Accelerated cooling of steel rebars establishment of technological and design parameters of the cooling unit by modelling and experimentation

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Abstract

The aim of this work is to develop a computer mathematical model that could be used to predict the design parameters of an accelerated cooling unit. These parameters include length and diameter of cooling tube, size, number and type of nozzles and amount of water needed. Such units are encorporated at the end of or before the last rolling mill of re-inforcing bars for the production of high strength steel re-bars. The production of high strength steel rebars from ordinary 0.2% C - 0.8% Mn by thermo-mechanical treating has been widely employed recently. The control of the cooling rates through the water flow (cross sectional area of tube and amount of water) and cooling time (length of unit which varies according to the rolling speed) affects the process greatly. The bars that leave the stand at about 1000°C, are cooled in a long tube with high pressure water. The outer surface cools to about 200-400°C forming a martensftic layer, while the inner areas remain hot (1000°C). Then both surface and core temperatures equalise at a certain temperature which greatly affects the strength of the cooled rebars. It is of great importance to be able to predict this temperature and previously mentioned design parameters to be able to build the cooling unit required to achieve certain strength levels. The results of the model have been used to develop a cooling unit at El-Ahlya National Company. The performance of the unit was verified experimentally, where several experiments were carried out for different bar diameters, in the range 12-16 mm, and various cooling conditions leading to different bar equalising temperatures.

Strength values in the range from 430 to 1500 MPa were obtained by changing cooling conditions. The obtained mechanical properties after cooling were compared with the predicted equalising temperatures. Also, the microstructures of the cooled bars were compared with those predicted by the cooling curves obtained from the mathematical model results. The results obtained from the model predicted to great proximfty the experimentally obtained results.

Keywords

High Strength Rebars, Accelerated Cooling, Design of Accelerated Cooling Units, Modelling, Heat Treatment.

Riassunto

Lo scopo di questo lavoro è quello di sviluppare un modello matematico computerizzato atto alla predeterminazione dei parametri di progetto di un'unità di raffreddamento accelerato. Detti parametri sono la lunghezza ed il diametro del tubo di raffreddamento, la dimensione degli ugelli, nonché il loro numero e tipo, come pure la quantità di acqua richiesta. Tali unità vengono incorporate o davanti o all'estremità dell'ultimo laminatoio di rafforzamento utilizzato nella produzione di barre rinforzate in acciaio ad altra resistenza, le cosidette rebar. Di recente è stato ampiamente adoperato il trattamento termomeccanicao per la produzione di queste rebar dall'acciaio a 0,2% C - 0,8% Mn. Il risultato del procedimento però viene fortemente condizionato dal controllo della velocità di raffreddamento, agendo sia sulla portata dell'acqua (essendo in questo caso i parametri la sezione del tubo e la quantità di acqua erogata), sia sul tempo di raffreddamento (lunghezza dell'unità di raffreddamento, variabile in funzione della velocità di laminazione). Le barre riscaldate a 1000°C che departono dalla gabbia vanno raffreddate con acqua erogata ad alta pressione in un lungo tubo. La superficie esterna si raffredda fino a 200-400°C, formandosi così uno strato martensitico, mentre le zone interne sono sempre calde (1000°C). Sia la superficie sia il nucleo si portano poi ad una certa temperatura d'equilibrio la quale sarà determinante per la resistenza delle rebar una volta raffreddate. Da ciò nasce l'importanza estrema della previsione di questa temperatura nonché i valori dei parametri di progetto summenzionati affinché si possa costruire l'unità di raffreddamento necessaria alla realizzazione dei livelli di resistenza voluti. I risultati forniti dal modello sono stati adoperati nello sviluppo di una unità di raffreddamento presso la El-Ahlya National Company. Le prestazioni di questa unità sono state poi verificate testando barre del diametro da 12 a 16 mm in condizioni di raffreddamento tali da portare a diversi tempi di raggiungimento dell'equilibrio termico. Cambiando le condizioni di raffreddamento si sono potuti ottenere valori di resistenza dai 420 ai 1500 MPa. Le proprietà meccaniche post-raffreddamento sono state poi confrontate con le temperature d'equilibrio termico previste, come pure le microstrutture delle barre raffreddate con quelle indicate dalle curve di raffreddamento calcolate dai dati forniti dal modello. Si è così potuto osservare l'approssimazione molto stretta tra i risultati previsti con l'aiuto del modello e quelli ottenuti sperimentalmente.

Parole chiave

Rebar ad alta resistenza, raffreddamento accelerato, progettazione di unità di raffreddamento accelerato, modellazione, trattamento termico.

