SIMULATION OF THE MANUFACTURING PROCESS OF SEAMLESS TUBES AT V&M DO BRASIL

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Abstract. *Some sizes of seamless tubes are manufactured, as it is well known, via continuous mandel rolling process. In this way, a billet is pierced by the Mannesmann process developing high deformation at high temperature, around 1200^{o}C. Subsequently, the hollow shell is rolled in a continuous rolling mill, over a mandrel bar, reheated and finished in a stretch reducing mill before reaching the final dimensions of the tube. The process is highly complex requiring the action of several variables simultaneously. Analysis of a production line such as this can, however, be done in terms of simple and relatively easily measurable variables such as strain, strain rate and temperature per pass. Once broken down in terms of these variables, the process can be simulated using hot torsion experiments.*

This paper describes first how the industry process can be described in terms of strain, strain rate, temperature per pass and interpass times. Equations are derived to calculate all the relevant quantities for the purpose of laboratory simulation. Hot torsion experiments are then conducted in order to simulate the process with special attention to the final microstructure obtained. These results are in turn compared to those obtained from tubes actually hot rolled in the industry line. Reasonable agreement between laboratory measurements and industry production is obtained in the present investigation, a strong indication of the validity of the experimental procedure here employed.

Keywords: *Hot rolling simulation, seamless tube manufacturing, hot torsion experiments.*

1. Introduction

Controlled rolling of microalloyed steels has been intensely studied in the late years of last century and is now a widespread technique in the industry of plates and strips. The materials and the techniques which evolved from this research effort allowed, among other things, (1) a cost reduction by the elimination of heat treatments such as quenching and tempering or normalizing and (2) the attainment of higher levels of strength, ductility, weldability and formability. During this process of improving and acquiring knowledge on the technique, great contributions came from studies carried out in the area of kinetics of precipitation of Nb, Ti, V and B as well as of recrystallization. A great deal of these studies employed either hot torsion or compression as the main experiment technique (Boratto et al., 1987; Jonas, 2000). Controlled rolling, however, has only been very scarcely used in the manufacturing of seamless tubes and, to this date, relatively few research works have been published in the literature (Barbosa et al., 1987; Pussegoda et al., 1990; 1991a; 1991b). These, on their hand, have basically described the simulation of some aspects of the industry process considering a particular set of gauges or have evaluated the performance of some alloys when subjected to a particular thermomechanical treatment.

The main difficulties found during the use of controlled rolling practice to the seamless tube industry are connected to the relatively narrow flexibility to incorporate some changes in the rolling parameters as, for instance, the strain per pass at the rolling schedule. This is particularly critical concerning the amount of deformation that can be accumulated prior to austenite transformation. The lack of the capability of proceeding to rapid cooling after deformation is also recognized as a drawback of the industry process. In addition, the usual thermo-mechanical route for seamless tube manufacturing presents some peculiarities when compared to processes for the production of flats, the most remarkable being the heavy reduction applied to the billet in a single pass at very high temperature during piercing and, on the other hand, the rather small reduction applied in the following passes. This is particularly true for the case of the low temperature passes at the stretch reducing mill.

This work, therefore, has as main goals (i) to study a hot rolling process for seamless tube manufacturing at an industry plant; (ii) to simulate the industry process via hot torsion testing and (iii) to compare microstructure obtained from hot torsion to that from the rolling line.

2. Experimental Procedure

Ordinary C-Mn steel was used in this research, the chemical composition being shown in Table 1.

Table 1: Chemical composition of C-Mn used in the present research, all number in weight%.

Steel	C	Mn	P	S	Si	Cr	Al	N
DINSt52	0.20	1.47	0.013	0.009	0.26	0.17	0.019	0.0065

Laboratory mechanical testing was carried out in a MTS servo-hydraulic machine computer controlled, equipped with a radiant furnace. Torsion samples, 6.3mm in diameter, 20mm of gauge length, were machined out of tubes hot rolled in the industry processing line. Care was exercised so as to have the axis of the machined sample always aligned with the axis of the tube. Deformation during torsion experiments was performed in a protective argon atmosphere in order to preserve the sample surface from oxidation. Torque and angular displacement signals were stored in a computer and converted into equivalent stress-equivalent strain data using method reported elsewhere (Backofen and Fields, 1957).

