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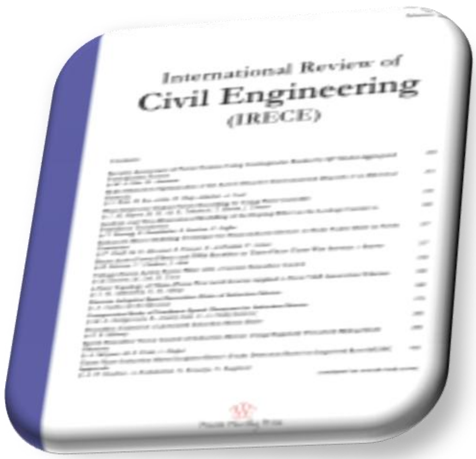


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# Effect of Different Rolling Schedules on the Mechanical Properties and Microstructure of C Mn (V-Nb-Ti) Pipeline Steel

A. Guedri[1, 4], D. Berdjane[2], S. Tlili[2], B. Merzoug[3], A. Zeghloul[4]

**Abstract** – *High strength low-alloy (HSLA) steels have been used for the production of welded pipes for more than 30 years.*
*However, the alloy design of pipeline grades is being continuously modified and the process technology optimized because of increasing demand of high strength toughness combination requirement of pipeline steels. The HSLA steels have demonstrated superior mechanical properties through controlled rolling. In the present investigation, the effects of processing parameters, such as finish rolling temperature, rolling reduction and cooling rate, on the final microstructure and mechanical properties of a grade X70 type HSLA steel has been studied by tensile and charpy impact tests and optical microscopy. To yield better mechanical properties of X70 microalloyed steel grade, the optimization of the rolling process in the laboratory experiment and rolling mill has been carried out.* 

***Keywords**: Controlled Rolling, Controlled Cooling, Processing Parameters, Micro Alloying, HSLA Steel, Mechanical Properties*



## I. Introduction

The American Petroleum Institute (API) provides standards for pipe that are suitable for use in conveying gas, water, and oil in both the oil and natural gas industries. The API 5L specification describes the requirements of chemistry, tensile test characteristics and toughness behavior.

The property requirements of steel vary depending on the particular application and operating conditions. The basic requirements, however, are high strength together with superior toughness at low temperature and excellent weldability.

It is also important that steels should exhibit superior corrosion resistance, especially when petroleum and natural gases in recent years have become more of the type that contain wet H2S (source of sulfur). This had necessitated strict control of sulfur and phosphorus and cleanliness of steel, in general. In casting, the parameters of concern are solidification microstructure, segregation, strand guiding system, casting temperature and the cooling rate.

In the case of thin-slab casting, the higher solidification rate results in smaller dendrite arm spacing, significantly reduced micro- and macro segregation and improved homogeneity [1].

Furthermore, the quality of the hot strips and its properties are determined by the rolling and cooling process parameters (pass schedule, cooling rate, recrystallization temperature), and the metallurgical events involved in recrystallization, grain coarsening, transformation, and the precipitation behavior [2].

Following the great progress of controlled rolling practice over the last two decades, accelerated cooling after hot rolling has currently been regarded as a further advanced thermomechanical treatment in hot rolling process. However, it is very important that HSLA steel plates with low cost and high quality can be manufactured using existing rolling mills in terms of thermomechanical processing or so-called thermomechanical control process.

In general, thermomechanical control process of plates consists of both controlled rolling and accelerated cooling after hot rolling. So, the controlled rolling parameters (reheating temperature, reduction, deforming temperature, inter-pass time) and cooling conditions (cooling rate and finish-cooling temperature) play a particularly important role [3].

The aim of controlled rolling process of microalloyed steels is to obtain required properties by controlling the final microstructure.

The final microstructure and mechanical properties depend strongly on the chemical composition, controlled rolling parameters and cooling conditions of the plate [5].

The present work is a laboratory study of the effects of the processing parameters on the microstructure and properties of standard pipeline grade X70 type API HSLA steel.

## II. Experimental Procedure

The chemical composition of the steel used in this investigation is given in Table I.

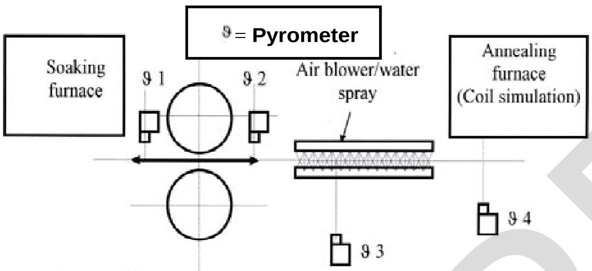
TABLE I
CHEMICAL COMPOSITION OF SAMPLE (IN % WEIGHT)

| C | Si | Mn | P | S | Cr | Mo |
|---|---|---|---|---|---|---|
| 0,139 | 0,130 | 1,51 | 0,011 | 0,004 | 0,01 | 0,01 |
| Al | N | Cu | Nb | Ti | V | Ni |
| 0,0243 | 0.0211 | 0,026 | 0,075 | 0,024 | 0,041 | 0,01 |