INTRODUCTION

The demand of high strength construction steels of lower weights is increasing nowadays. High strength can be obtained through alloying additions such as vanadium and manganese, which will increase the cost per ton, or by the interrupted accelerated cooling process after hot rolling. The latter process has a large degree of flexibility where several rebar grades with yield strength of 400 to 725 MPa can be manufactured using the same steel (e.g. 0.2% C and 0.85% Mn) composition independent of the rebar size [1-4]. Two main accelerated cooling processes have been developed, these are known as temprimar and tempcore processes. The first process consists of multiple subsequent quench and temper cycles after the rebar has left the last rolling stand. The repeated actions of quenching and tempering causes the formation of a thin layer of martensite up to a certain depth below the surface while the core remains austenitic. The depth of the martensite layer is mainly governed by the heat transfer process which determines the distance at which the temperature drops to blow the M_s temperature. The tempcore process involves a single quench and temper cycle after the last rolling stand, the time of accelerated cooling varies between 2-3 seconds so that the outer surface of the bar is quenched forming a martensitic layer. The control of cooling conditions is with the aim of producing only a rim of martensite on the surface not exceeding about 30% of the cross-section. The core of the bar which still remains hot and of austenitic microstructure, would heat the surface and cool down to form a ferritic fine pearlitic structure during the air cooling on the bed. Again, the depth of the martensitic layer is determined through the heat transfer process. The cooling rate of the core is also increased in comparison with conventionally hot-rolled bars, then the structure of the central region of the bar is refined. The outer shell of the bar is subsequently tempered by the heat transferred from the core of the bar. The self tempering temperature which is the final equalising temperature that the bar reaches should be in the range 500-700°C. The effect of thermo-mechanical treatment on improving strength of low and medium carbon, alloyed and unalloyed steels have been extensively studied [5-9], this effect have been greatly attributed to the refinement in grain size which contributes to both strengthening and toughening of the steel.

Previous work [2] on basic isothermic TTT-diagrams has concluded that for all steel grades within the carbon range of 0.2% or less to 1% and with an alloy content of 1.7% maximum, the equalisation of the temperatures between the core and the quenched surface layer of the rebar has to take place wfthin 6 to 6.5 seconds. It has also been reported [2] that uniform and homogeneous extraction of heat from the surface of the bar is characterised by a maximum heat transfer coefficient of 50000 $Wm^{-2}\,K^{-1}$.

The aim of this work is to design a cooling unit and develop a mathematical model based on the finite difference method to predict the temperature distribution in the rebar across their diameter and length. Then, accordingly predict and coorelate the cooling rates in the surface and core layers with the final expected microstructures using the known continuous cooling curves for similar steels. It is also our target to present a program that could be used as a design guide to determine the conditions suitable for each bar diameter and speed to achieve the required surface, core and equalising temperatures and accordingly the desired microstructures.

DESCRIPTION OF THE MODEL

The model solved the heat transfer equation on the explicit finite difference numerical scheme [10]. This method has been chosen for its well known flexibility and accuracy in calculating the temperature distribution in regular-shaped solids under transient heat flow conditions. Due to the axial symmetry of the circular cross-section of the steel bar, the cylindrical co-ordinate system is used [11]. Under the assumptions of equal temperature along the perimeter of the steel bar; $\delta T/\delta\theta=0$, and the independency of the thermophysical properties (K,p,c) of the steel on the temperature, the transient heat flow equation takes the following form:

$$\delta T/\delta t = \alpha(\delta^2 T/\delta r^2 + 1/r{*}\delta T/\delta r + \delta^2 T/\delta z^2) \qquad (1)$$

within the domain of $0 < r < R_O$ and $0 < Z < L$. At the symmetry line, where r = 0, equation (1) can be written as the following:

$$\delta T/\delta t = \alpha(2\delta^2 T/\delta r^2 + \delta^2 T/\delta z^2) \qquad (2)$$

The boundaries of the steel bar, where $r = R_O$ and Z = 0 or Z = L, are subjected to heat loss by convection and radiation. The temperatures at these locations are determined by the heat balance equation which in general have the form:

$$k\,\delta T/\delta n - h_c\,(T - T_a) - \sigma E\,(T^4 - T_a^4) = 0 \qquad (3)$$

The radiation term in eq. (3), where the temperatures are in deg. Kelvin, is considered in the model when the steel bar is outside the cooling unit. While, the convective heat transfer coefficient is calculated inside and outside the cooling unit. The steel bar is discretized into small elements along both the radius and length of the steel bar. The stability of the numerical solution depends on the time increment, which is affected by the mesh size and the thermophysical properties of the bar material. The smallest time step throughout the domain is calculated first and kept constant during the complete solution.

APPLICATION OF THE MODEL

The major parameters expected to affect both the cooling and the equalisation temperature of the bars are; bar diameter, bar initial temperature, flow rate of the cooling water, rolling speed, and the cooling time. Each parameter was tested individually and the others being fixed. The effect of cooling time on core, surface, and equalising temperatures is illustrated in Fig. 1 for different bar diameters. Bearing in mind that the industrial cooling unit is required to cool the outer layers to below 200°C and to provide equalising temperatures in the range from 550 to 700°C, it can be concluded from the previous figures that water flow rate of 60 m 3 /h for a cooling time in the range of 2-3 seconds is sufficient for