Billets were rolled at the plant and data on pass temperatures, delay times, feeding speeds, rolling rotary speeds, intermediate reheating temperatures and annealing times were acquired in order to estimate the parameters needed to simulate the process using torsion experiments. A single gauge tube, ∅127 x 15.90mm, was used in the trials since the main objective of the work was related to the evaluation of the simulation technique.

During hot rolling, strain rates are usually high, in special at the finishing stages, and delay times are rather short. For this reason, some adjustments were made in order to simulate the industry process at the laboratory scale. These needed simplifications were, nonetheless, adopted only after the consequences to the simulation were assessed. For this purpose, a model published earlier for strip mill (Siciliano Jr et al, 1996, 2000) was here modified and used. The model allowed estimates to be made of possible deleterious results due to oversimplification of the industry process in the laboratory simulations.

Microstructure was examined by optical metallography after etching using teepol and nital 2% on a polished surface parallel to the axis direction, located at a depth of 0.25mm of the sample outer surface. Grain sizes of austenite and ferrite were measured by the mean intercept method (Padilha and Ambrósio Filho, 2004), taking care, in the case of ferrite grains, to account for the presence of pearlite.

3. Results

3.1. Thermomechanical processing route at industry

A part of tubes at V&M do Brasil plant in Belo Horizonte are manufactured in a continuous mandrel mill. Billets are firstly pre-heated at 1280°C in a rotary hearth furnace and transported to the piercer mill where the piece is severely deformed in a single pass. Figure 1a shows an outline of the piercing process. The hollow is then transferred to a six-stand reducing mill where the outer diameter is deformed before proceeding to a continuous mandrel mill for further processing. Here, the piece is deformed in eight passes in two rolls stands as illustrated at Figure 1b. The stands of this mill are positioned so that the pair of axis of a given stand makes 90^o with the pair of the following stand. In this way, deformation is applied at alternate 90^o difference between stands. The wall thickness after the mandrel mill is close to gauge expected for the tube.

The tube is fed then to an intermediate reheating furnace where it is soaked at 950^{o}C. After withdrawal from the furnace, the tube is descaled and deformed in a 24 stand stretch reducing mill. The number of passes applied in this mill depends on the final dimensions that must be achieved for the product.

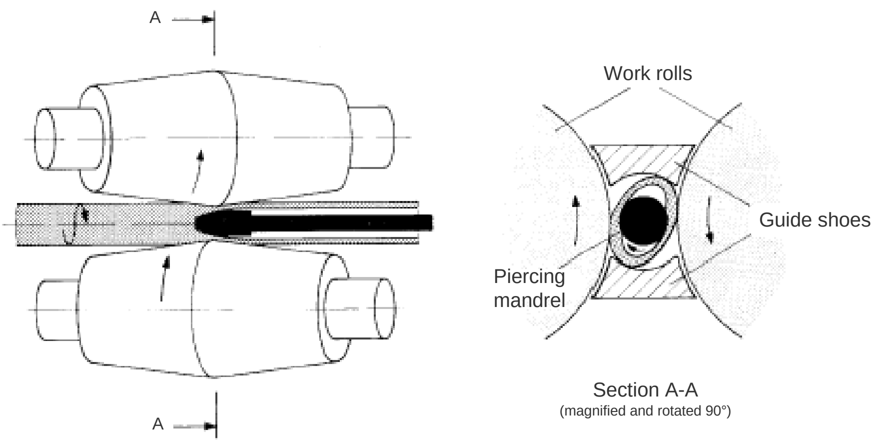
In order to simulate the industry rolling schedule via hot torsion experiments, it is necessary first to calculate the values of strain and strain rates applied at a given pass. This can be performed as earlier published in the literature by Barbosa et al. (1987) and Pussegoda et al. (1991). Deformation in each pass is calculated from the individual components: ε_l, longitudinal, ε_t, thickness and, ε_c, circular equivalent strains using:

$$\varepsilon_{eq} = \frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_l - \varepsilon_t\right)^2 + \left(\varepsilon_t - \varepsilon_c\right)^2 + \left(\varepsilon_c - \varepsilon_l\right)^2} \tag{3.1}$$