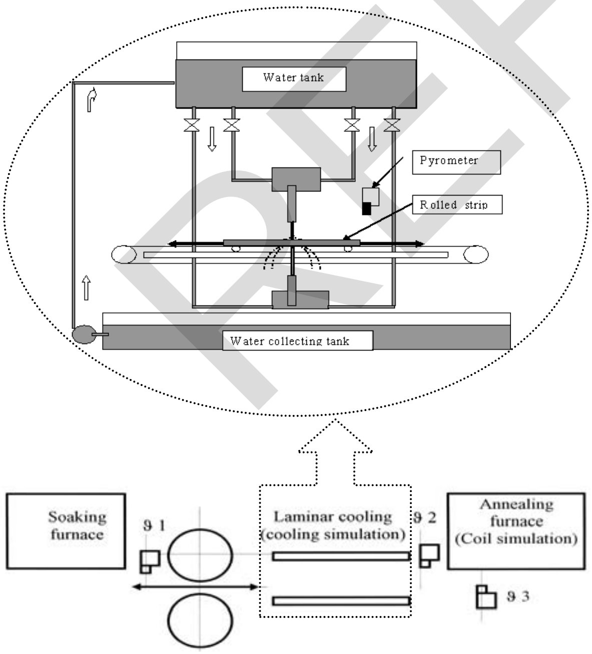
The steel was supplied by the Elhadjar Iron and Steel Factory (Elh-ISF), Algeria. Plate-controlled rolling process followed by controlled cooling tests was carried out on laboratory rolling mill with 330 mm diameter rolls and rolling speed of 1m/s. In the present work, slabs (55x100x100) $mm^3$ were reheated at 1250°C for 30 min, and were rolled to 12-mm-thick plates with six to ten phases as two different rolling schedules (see Figs. 1).

### *II.1. Rolling, Cooling and Annealing Technology*

The first schedule (I) consisted of six passes (finish rolling simulation only) with finish temperatures of 800°C, 750°C and 700°C. The material was heated in a furnace; afterwards it cooled to rolling temperature in ambient air.




(a) Equipment for cooling of rolled strips with compressed air or water spray




(b) Equipment for laminar cooling of rolled strips

Figs. 1. Schematic diagram of basic concept of the laboratory equipment used for the experiments

After rolling, the steel was cooled by water spraying, compressed air and in ambient air to temperatures between 650°C, 600°C and 550°C. This was followed, as in the former experiments, by a holding on finish temperature for 2 hours. New is, after the two hours of holding no cooling in ambient air to 20°C, but a furnace cooling to 300°C.

Objection was to see possible effects of slower cooling rates on the properties after coiling. The program of this schedule can be seen below.

The schedule (II) was, more adapted to the real rolling conditions in (Elh-ISF). So it consisted of 5 roughing passes and of 5 finishing passes, all in all 10 passes.

More passes were not possible because of the delivered raw material thickness of 55mm. The roughing passes laid at temperature between 1200°C and 1050°C, followed by cooling in ambient air and the finishing passes between 950°C and 800°C, res.750°C. After the rolling process two cooling systems were used: Laminar water cooling and cooling with compressed air.

After Rolling, annealing and cooling the samples were mechanic worked to get specimen for tensile tests, notch impact tests (at room temperature as at lower temperature of 0°C and -30°C with longitudinal specimen) and microstructure investigations.

### *II.2. Cooling Tests*

Four different cooling systems were used, in order to simulate the rolling conditions in (Elh-ISF), as good as possible and to check the possibilities of improving the mechanical properties of steel X70. Thus way very different cooling rates were possible. At the rolling schedules (I) and (II), all experimental methods were in operation, so that a good comparison of the effects of the differing cooling methods and especially of differing cooling rates on the properties of the finished strip is possible.

The real temperature in the centre of a finish rolled strip was always measured with thermocouples. Table II gives an overview of the used cooling methods and cooling rates. As expected, laminar cooling shows the highest cooling rates (50K/s), followed by water spraying (21K/s). Compressed air brought not so high cooling rates (3,6 K/s),the lowest rates had cooling in ambient air (1,1K/s). The problem with the used configuration for water spraying was especially a strong reheating effect after the end of cooling. So a reheating of about 35K to 40K took place, which could have affected the properties of the final strips. At the other cooling systems, especially at laminar cooling, such a reheating effect was also seen, but of much smaller magnitude.

Apparently at cooling with water spraying the strip was not cooled completely to the centre, though the pyrometer indicated the desired surface temperature, so that such a reheating could appear. A discussion of the results of different cooling systems (cooling rates) on the mechanical properties of the finish rolled strips will be appear later (see III.1.3.).



TABLE II
USED COOLING METHODS AND COOLING RATES OF ALL EXPERIMENTS

| Cooling method | Rolling Schedule | | Cooling rate between 800°C and 600°C |
|---|---|---|---|
| Ambient air | I | | 1,1 K/s |
| Compressed air | I | II | 3,6 K/s |
| Water spray | I | | 21 K/s |
| Water Laminar cooling | | II | 50 K/s |

### *II.3. Rolling Experiments*

#### *II.3.1. Rolling Schedule (I)*

After rolling according to schedule (I) the strips were cooled by water spray or compressed air res. ambient air.

Afterwards the specimens were kept two hours at coil temperature in a furnace. Alter this, the furnace was switched off and the rolled strips cooled in a longer time period within the furnace to 300°C. Later they cooled down to room temperature in ambient air.