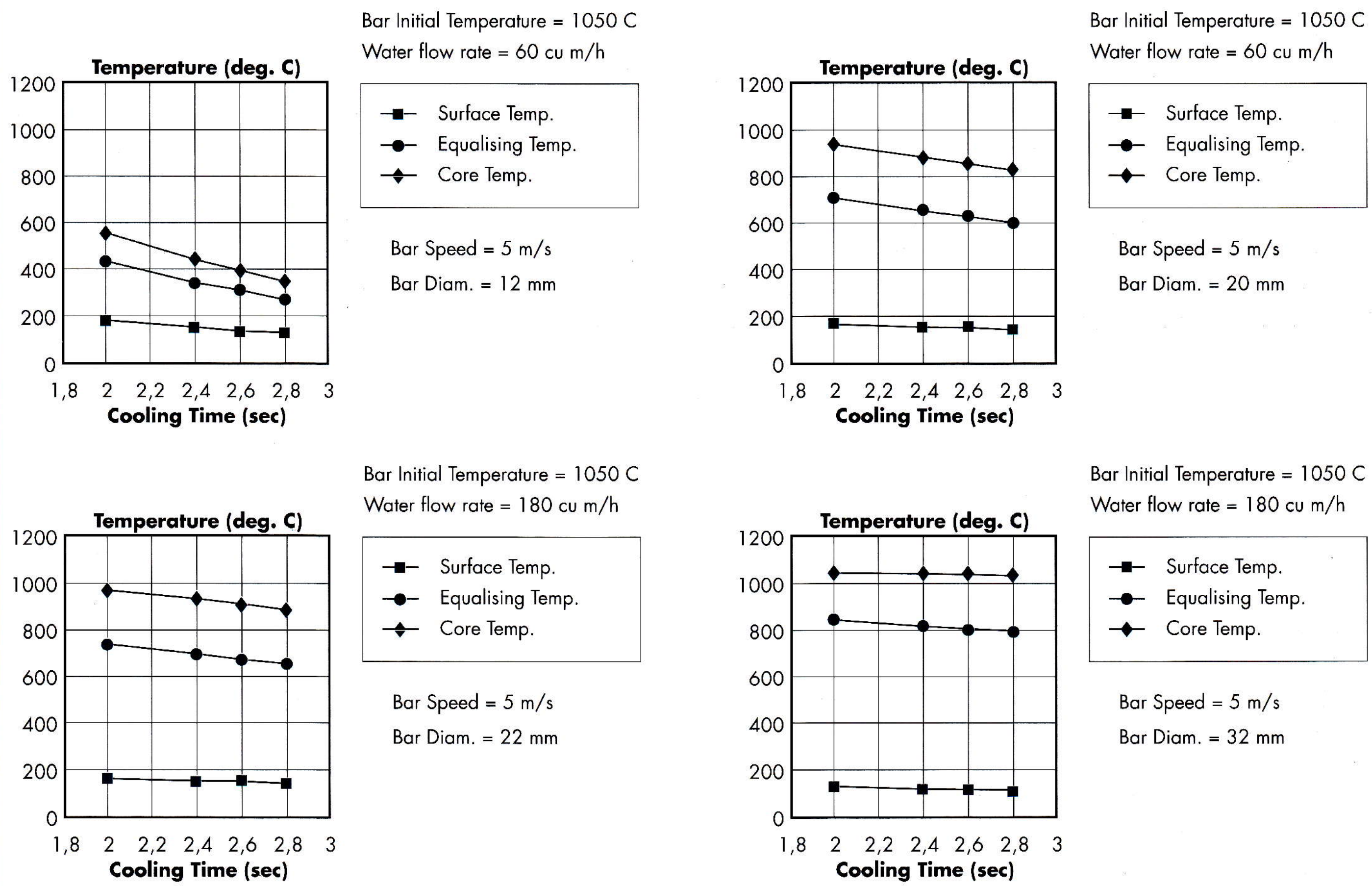


Figure 1: Effect of the cooling time on core, surface and equalising temperatures for different bar diameters

bar diameters 12-20 mm at rolling speed of 5 m/s. Whilst, water flow rate of at least 180 m3 /h is required to achieve similar results for larger bars (22-32 mm) for the same cooling time and at the same rolling speed.

A cooling time of 2 seconds means a cooling unit 10 m long for bar velocity of 5 m/s, and 32 m long if the rolling speed is 16 m/s.

Lower equalising temperatures are obtained either by longer cooling times (i.e. increasing the length of the cooling unit) or by increasing the water flow rate.

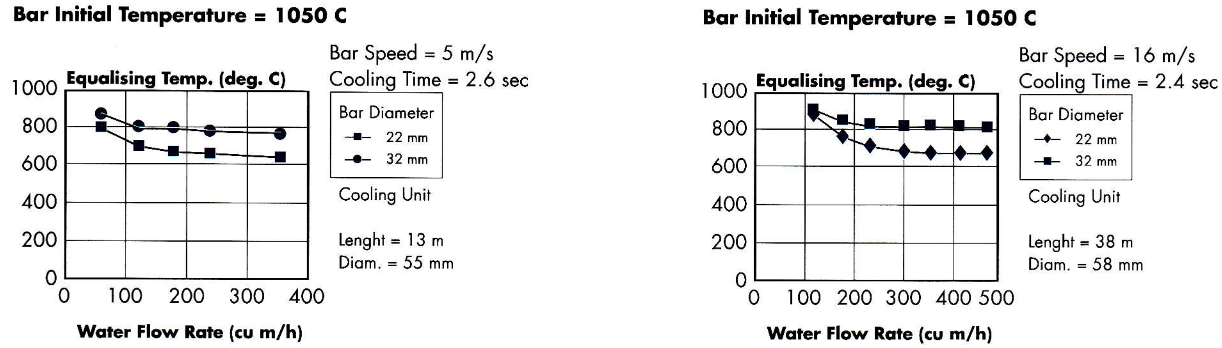


Figure 2: Effect of the water flow rate on the equalising temperature

Figure 2 shows the effect of increasing the water flow rate on the equalising temperature for rolling speeds of 5 and 16 m/s. The water flow rate should increase as both bar diameter and rolling speeds increase. The water flow rate mentioned in this context is the water flow rate entering at each section per unit time, which is different from the total water flow consumption by the cooling unit per unit time; as the design involves several water feed inlets along the cooling tube. The previous results indicate that increasing the water flow rate is very effective up to a certain value, for each bar diameter