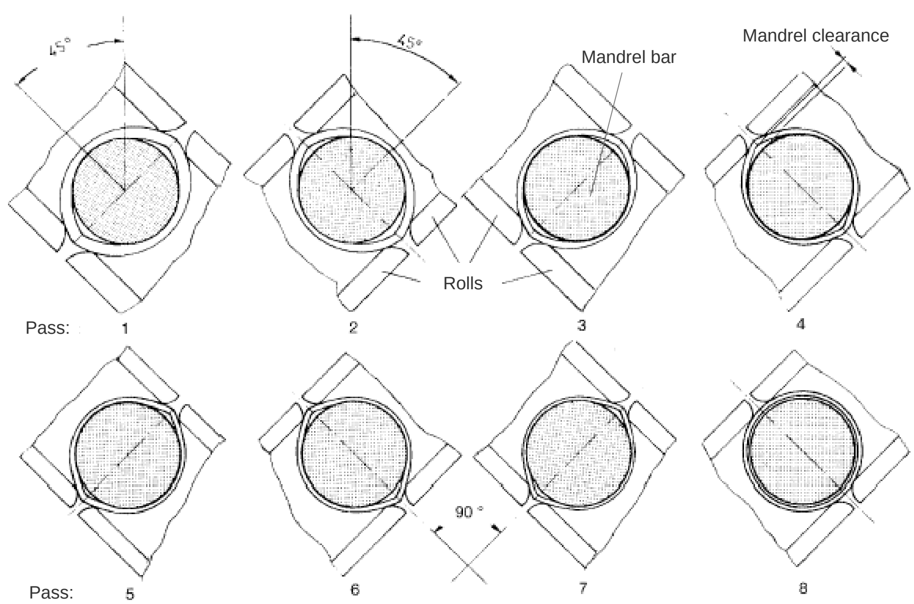
The strain rate at a given pass can be then estimated from

$$\dot{\varepsilon} = \frac{\varepsilon_{eq}}{t_c} \tag{3.2}$$

where t_c is the contact time, evaluated from the geometry and kinematics of each pass. Details of the derivation of equations used in the particular case of this paper are beyond the scope of this work and will be presented in a separate cover, being of relevance here just to present the schedule as computed using Eqs. (1) and (2). Hence, taking the gauge 127.0 x 15.90mm of tube ordinarily produced at V & M plant, data on strain and strain rates were computed as just mentioned and put together with data collected from the industry line, that is, temperature at the pass and the delay times between stands. Table 2 gives details of the calculated schedule.



(a)



(b)

Figure 1: Diagrams showing details of the geometry of (a) the piercing operation during first deformation of the seamless tube process and of (b) the eight cross sections of passes at the mandrel mill, noting that deformations are given at this mill at 90^o alternate angles.

3.2. Thermomechanical processing route at torsion testing

Hot torsion has often been used as a modeling technique for hot rolling, as documented in the literature (Pussegoda et al., 1991a; Jonas, 2000) . Mechanical testing, however, cannot duplicate the exact conditions found in hot rolling. This is particularly true for the values of strain rates that can be achieved at hot torsion as compared to those usually found at the finishing stages of any hot processing industry line. Therefore, the industry schedule must be somehow simplified in order to be simulated at laboratory conditions. Most of the simplifying assumptions are, in general, related to decreases in strain rates or to the accumulation of successive passes joining them in a single deformation. The consequences of these simplifying procedures have, however, first to be checked in order to start using them in the torsion experiments. For this purpose, a microstructure model put forwarded by Siciliano et al. (1996, 2000) was here employed.

The simplifying steps, as just mentioned, dealt mostly with using strain rates at torsion smaller than those encountered in rolling as well as accumulating passes or eliminating interpass times. Both cases, however, occurs at the finishing passes where the kinetics of static recrystallization is severely retarded and strain is accumulated from pass to pass as it would take place in a continuous rather than interrupted type of torsion experiment. Nonetheless, as mentioned above, all simplifying procedures were examined and evaluated through the use of a microstructure model applied to the case of hot torsion and to the industry schedule. In all instances, there was clear indication that the microstructure evolved in similar manner, suggesting, at first glance, that the reducing changes in simulation variables did not affect or compromise the procedure used here to simulate the industry schedule.