Fig. 2 shows graphically the temperature-time regime of rolling schedule (I) until the finish of cooling to coil temperature by water spray or air. In Fig. 3 the complete technological process can be seen. It starts with the withdrawal of the specimens after soaking and finishes with the extraction of the strips from the furnace after cooling to 300°C and following cooling in ambient air to 20°C. All in all it required 17h52mn20s to cool down to 300°C and 18h to reach 20°C. This is in a very good with the cooling times of a complete coil in (Elh-ISF).

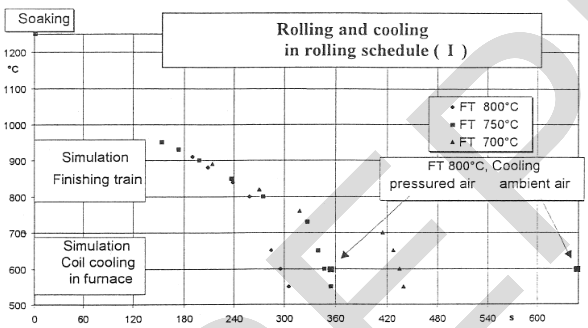



Fig. 2. Temperature-time regime at rolling in schedule (I), with water-spray / air cooling

#### *II.3.2. Rolling schedule (II)*

At rolling schedule (II), the roughing process needed 90 seconds (cooling of the strip after each pass in ambient air), finishing took place within 150 seconds.

The complete rolling process according to rolling schedule (II) took 237 seconds. Especially here was a longer interpass time of 50s at cooling of the strip in ambient air between roughing and finishing. This should simulate the transport of the strip from roughing mill to finishing mill. The simulation of coil cooling was finished after 7400s (2 hours holding at cooling temperature after finish rolling).

Afterwards the strips were extracted from the furnace and cooled in ambient air. So the complete process ended after 11000s at a temperature of 20°C. Fig. 4 shows the temperature-time regime of die complete technological process according to rolling schedule (II) including simulation coil cooling in the furnace and afterwards cooling in ambient to 20°C. If we compare the temperature-time regime of rolling schedule (I) and (II), (see Fig. 3), so we realise the time differences of both rolling and cooling strategies (64800s at (I) and 11000s at (II)).

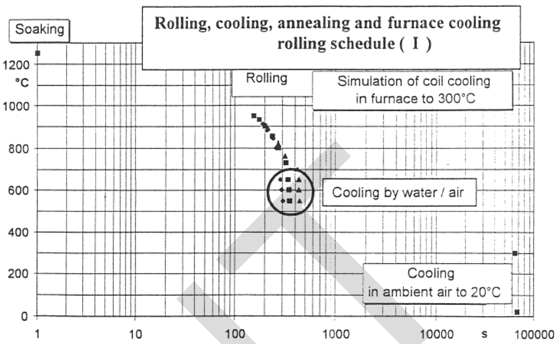



Fig. 3. Temperature-time regime of the complete technological process including furnace cooling at rolling schedule (I)

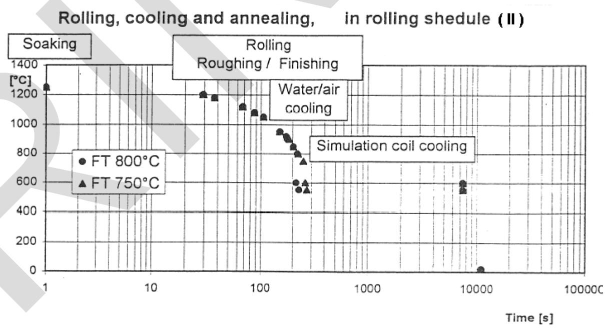



Fig. 4. Temperature-time regime of the complete technological process in rolling schedule (II)

## III. Results and Discussion

### *III.1. Mechanical Properties*

The reheating temperature, amount of reduction, rolling schedules, deforming temperature, inter-pass time, finish rolling temperature and cooling rate are important controlled rolling parameters affecting strength and toughness [3]. For the investigations of mechanical properties from each finish rolled strip were, depended on strip length or width, 2 or 3 tensile test specimen prepared and tested. Again the flat tensile specimen DIN 50 125 - E 10×25×90 was used.

#### *III.1.1. Tensile Tests*

##### *III.1.1.1. Schedule (I)*

The tests were made at the Institute of Material Sciences at TU Bergakademie Freiberg.

A summary of the mechanical properties of the strips rolled according to rolling schedule (I) is shown in Table III.

TABLE III
MECHANICAL PROPERTIES OF STRIPS ROLLED ACCORDING TO ROLLING SCHEDULE (I)

| Strip N° | Temp. (°C) (Tf) | (Tb) | Cooling with | R MPa | Rm MPa | A (%) | Z (%) |
|---|---|---|---|---|---|---|---|
| A 1/2 | 800 | 600 | Air | 488 | 572 | 25,75 | 40,1 |
| A 3/4 | 800 | 600 | Press. Air | 518 | 610 | 25,5 | 41,9 |
| A 17/18 | 800 | 650 | Water - Spray | 517 | 605.5 | 18,75 | 42,2 |
| A 11/12 | 800 | 600 | Water - Spray | 515 | 614 | 16,0 | 42,7 |
| A 5/6 | 800 | 550 | Water - Spray | 519 | 622 | 17,0 | 44,7 |
| A 19/20 | 750 | 650 | Water - Spray | 509 | 612 | 18,5 | 43,8 |
| A 13/14 | 750 | 600 | Water - Spray | 520 | 620 | 18, 25 | 42,5 |
| A 7/8 | 750 | 550 | Water - Spray | 522 | 626 | 19, 25 | 44,4 |
| A 21/22 | 700 | 650 | Water - Spray | 516 | 626 | 18,0 | 47,8 |
| A 15/16 | 700 | 600 | Water - Spray | 520 | 628 | 19,0 | 44,1 |
| A 9/10 | 700 | 550 | Water - Spray | 524 | 638 | 17, 5 | 42,9 |

From this table it can be seen, that the yield strength R of all rolled strips fulfils the requests of norm API 5L for steel X70 (482MPa).