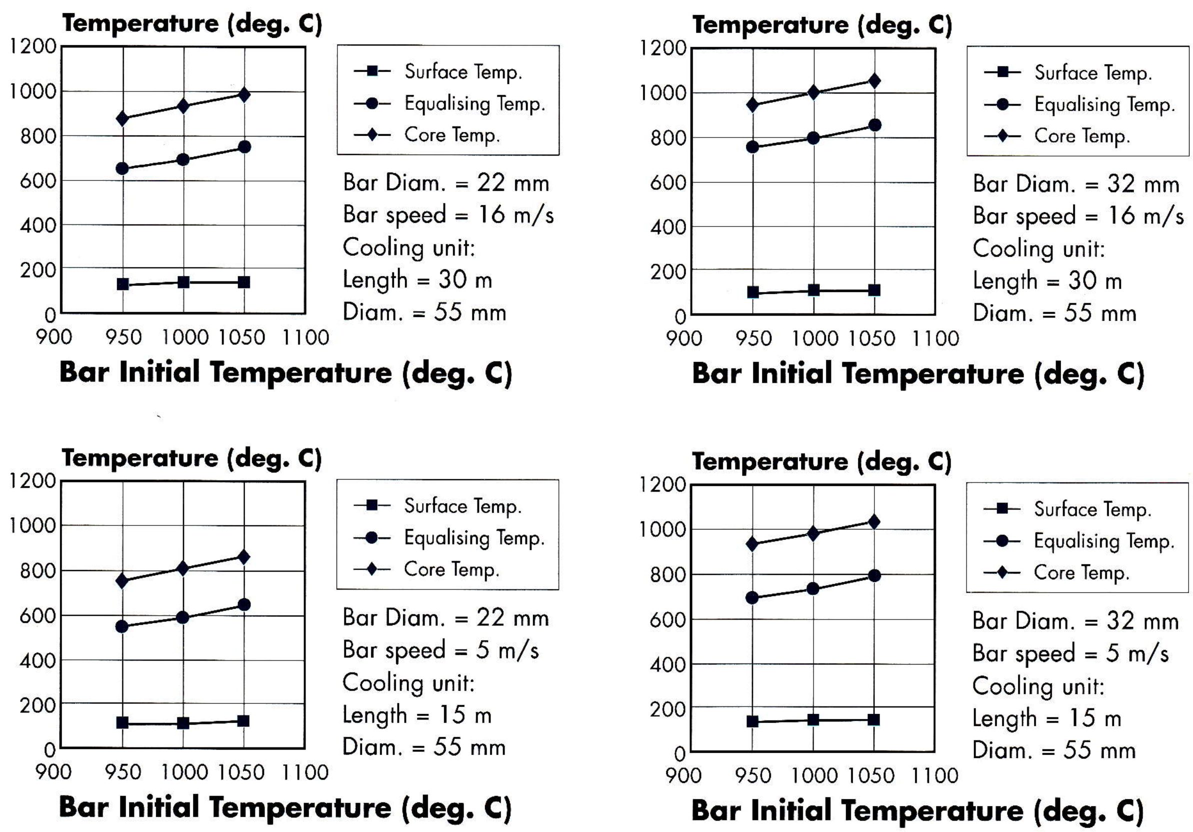


Figure 3: Effect of the bar initial temperature on core, surface and equalising temperatures

and rolling speed, after which increasing the water flow rate, though, causing a great increase in the heat transfer coefficient (reaches 100,000 w/m2/.K) and a high water velocity/ bar speed ratio, would not lead to a comparable decrease in equalising temperatures. Bar initial temperature has a pronounced effect on reducing the surface, center and equalising temperatures of the quenched rebars. Figure 3 shows the effect of changing bar initial temperature in the range