In this way, the six passes at the reducing mill were simulated as just a single deformation in torsion since times in between passes at the mill were of the order of 0.3 to 0.2s and the strains per individual passes were less than 0.05, adding after the sixth stand a total equivalent strain of approximately 0.2, altogether. In the same manner, the eight passes given at the continuous mandrel mill were simulated by the application of three passes to the hot torsion sample; the first and the second were identical to that given in the mill except for strain rates and a third pass of equivalent strain 0.21, representing the accumulated straining given to the tube from pass 3 to 8, since, in the mill, time intervals for these passes were shorter than0.4s. Finally the eight passes of the stretch reducing mill applied to the tube gauge being here simulated, were modeled by a single pass of equivalent strain 0.22 not only because the times between stands at this mill are rather short but also because the strain for individual passes were too small, the largest being 0.05. A comparison between industry and laboratory schedule parameters can be seen in Table 2.

3.3. Flow curve and microstructure analysis

Figure 2 shows the flow curves obtained from hot torsion experiments. Figure 2a shows the curves for the simulation of the complete industry schedule. The first curve represents the flow stress for the piercing operation. Clearly dynamic recrystallization occurs since the curve displays both peak and steady state stresses, as it is clearly visible. This is also expected since, as mentioned before, deformation at piercing is severe, equivalent strains being often larger than 1 and temperatures at which this pass is given is high, of the order of 1200^{o}C. Dynamic recrystallization also occurred in the first pass of the continuous mandrel mill, although this is not rightly evident. In fact, in order to make sure weather dynamic recrystallization is occurring or not, the flow curve of Figure 2b must be differentiated according to method proposed by Poliak e Jonas (2003), as shown in Figure 2c. As a result, passes 2 and 3 are followed by metadynamic recrystallization. Further, according to Poliak and Jonas´ method, dynamic recrystallization occurred at a strain of 0.23 for the piercer, 0.11 for the simulation of the reducing mill, 0.17, 0.18 and 0.14 respectively for the first, second and six last passes of the continuous mandrel mill.

Figure 3 shows a comparison between microstructure obtained from hot torsion simulation (3a) and from the industry sample (3b). The microstructure is a mixture of ferrite and pearlite. The hot torsion sample produced a ferrite average grain size of approximately 21 ± 2μm and a volume fraction of 76%. The industry sample gave a ferrite average grain size of 16 ± 2μm and 64% of volume fraction. Given all the simplifying procedures introduced during simulation in respect to the industry schedule parameters, the differences presented by both samples were surprisingly small. In order to check further the evolution of microstructure during hot torsion simulation, samples were quenched at points of interest such as after reheating of the billet, after deformation at the continuous mandrel mill, after reheating at the intermediate furnace and, finally, after the stretch reducing passes. Austenite grains were measured for samples cooled from these four points of the simulation schedule and the results were, respectively, 244 ± 19; 65 ± 5; 62 ± 4 e 45 ± 5μm.

Table 2. Data for schedule for thermomechanical processing of a 127.0 x 15.90mm gauge tube at the industry and for schedule used in the hot torsion experiments. The delay time after a given pass is t_{ip}.

