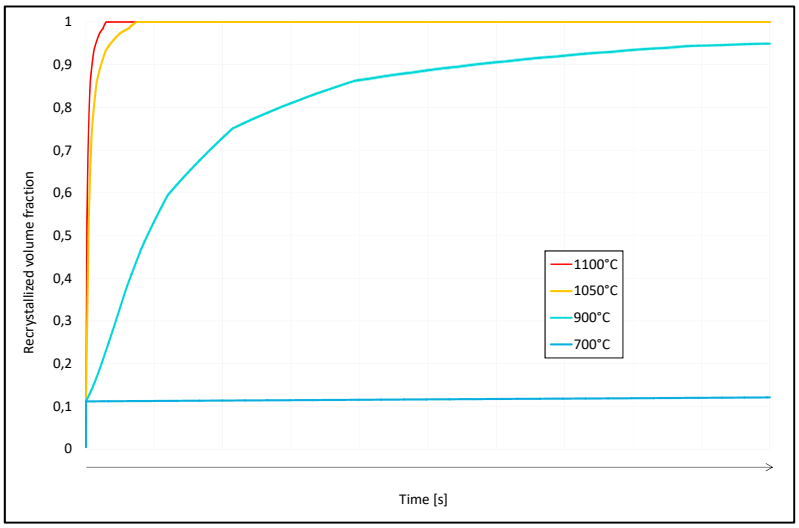

Figure 5. Recrystallized volume fraction over time for four annealing temperatures.

The recrystallized volume fraction (Figure 5), reaches the unitary value only for the higher temperatures (1100°C and 1050°C). For 1100°C the strip is fully recrystallized in half the time it is at 1050°C. For the lower temperatures, the full recrystallization is never reached.

3. Conclusion

Results from a recrystallization and grain growth model based on statistical assumptions have been here discussed. In particular, the effects of the annealing temperature and the cold reduction rate of the strip prior to the annealing have been analyzed. Results show that:

- The recrystallized grain size depends on the amount of deformation, being smaller for large amounts of deformation. In fact, for the 30% cold reduction rate the final grain size is about 21 μm instead for 90% is 19 μm.

- The temperature at which recrystallization occur decreases as strain increases. The model shows that for 60% and 90% of cold reduction rate the recrystallized volume fraction reaches the unitary value respectively 5 and 12 times earlier with respect to the 30% case.

The annealing temperature has a profound effect on the recrystallization kinetics. Recrystallized volume fraction reaches unitary values in shorter amount of time when the annealing temperature is higher. At 1100°C isothermal annealing process the microstructure is fully recrystallized, and it does it in a half time with respect 1050°C. For the lower temperatures, the microstructure does not fully recrystallize. Also mean radius size increases with increasing temperature coherently to the increase of the mobility parameter, as expected.

References

Abbruzzese, G.; Heckelman, I., Lücke, K., 1992, Acta Metallurgica et Materialia, 40, 533-542.
Abbruzzese, G.; Lücke, K., 1986 Acta Metallurgica, 34, 905-914.
Anderson, M.P.; Srolovitz, D.J.; Grest, G.S; Sahni, P.S, 1992. Acta Metallurgica, 32, 783-791.
Baddoo, N.R., 2008. Stainless steel in construction: A review of research, applications, challenges and opportunities. J. Constr. Steel Res., 64, 1199–1206.
Boulané Petermann, L., 1996. Processes of bio-adhesion on stainless steel surfaces and cleanability: A review with special reference to the food industry. Biofouling, 10, 275–300.
Bregliozzi; G., Ahmed, S.I.-U.; Di Schino, A.; Kenny, J.M.; Haefke, H., 2004. Friction and Wear Behavior of Austenitic Stainless Steel: Influence of Atmospheric Humidity, Load Range, and Grain Size. Tribol. Lett., 17, 697–704.
Bregliozzi, G.; Di Schino, A.; Kenny, J.M.; Haefke, H., 2003. The influence of atmospheric humidity and grain size on the friction and wear of AISI 304 stainless steel, Materials Letters, 57, 4505-4508.
Corradi, M.; Di Schino, A.; Borri, A.; Rufini, R., 2018. A review of the use of stainless steel for masonry repair and reinforcement. Constr. Build. Mater., 181, 335–346.
Di Schino, A., 2017. Analysis of heat treatment effect on microstructural features evolution in a micro-alloyed martensitic steel. Acta Metall. Slov. 22, 266-270.
Di Schino, A.; Di Nunzio, P.E., 2017. Metallurgical aspects related to contact fatigue phenomena in steels for back-up rolls. Acta Metall. Slov. 23, 62-71.
Di Schino, A.; Porcu, G.; Longobardo, M.; Turconi, G.; Scoppio, L., 2006, Metallurgical design and development of C125 grade for mild sour service application. In NACE- International Conference Series, San Diego, CA, USA, 2006; pp. 06125-0612514.
Di Schino, A., Valentini; L., Kenny, J.M.; Gerbig, Y.; Ahmed, I.; Haefke, H., 2002. Wear resistance of a high-nitrogen austenitic stainless steel coated with nitrogenated amorphous carbon films. Surf. Coat. Technol., 161, 224–231.
Di Schino, A.; Kenny, J.M.; Abbruzzese, G., 2002. Analysis of the recrystallization and grain growth processes in AISI 316 stainless steel. J. Mater. Sci., 37, 5291–5298.
Di Schino, A.; Kenny, J.M.; Salvatori, I.; Abbruzzese, G., 2002. Modelling primary recrystallization and grain growth in a low nickel austenitic stainless steel. J. Mat. Science, 36, 593-601.
Di Schino, A.; Di Nunzio, P.E.; Turconi, G.L., 2007. Microstructure evolution during tempering of martensite in e medium C steel. Materials Science Forum, 558-559 (Part 2), 1435-1441.
Di Schino, A.; Guarnaschelli, C., 2007. Microstructure and cleavage resistance of high strength steels. Materials Science Forum, 2010. 638-642, 3188-3193.
Edward, J.T., 1970. Journal of Chemical Education 4 , 261-270.
Hillert, M., 1965. Acta Metallurgica 13, 227.

Kawasaki, K.; Nagai, T.; Nakashima, K., 1989. Philosophical Magazine Part B, 60, 399-42.
Krill III,C.E.; Chen, L.Q., 2002. Acta Materialia, 12, 3057-3073.
Kumar Sharma, D.; Filipponi, M.; Di Schino, A.; Rossi, F., Castaldi, 2019. Metalurgija, 58, 347–351.
Nilsson, J.O, 2014. Can mankind survive without stainless steel ?.
Rufini, R.; Di Pietro, O.; Di Schino, A., 2018. Predictive Simulation of Plastic Processing of Welded Stainless Steel Pipes. Metals, 8, 519.
Saha Podder, A.; Bhanja, A., 2013. Applications of Stainless Steel in Automobile Industry. Adv. Mater. Res., 794, 731–740.
Talha, M.; Behera, C.K.; Sinha, O.P.; 2013. A review on nickel-free nitrogen containing austenitic stainless steels for biomedical applications. Mater. Sci. Eng. C, 33, 3563–3575.
Valentini, L.; Di Schino. A.; Kenny, J.M.; Haefke, H., 2002. Influence of grain size and film composition on wear resistance of utra fine grained AISI 304 stainless steel coated with amorphous carboon films. Wear, 253, 458-464.
Zitelli, C.; Folgarait, P.; Di Schino, A., 2019. Laser Powder Bed Fusion of Stainless Steel grades: a review, Metals, 9, 731.