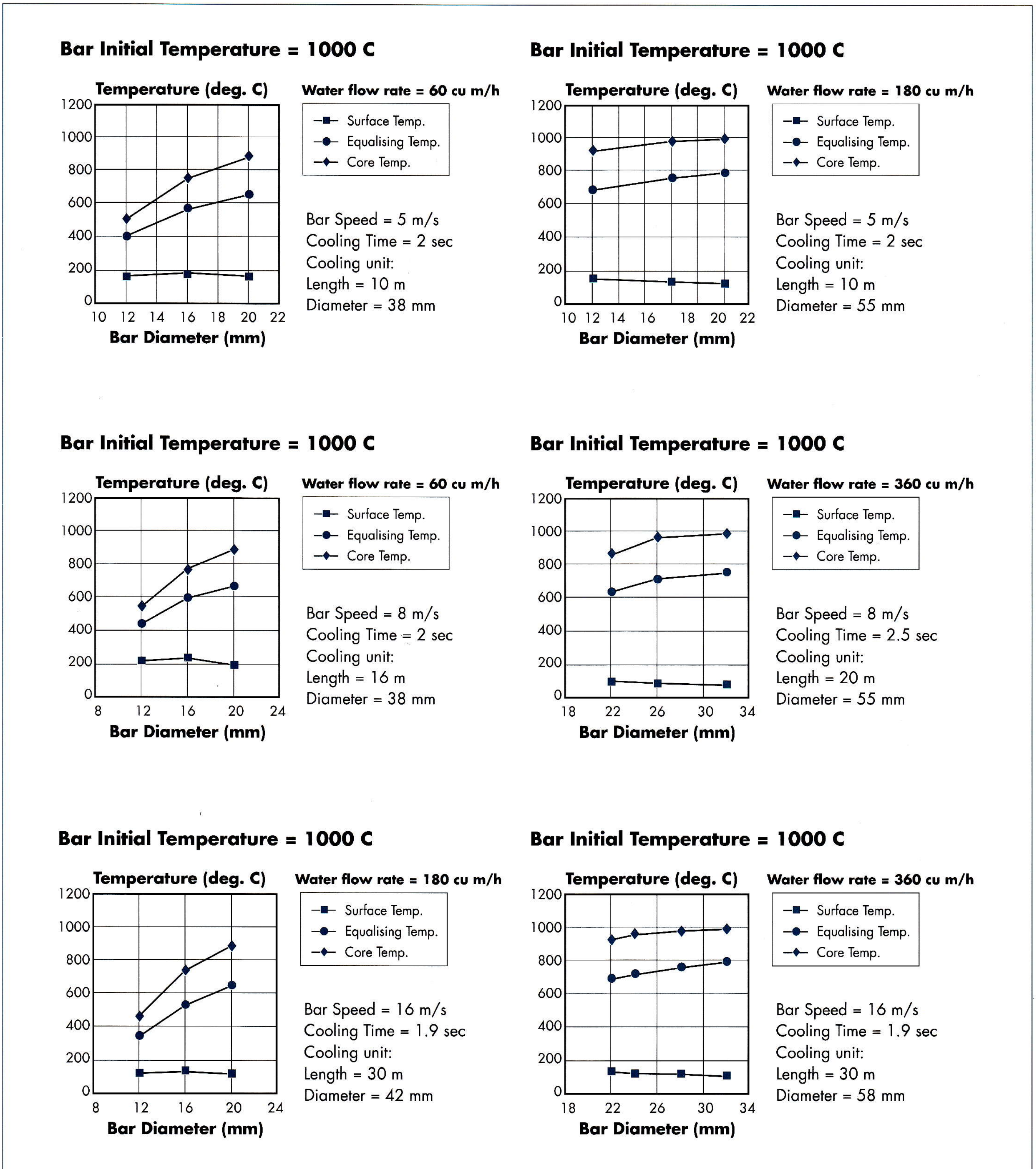


Figure 4: Effect of bar diameter on core, surface and equalising temperatures

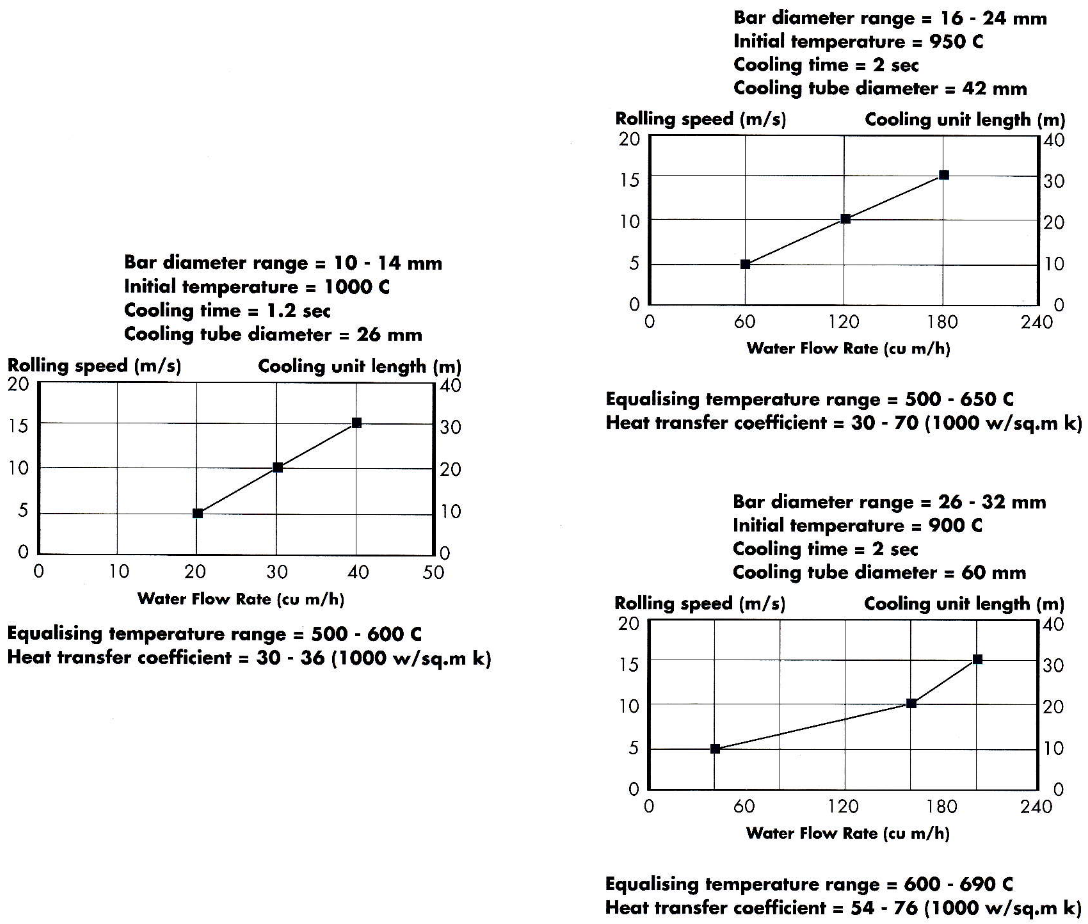


Figure 5: Cooling conditions that yeld equalising temperatures in the range 500-690 °C

of 950-1050°C. The calculated equalising temperatures for different bar diameters are given in Fig. 4. Quite low surface temperatures are obtained in all cases (below 200°C), the equalising temperatures are, however, too high for bar diameters above 22 mm. This indicates the necessity of increasing C and Mn contents or introducing Nb or Ti for larger diameter bars. For bar diameters below 22 mm the equalising temperatures are between 700 and 350°C and are expected to produce high strength rebars. Water flow rates, rolling speeds and lengths of cooling units required to obtain equalising temperatures in the range from 500 to 690°C are given in Fig. 5.

DESIGN OF THE COOLING UNIT

A schematic layout of the cooling process is shown in Fig. 6, where the cooling unit consists of three cooling sections each 4.3 m length. The number and length of the cooling sections depend upon the bar velocity, equalising temperature and the cooling