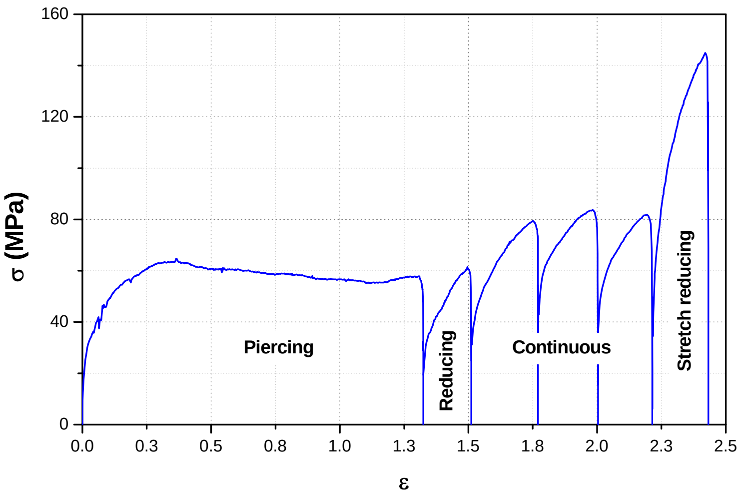
Equipment	Pass	127.0 x 15.90mm				Simulation			
		ε	$\dot{\varepsilon}$ (1/s)	T (°C)	t_{ip} (s)	ε	$\dot{\varepsilon}$ (1/s)	T (°C)	t_{ip} (s)
Rotary Hearth Furnace	-	-	-	1280°C / 30min	70	-	-	1280°C / 30min	70
Piercing Mill	1	1.32	1.44	1220	10	1.32	1.44	1220	10
Reducing Mill	1	0.03	1.65	1200	0.32	0.19	1.00	1175	30
	2	0.05	2.25	1190	0.29				
	3	0.05	2.41	1180	0.27				
	4	0.04	2.34	1170	0.25				
	5	0.02	1.76	1160	0.24				
	6	0.001	0.10	1150	30				
Continuous Mandrel Mill	1	0.26	7.44	1150	0.48	0.26	2.00	1130	0.48
	2	0.23	13.22	1130	0.38	0.23	2.00	1130	0.38
	3	0.09	9.16	1110	0.36	0.21	2.00	1130	200
	4	0.06	8.36	1090	0.34				
	5	0.02	5.05	1070	0.34				
	6	0.01	3.56	1050	0.33				
	7 + 8	0.02	6.23	1030	200				
Cooling Bed I	-	-	-	830	600	-	-	830	600
Intermediate Reheating Furnace	-	-	-	940	5	-	-	940	5
Stretch Reducing Mill	1	0.02	1.39	930	0.25	0.22	1.00	915	1200
	2	0.04	2.29	924	0.24				
	3	0.05	2.54	919	0.24				
	4	0.05	2.61	913	0.24				
	5	0.03	2.23	907	0.23				
	6	0.01	1.38	901	0.24				
	7	0.004	0.84	896	0.24				
	8	0.003	0.68	890	1200				
Cooling Bed II	-	-	-	400	-	-	-	400	-

4. Discussion

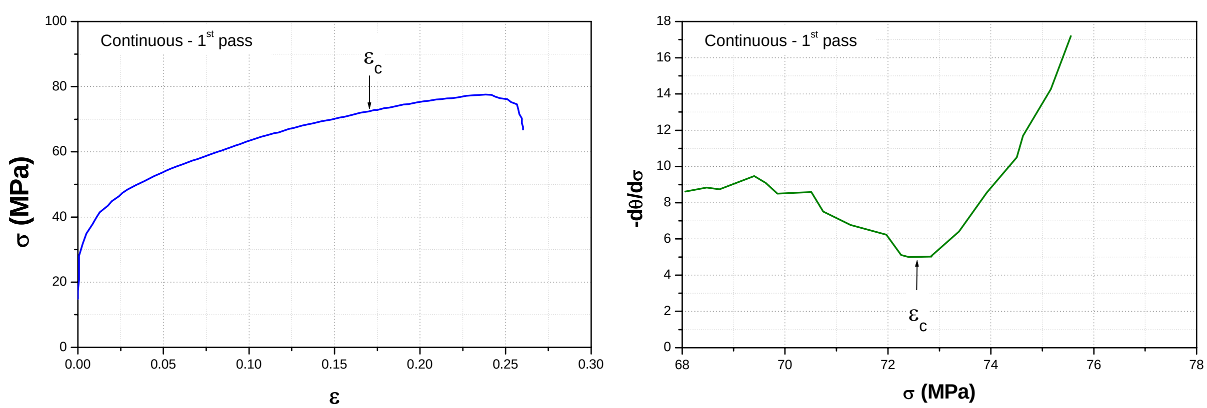
In general, continuous hot rolling of seamless tubes can be divided into two stages: roughing, comprised by piercing, reducing and mandrel mill passes and finishing, represented by the stretch reducing passes given after the intermediate furnace. The first stage resembles that of strip rolling in the sense that deformation, a total approaching 2.5 of equivalent strain, is applied above 1000°C at strain rates in between 1 e $10s^{-1}$ and inter pass times between the three mills of the order of 10 a 30s. Finishing, on the other hand, presents significant differences when compared the same stage for strip rolling. Finishing temperatures for seamless tube rolling are usually 50 to 100°C lower than that for strip rolling. In addition, the total equivalent strain applied during stretch reducing is considerably smaller than that for strip rolling and, finally, the strain rates and delay times between stands are, at least, an order lower than that found for flats. By comparison with hot rolling of wire rods at the finishing stage, seamless tube rolling presents also some significant differences: the strain rates for stretch reducing is two orders of magnitude lower and the delay times an order of magnitude higher than those found for the wire rod mill.