Or in other works, that means for all investigated rolling conditions (finish rolling temperature of 800°C, 750°C and 700°C) that the type of cooling (water spray, compressed air and ambient air) did not affect the mechanical properties essentially.

The tensile strength Rm is also in the range of norm API 5L (here the request is 565 MPa).

The rolling conditions did affect less the tensile strength, but especially at low finishing and coil temperatures we see higher values.

The data of the elongation in Table III show, that only two rolled strips with a finishing temperature of 800°C, cooled down by ambient air or compressed air to a coil temperature of 600°C were in the range of norm API 5L.

The other values, all cooling with water spray, were out of API 5L.

Here arises the question, if the elongation does not so much depend on finishing or coil (annealing) temperature, but on type of cooling.

But if we see the different cooling systems within this project (ambient air, compressed air, water spray and laminar cooling), so appeared at water spraying one problem. The cooled strip reheated again after finish of cooling.

The method of water spraying brought besides laminar cooling the highest cooling rates, but in combination with a reheating affect after the end of cooling, here began a new rise of temperature between 35K and at, 40K. So the real temperature after cooling was higher than expected.

Immediately after water spraying also followed the transport to the annealing furnace (simulation coil cooling).

Here the process of holding at finish cooling temperature started with higher values than expected.

The strip had still to cool down in the furnace to the desired coil temperature and it should have needed a longer time period to catch the real finish/coil temperature.

So it seems from this point of view, that the cooling rate is of much lower importance than the real finish/coil temperature after rolling.

The other cooling systems, especially water laminar cooling, showed also a reheating affect, but of much smaller magnitude.

Here was no affect on the later investigated mechanical properties.

Fig. 5 to Fig. 8 illustrate the correlation between finishing, coil temperature and mechanical properties of strips rolled according to the rolling schedule(I). This confirms the results of the former rolling programs, both low finish as low coil temperatures have a positive effect on yield and tensile strength.

But the main effect on the mechanical properties is the coil temperature. By reduced coil temperatures the mechanical properties such as yield and tensile strength improve.

So the best values of $R$ and $R_m$ were found at a finish temperature of 700°C and a coil temperature of 550°C.

As in the experiments before, the relation $R/R_m$ seems to find lower values at lower finish temperatures that mean, the finish temperature affects tensile strength $R_m$ more than yield strength $R$.

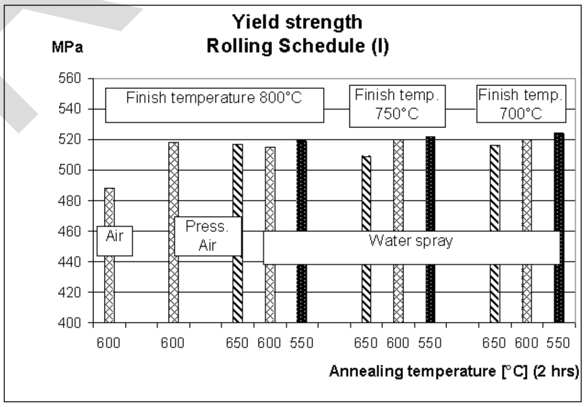



Fig. 5. Influence of finish and coil temperature on yield strength, water spraying

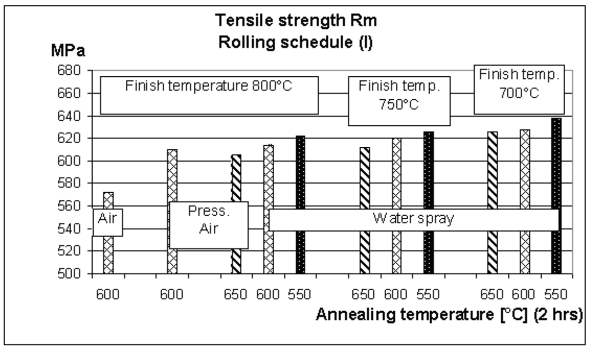



Fig. 6. Influence of finish and coil temperature on tensile strength, water spraying