time, so that the time of the overall cooling process should take place in 2-3 seconds. Each cooling section consists of back stripper, main cooling nozzle, cooling tube and a front stripper. The function of the back stripper is to cut the water spray coming back from the cooling nozzle, whereas the front stripper deflects the water spray after leaving the cooling tube. Each cooling section is contained in a sheet metal box with a special cover to prevent water from splashing around and directs the water to the collecting drain. The water out of the cooling section is directed to a cooling tower

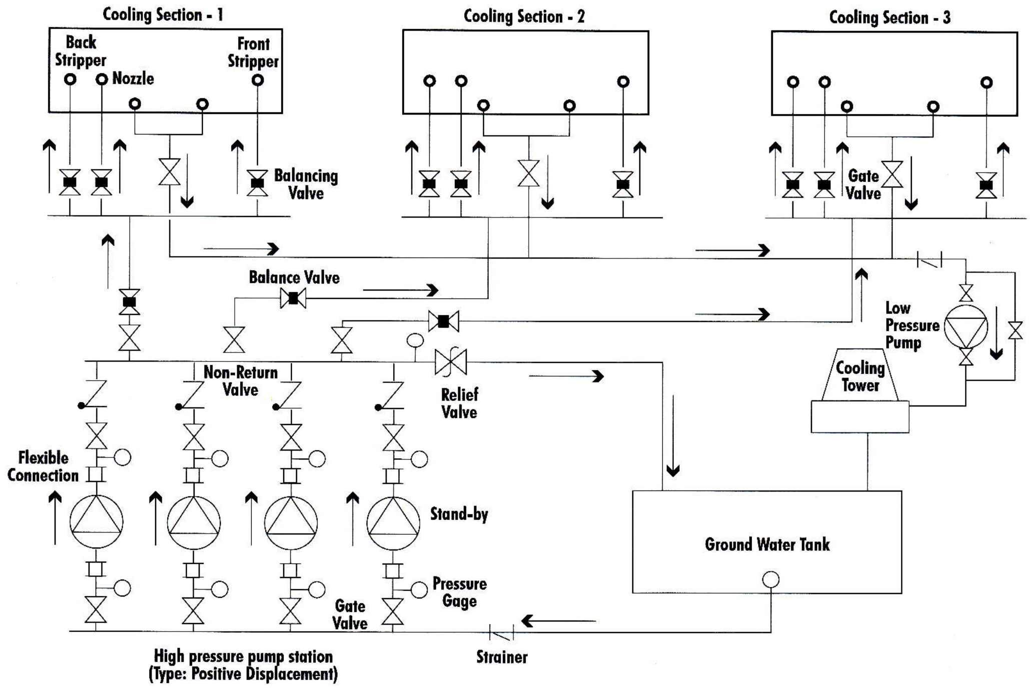


Figure 6: Schematic layout of the developed cooling circuit

using a low pressure pump to cool the water and send it back to the ground tank to be circulated again. The three headers, feeding the cooling water to the cooling sections, are interconnected to the main header of the pump station through balancing valves. The strippers and the nozzles are interconnected to the main headers with balancing valves and piping systems to control both flow direction and quantity of the cooling water. Figure 7 shows the left side cooling section