During roughing, seamless tube rolling caused a strong decrease in austenite grain size: from 244µm, just leaving the rotary furnace, to 66µm after the continuous reducing mill. Piercing, carried out right after reheating, refined austenite grain size to approximately 65µm, as calculated from the microstructure model. This may have resulted from the occurrence of dynamic recrystallization followed by metadynamic recrystallization after piercing. On the other hand, in spite of the powerful refinement brought about by the dynamic and metadynamic softening mechanisms, grain size at the end of roughing kept around 65µm as a result of grain growth during interpass times. The absence of microalloying elements, in special of Ti, contributed to this behavior, not preserving the grain refinement achieved during deformations.

During finishing at the stretch reducing mill, austenite grain size decreased from 62 to 45µm in accordance to the microstructure model which predicted a drop in grain size from 60 to 40µm, considering full recrystallization of the microstructure after the mill. The model also predicted a ferrite grain size of 18μm at room temperature, a value close to that measured from the hot torsion simulation sample, 21μm and from samples hot rolled in the industry, 16μm. The small variation in the ferrite grain sizes just presented may, on the other hand, be caused by a number of factors, among them the simplifying assumptions used in the computation of the industry schedule and the simplification procedures introduced in the simulation via hot torsion experiments. It is always important to remember that, in the computation of the strains per pass for the hot torsion experiments, redundant deformation or any kind of heterogeneous deformation inherent to the industry rolling process had to be overlooked due to the intrinsic difficulty in their assessment. This might have been of special importance during the first pass of the schedule in the piercing process.



(a)



(b)

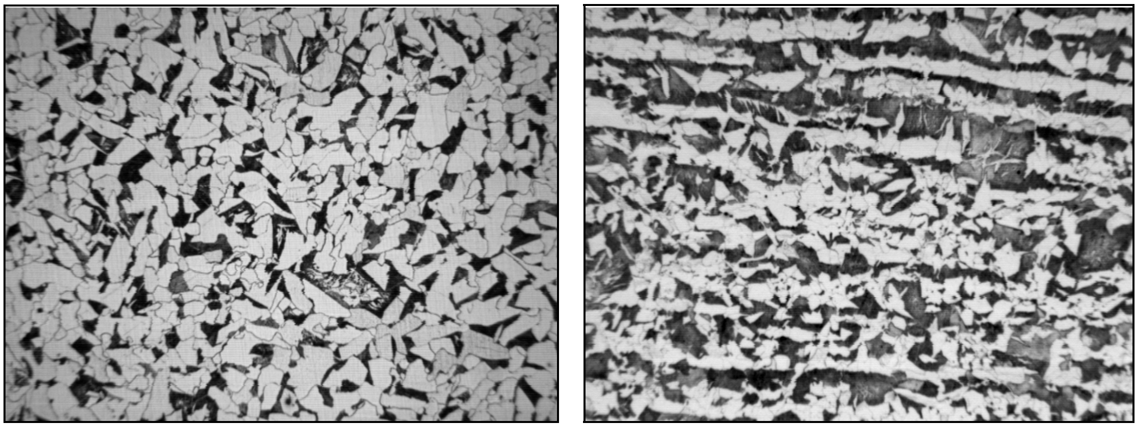
Figure 2: Stress-strain curves obtained from hot torsion tests for the simulation of complete rolling schedule (a). Detail for the stress-strain curve for the first pass of the continuous mandrel mill showing the initiation of dynamic recrystallization at a critical strain value, ε_c, (b).

5. Conclusions

The following are conclusions of this work:

1. Hot torsion experiments can be used as an useful tool for the simulation of an industry process such rolling of seamless tube;

2. Ferrite grains similar in size were obtained from either hot torsion samples or from hot rolling specimens. The torsion samples presented values of grain sizes slightly larger, 21μm, as opposed to 16μm from the industry specimens. This results, however, is close enough as to validate the experimental technique, suggesting that the simplifying procedures used in the tests introduced marginal effects on final grain size.



(a) (b)

Figure 3: Microstructure obtained after simulation of a complete industry schedule via hot torsion experiments (a) and from sample hot rolled in the industry from a 127.0 x 15.90mm gauge tube (b), (nital 2%. 200X).

6. Acknowledgments

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