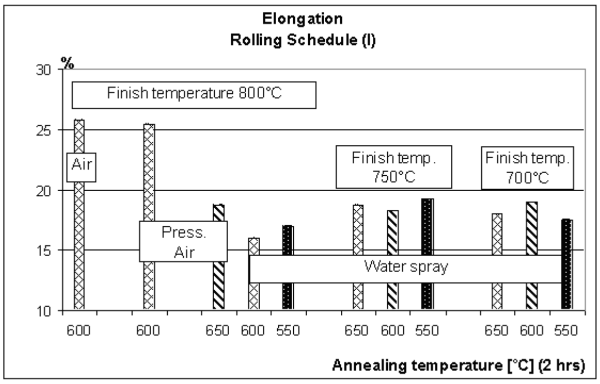



Fig. 7. Influence of finish and coil temperature on elongation, water spraying

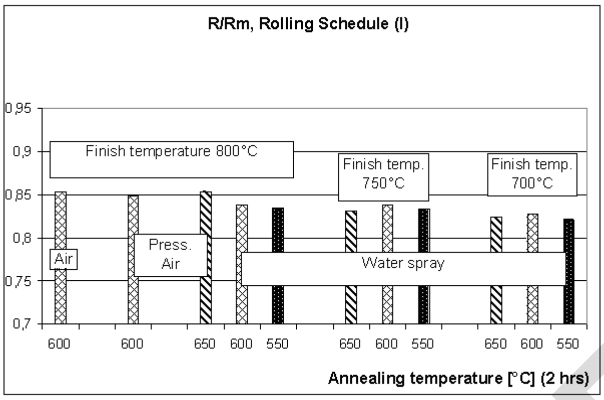



Fig. 8. Influence of finish and coil temperature on relation yield strength to tensile strength, water spraying

To reach a low coil temperature it is suggestive to adjust also a low finish rolling temperature. So both yield as tensile strength, could be improved by the same technological procedures [6]. As described before, the elongation at water spraying did not reach the values of other cooling methods. This is especially seen in Fig. 7. The strips cooled to coil temperature in ambient air or with compressed air show a higher elongation than after water spraying. Apparently this is an effect of the discussed reheating phenomenon of the cooled strips after water spraying. The reduction of area after water spraying, also did not reach the results of other rolling and cooling technologies.

### *III.1.1.2. Schedule (II)*

The rolling schedule (II) was characterized by finish rolling temperatures of 800°C and750°C, followed by laminar water cooling or cooling with compressed air to coil temperatures of 600°C and 550°C. Especially by the laminar cooling it was aspired to simulate the real rolling conditions in (Elh-ISF) as close as possible. The realized rolling and cooling conditions as the found mechanical properties are illustrated in Table IV.

With the rolling schedule (II), especially the distribution of reduction and temperature on the different passes, alone brought essentially better values. If we summarise all data in Table IV, independent from the rolling conditions and cooling temperature, so we find especially for the tensile strength, 6% higher values after water laminar cooling than after cooling with compressed air. Nearly the same relations show the yield strength.

This should be a result of the higher cooling rate (3,6K/s after cooling with compressed air and 50K/s after laminar cooling).

Or in other works, the most effective cooling method is water laminar cooling, which brings also the best results in mechanical properties.

TABLE IV
MECHANICAL PROPERTIES OF STRIPS ROLLED ACCORDING TO ROLLING SCHEDULE (II)

| Strip N° | Temperature (°C) (Tf) | (Tb) | Cooling with | R (MPa) | Rm (MPa) | A (%) |
|---|---|---|---|---|---|---|
| 1 | 800 | 611 | Water | 554,2 | 652 | 25 |
| 7 | 800 | 570 | Water | 554,2 | 691,7 | 24,5 |
| 11 | 750 | 606 | Water | 563,5 | 676 | 26,5 |
| 16 | 750 | 564 | Water | 562,5 | 685,4 | 25 |
| 2 | 800 | 606 | Water | 550 | 689,6 | 28 |
| 13 | 750 | 620 | Water | 556,2 | 660,4 | 25 |
| 3 | 800 | 600 | Compressed Air | 541,7 | 641,7 | 26 |
| 6 | 800 | 550 | Compressed Air | 560,4 | 687,5 | 26 |
| 12 | 750 | 600 | Compressed Air | 543,7 | 646,7 | 26,5 |
| 18 | 750 | 550 | Compressed Air | 564,6 | 669,8 | 28 |
| 4 | 800 | 600 | Compressed Air | 538,5 | 649 | 26 |
| 9 | 800 | 550 | Compressed Air | 541,7 | 653,1 | 24,5 |
| 14 | 750 | 600 | Compressed Air | 543,8 | 649 | 27 |
| 19 | 750 | 550 | Compressed Air | 545,8 | 645,8 | 25 |

### *III.1.2. Toughness Tests*

#### *III.1.2.1. Schedule (I)*

In the toughness tests, as before in the other investigations, ISO-V-notch impact test specimen (ISO-V- DIN 50 125) were used (dimensions 50×10×10mm, tested cross section 10×8mm).

Only longitudinal specimens were tested in a temperature range between 20°C and -30°C. Fig. 9 and Fig. 10 show the average values of notch impact toughness after rolling according to the rolling schedule (I) at all test temperatures. As expected, the highest values of toughness were found at 20°C, at lower temperatures the toughness deteriorates. Cooling with compressed or in ambient air brought the best results, in contrast cooling after water spraying showed significant worse toughness. Also a low test temperature does not affect the relations of toughness after water spray and air cooling. But the requests of norm API 5L (65J at 20°C) were fulfilled by all rolling and cooling conditions of rolling schedule (I). Even the values of the tests at a temperature of -30°C would have fulfilled the requests of the norm for 20°C.

A steep fall of toughness was not found up to -30°C, but the former experiments showed, that this starts first at lower temperatures. The influences of finish rolling and annealing temperatures (simulation coil cooling) on toughness at 20°C, 0°C and -30°C are illustrated in Fig. 9 and Fig. 10. The values vary within smaller ranges.