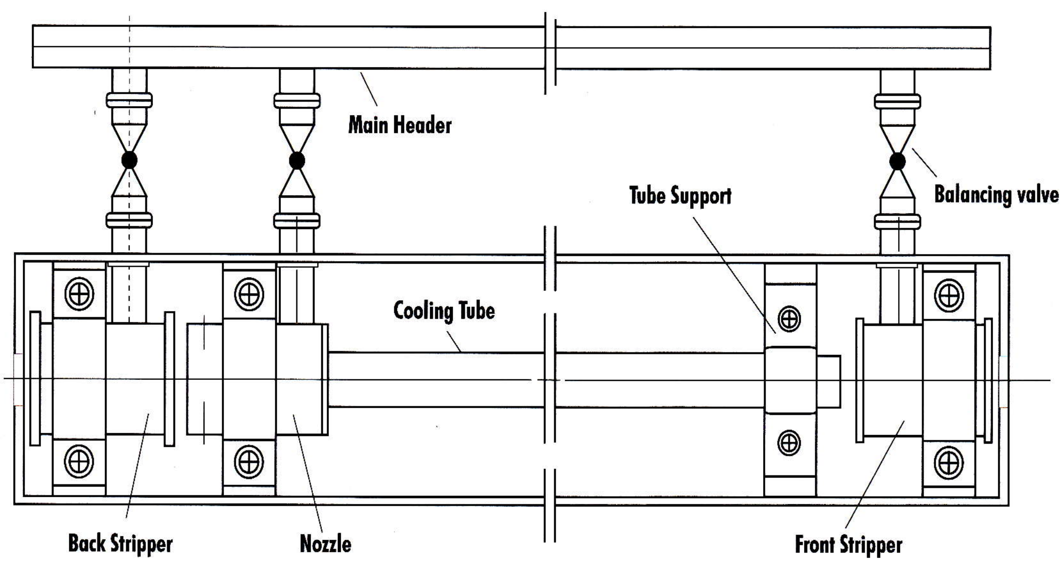


Figure 7: Layout of one cooling section complete with the necessary componentes

TABLE 1 - Experimental results of tests

No of Acting Pumps	Equivalent Water Flux m³/hr	No. of Units	Equivalent time, sec	Carbon equivalent CE	σ_y MPa	UTS Mpa	δ%
(1) Experiment No. 1 on Bar Size 13 mm (Stripper Fully Open)							
	Hot Rolled			0.19	307	422	
1	30	2	1.73	0.22	382	481	31.5
2	60	2	1.73	0.22	328	466	36.0
1	20	3	2.6	0.21	355	448	34.0
2	40	3	2.6	0.25	455	546	24.5
3	60	3	2.6	0.34	643	732	13.5
(2) Experiment No. 2 on Bar Size 16 mm (Strippers Fully Open)							
1	60	1	0.87	0.17	299	423	26.0
2	120	1	0.87	0.16	297	420	29.2
3	180	1	0.87	0.45	452	646	14.4
1	30	2	1.73	0.42	437	637	21.1
2	60	2	1.73	0.46	433	640	12.6
				0.48	439	643	19.8
3	90	2	1.73	0.38	738	848	5.8
				0.21	615	760	7.3
1	20	3	2.6	0.17	296	421	30.8
				0.27	378	528	25.4
2	40	3	2.6	0.23	348	462	26.2
				0.20	348	459	30
3	60	3	2.6	0.39	734	868	8.8
(3) Experiment No. 3 on Bar Size 12 mm (Strippers 30% Open)							
	Hot Rolled			0.29	325	445	33.3
3	60	3	2.6	0.24	592	725	4.2
3	90	2	1.73	0.24	-	860	5.5
3	180	1	0.87	0.27	-	944	4.6

TABLE 2 - Mechanical properties of cooled bars by various cooling conditions and determined equalising temperatures

Condition No	No. of Units	No. of Pumps	Predicted Temp.oC	Predicted Equalising Time, Sec.	Strength UTS Mpa	Surface Hardness HV	Carbon equivalent CE
			(a)	13 mm Ø			
1		Hot Rolled			421	105	0.19
2	2	1	662	4.6	480	115	0.22
3	2	2	506	4.5	470	115	0.29
4	3	1	793	6.2	451	105	0.21
5	3	2	425	6.0	549	130	0.25
6	3	3	326*1	5.9	735	205	0.34
			(b)	16 mm Ø			
	1	1	763	4.1	421	140	0.17
7	1	2	726	4.1	421	140	0.16
8	1	3	714	4.2	647	192	0.45
9	2	1	715	5.3	637	190	0.42
10	2	2	609	5.3	642	195	.42-.48
11	2	3	571	5.3	760-848	270	.21-.38
12	3	1	776	7	421	130	0.17
13	3	2	533	7	490	150	0.23
14	3	3	466**2	6.7	872	220	0.39

Experimentally determined Temperature   * 1. 350-400
  * 2. 450-500

N.B.: The equalising temperatures were determined experimentally for some specimens by tempering at different temperatures and air cooling till hardness dropped.

and shows the back stripper, main nozzle, cooling tube, tube supports and the front stripper, while, Fig. 8 shows the construction of the developed cooling nozzle and strippers used with the cooling sections.