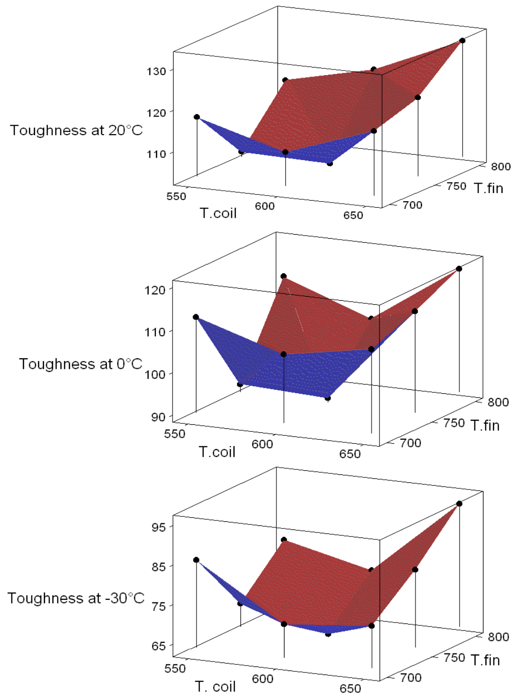



Fig. 9. Influence of finish and coil temperature on toughness, water spraying

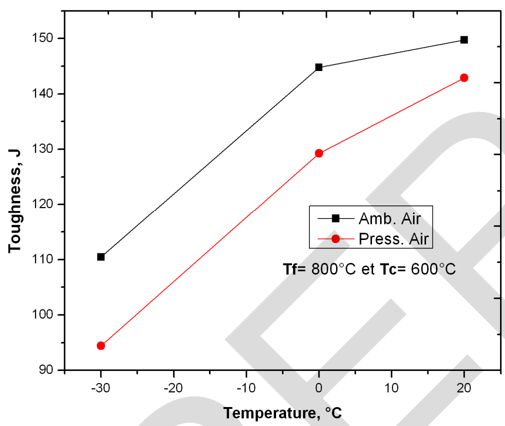



Fig. 10. Influence of finish and coil temperature on toughness, ambient and compressed air

After cooling with water spray the whole sequences of finish temperatures (800°C, 750°C and 700°C) as well as the different coil (annealing) temperatures (650°C, 600°C and 550°C) show very small variations of toughness. The differences are reduced further at low test temperatures as 0°C and -30°C. The best toughness at rolling according to the schedule (I), showed strips with cooling in ambient air or in compressed air.

*III.1.2.2. Schedule (II)*

After rolling according to the rolling schedule (II) the toughness tests, like those in schedule (I), were made with longitudinal specimen at test temperatures of 20°C, 0°C and -30°C. The results are assembled in Table V.

TABLE V
LOW TEMPERATURE TOUGHNESS OF STRIPS ROLLED ACCORDING TO ROLLING SCHEDULE (II)

| Strip N° | Temperature (°C) | | Cooling with | Toughness longitudinal (J) | | |
|---|---|---|---|---|---|---|
| | Fin (FT) | Coil (CT) | | 20°C | 0°C | -30°C |
| 1 | 800 | 611 | Water | 143,9 | 121 | 93,4 |
| 7 | 800 | 570 | Water | 139 | 125,6 | 84,6 |
| 11 | 750 | 606 | Water | 140,5 | 116,8 | 75,6 |
| 16 | 750 | 564 | Water | 145 | 115 | 78 |
| 2 | 800 | 606 | Water | 135,7 | 124,3 | 78,2 |
| 20 | 800 | 540 | Water | 106,9 | 72,2 | 47,3 |
| 13 | 750 | 620 | Water | 144,6 | 127,8 | 69,2 |
| 21 | 750 | 545 | Water | 85,1 | 64,8 | 54,7 |
| 3 | 800 | 600 | Comp.Air | 125,3 | 106,8 | 92,3 |
| 6 | 800 | 550 | Comp.Air | 129,5 | 120 | 78 |
| 12 | 750 | 600 | Comp.Air | 131,2 | 114,5 | 75,6 |
| 18 | 750 | 550 | Comp.Air | 137,4 | 105,8 | 74,8 |
| 4 | 800 | 600 | Comp.Air | 141,4 | 121,4 | 67,6 |
| 9 | 800 | 550 | Comp.Air | 145,2 | 140,2 | 94,1 |
| 14 | 750 | 600 | Comp.Air | 144,2 | 129,6 | 94 |
| 19 | 750 | 550 | Comp.Air | 96,6 | 88,8 | 56,2 |

The found toughness fulfilled all the norm API 5L, independent from rolling and cooling technology.

Remarkable and hardly explainable, considering the former results, are some low toughness after a finishing temperature of 750°C and a coil temperature of 550/545°C both after laminar as after cooling with compressed air.

*III.1.3. Effects of Different Cooling Systems on Mechanical Properties*

Four different cooling systems were tested, to see the effects of varied cooling strategies on the mechanical properties of steel X70 and to simulate the practical cooling and coil conditions in (Elh-ISF) as close as possible. Right from the start of the investigations besides cooling in ambient air also a compressed air cooling on both rides of the rolled strip was used. With the cooling rate of about 3,6 K/s could be realized, compared with 1,1 K/s at cooling in ambient air.

So a water spraying system was developed. This worked like the used system for cooling with compressed air and brought cooling rates of about 31K/s. But the experiments with water spray cooling showed also, that after finish of cooling a reheating affect appeared. The cooled strip heated again, using the residual heat.

To avoid this and to simulate the practical conditions in (Elh-ISF) as close as possible with cooling rates of about 50K/s. For these purposes the mechanical properties depending on finish and cool temperature and especially on the cooling rate were assembled. This is illustrated in Figs. 11 and 12. As we can see at the mechanical properties of steel X70, the cooling rate is of lower weight, but water laminar cooling brought the best results.

So the yield strength of the finish rolled and cooled strip improves beginning from cooling in ambient air over water spraying and compressed air to laminar cooling. If we observe the cooling rate only, water spraying (31K/s) brought better values than compressed air (3,6K/s) and lay beside laminar cooling (50K/s).

But this isn't so. An explanation for this phenomenon should be the already discussed reheating phenomenon of the cooled strip after water spray cooling. On the other hand does this mean that the achievement of a precise cooling temperature is of more importance than the cooling rate. The cooling rate affects the properties relatively low, if we compare the results of tensile tests in Fig. 11. So, the yield strengths after cooling in ambient air and laminar cooling do not differ substantially (13,5% only). Concerning the tensile strength we see the same relations (14%). Amazing are the high values of elongation after cooling in ambient air.

Here water spraying brought the lowest values, which differ to a maximum of 36% compared to either compressed air or laminar cooling. Concerning the toughness, (Fig. 12), cooling in ambient air brought at all test temperatures good results. Here also a cooling with water spray showed the lowest data. That does not also change at low test temperatures of 0°C or -30°C.

If we see all tested mechanical properties (tensile and toughness) as an entity, so the best results for steel X70 were found after laminar cooling, especially at finish cooling temperatures below 600°C.

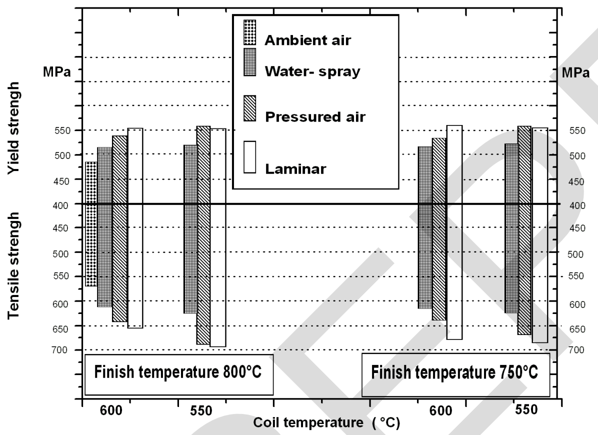



Fig. 11. Effects of different cooling technologies on yield strength, tensile strength

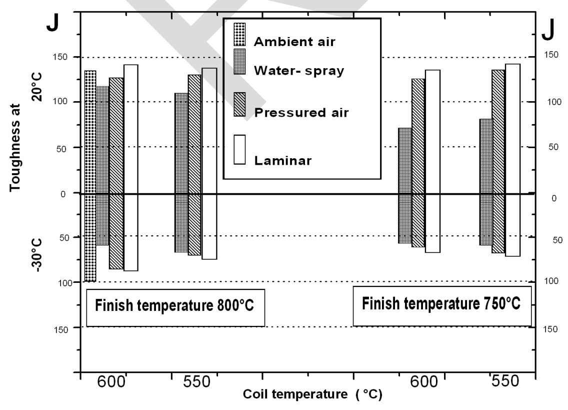



Fig. 12. Effects of different cooling technologies on toughness

*III.2. Microstructure*

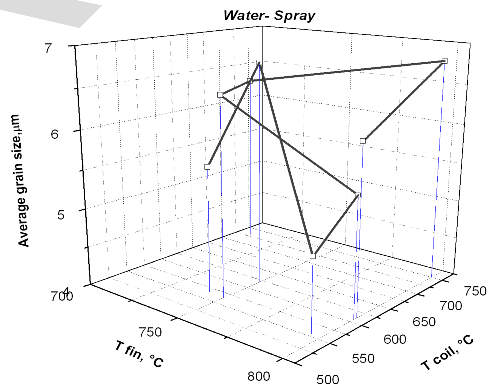
In order to estimate the existing grain size very precisely, for the microstructure investigations of each rolled strip one specimen was extracted and prepared. In an area of 10 mm × l0 mm, 6 to 8 micrographs were taken and the grain size measured.

The grain sizes of all rolled strips according to rolling schedule (II) do not differ very much, see Figs. 13(a), (b). It is observed that the ferrite grain refinement is mostly the result of the deformed austenite below the recrystallization temperature and accelerated cooling after deformation; both processes increase the nucleation of ferrite phase [7]. Several increase mechanisms of nucleation rate of ferrite by deformation have been put forward.

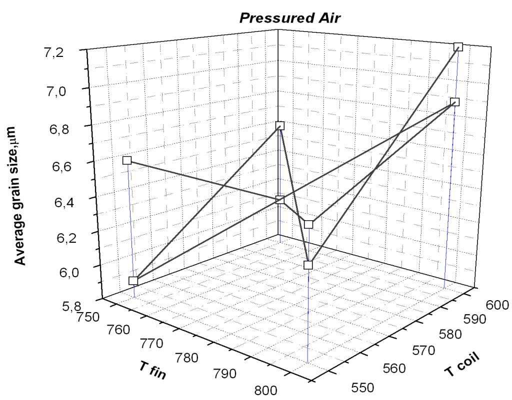
These include an interrelation between the increased nucleation rate of ferrite with the:

a. bulges formed by local austenite grain boundary migration [8],
b. formation of subgrains near the deformation austenite grain boundaries,
c. strain energy of the dislocations stored in deformed austenite [9]. The grain refinement is obtained by control of the rolling conditions time, temperature and deformations during the whole production process.

Grain refinement in steels is enhanced through a combination of controlled rolling and microalloying.




(a)




(b)

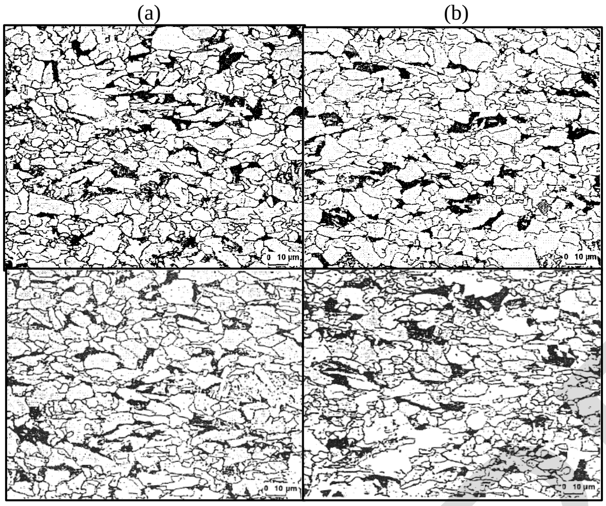
Figs. 13. Average grain size of strips rolled according to schedule (II) (a) Water spray (b) Compressed air

The primary grain refinement mechanism in controlled rolling is the recrystallization of austenite during hot deformation. Small additions of alloying elements like *Nb*, *V* and $T_i$ result in the formation of carbonitrides in the microstructure. These very fine precipitates are effective in preventing grain growth.

By the use of controlled rolling, recrystallization is retarded during the last passes. The average grain sizes after rolling according to the rolling schedule (II) was found between 5,0 and 7,2μm. The different finish rolling temperatures as cooling strategies didn't affect much the grain size as the shares of recrystallized phases.

Here the phase proportions were not investigated in detail. Figs. 14 show exemplary micrographs of selected strips, commented in Table VI.

(a) (b)



(c) (d)

Figs. 14. Micrographs of selected strips: 7, 14, 16 and 19

TABLE VI
GRAIN SIZE (μm) FOR LAMINAR COOLING (STRIP 7AND16) AND COMPRESSED AIR COOLING (STRIP 14 AND 19)

| Strip | 7 | 16 | 14 | 19 |
|---|---|---|---|---|
| Ferrite grain size | 6,8 | 6,5 | 6,1 | 6,6 |
| Finish rolling temperature | 800 | 750 | 750 | 750 |
| Coil temperature | 570 | 564 | 600 | 550 |
| Annealing 2hrs at | 550 | 550 | No annealing after cooling | |
| Figs. 14 | (c) | (d) | (a) | (b) |

## IV. Conclusion

In experimental investigations the deformation conditions at hot strip rolling should be simulated. Objection was a corporate optimisation of rolling technology, to create advantageous microstructures and to improve the mechanical properties of the finished strip. The investigated material is used for weldable pipelines. Within this work the following investigations were:

- Investigation of 4 different cooling technologies (ambient air, compressed air, water spray and water laminar cooling),
- Different simulations of coil cooling after rolling (annealing in a furnace), with holding times between 10 minutes and 24 hours,
- Metallographic investigations of most rolled strips,
- Tensile tests, (yield strength, tensile strength, elongation and reduction of area),
- Toughness tests between 20°C and -30°C, longitudinal and partly transverse.

The finish temperature of the rolling experiments was verified between 850°C and 700°C.

The results of all in laboratory with different technologies rolled strips confirmed the conclusions, which were also found at the investigations of strips rolled in (Elh-ISF), that a reduced finish temperature improves mechanical properties of the final strip as yield strength and tensile strength. But the finish rolling temperature affects the mechanical properties only slightly.

Of far greater importance on the quality of the hot strips is the coil temperature. Different coil temperatures were simulated in the experiments by varying heat treatment temperatures in a furnace (between 500°C and 630°C) res. annealing times (between 30 minutes and 24 hrs) alter finish rolling. All rolling experiments showed, that at a reduced coil temperature improves both yield strength as tensile strength and reduction of area.

The relation between yield strength and tensile strength was not affected essentially. Where as the elongation marginal deteriorated at low coil temperatures. Maximum yield strengths of about 560 MPa were reached, as maximum tensile strengths of about 675 MPa. Few strips with a low coil temperature of 550°C showed no yield strength, but tensile strength of more than760MPa. These strips had also a deterioration of elongation and toughness. So coil temperature at 550°C or below are not recommendable. As result of all investigations a possible finish rolling temperature for steel X70 between 850°C and 830°C is proposed.

These would result in a coil temperature of about 560°C.So an optimum balance between strength and toughness properties should be found. The restrictions of roughing, finishing and coil temperatures would also reduce the partly large range of properties of different strips. The average grain sizes after rolling was found between 5 and 7,2 μm. The different finish rolling temperatures as cooling strategies didn't affect much the grain size as the shares of recrystallized phases.

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