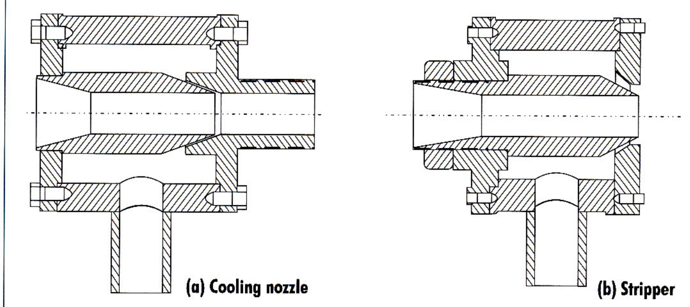


Figure 8: Layout of the developed nozzle and stripper

EXPERIMENTAL WORK

A semi-industrial accelerated cooling unit was designed, fabricated and installed after the last stand of bar rolling mill. The cooling unit consisted of three similar cooling sections each of about 4-m long. Each section contained one cooling nozzle followed by a cooling tube of about 3.5 m length. To cut off the water jets moving in the rolling direction and opposite to the rolling direction one water stripper was mounted before the cooling nozzle and another one was mounted after the cooling tube. The three cooling nozzles and the six water strippers were fed by three pumps having total water flow of 180 m3/hr and head of 13 atm. Valves were used to distribute the water between the cooling nozzles and the water strippers. The diameter of the cooling tube was 38 mm. The cooling nozzle and the two strippers of each section were fixed firmly in a steel container in which the used water was collected and pumped back by low pressure pump to a water tank. In order to create different conditions of cooling several experiments were conducted using different number of cooling sections and acting pumps; e.g. one, two or three pumps could be used to supply water to one, two or three cooling sections alternatively. The strength, hardness and microstructure of the cooled bars were determined experimentally and compared with the equalising temperature and cooling rate determined by the model.

RESULTS AND DISCUSSION

Table 1 shows the results of the experiments conducted on accelerated cooling of steel rebars, from which the great effect of changing cooling conditions and carbon equivalent on the mechanical properties is obvious. Figure 9 shows the relation between the ultimate tensile strength of the cooled bars (13 and 16 mm Ø) and the equalising temperature determined by the model the cooling conditions that produced such temperatures are given in Table 2.

The strong dependence of the strength on the equalising temperature is obvious and clearly explained by the fact that slower and insufficient cooling rates would lead to higher equalising temperatures and accordingly lower strength. Most

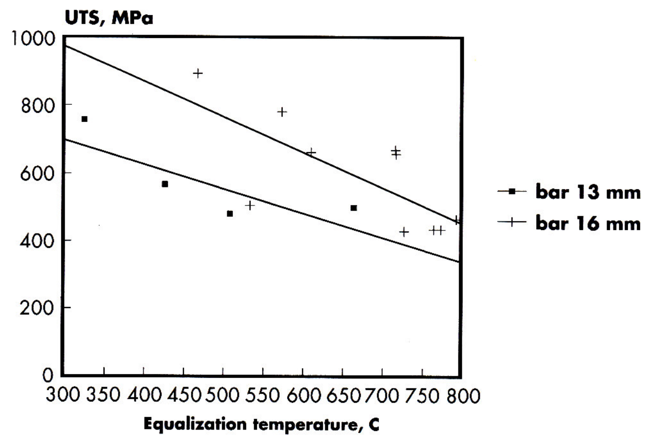
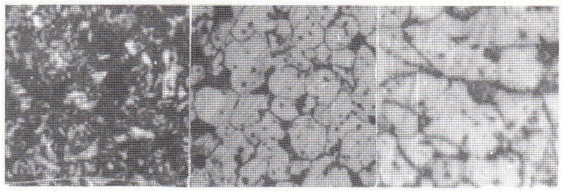


Figure 9: Relation between predicted equalising temperature and obtained strenght

a- Expexted microstructure — M | F+P | F+P

a- 16 mm bar using 3 pumps, 2 units

Actual microstructure

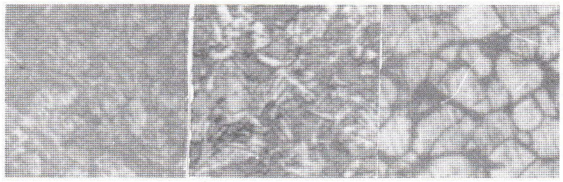


Hardness HV — 270 | 220 | 100

b- Expexted microstructure — M+B+P | B+P | F+P

b- 16 mm bar using 3 pumps, 3 units

Actual microstructure

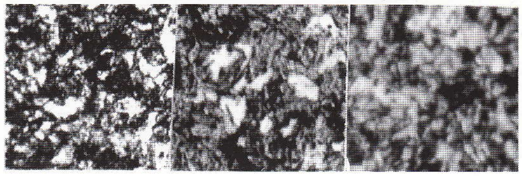


Hardness HV — 215 | 195 | 190

c- Expexted microstructure — M | M+B | F+B

c- 12 mm bar using 3 pumps, 3 units

Actual microstructure



Hardness HV — 219 | 187 | 176

Figure 13: Microstructure of cooled bars from surface (left) to center (right)

equalising temperature for the condition using 2 units is such that the core contains pearlite against finer pearifte for the condition using 3 units.

Figure 13 shows comparison between the expected microstructure of the cooled bars determined by the model for certain conditions of cooling versus the microstructure and hardness of these bars, determined experimentally.

From Table 2, it is obvious that the general trend is that increasing number of acting pumps for a fixed cooling time leads to a slight increase in strength when the time is insufficient and a great increase in strength when cooling time reaches 2.5 seconds. Also, it is obvious that increasing time only does not cause a great increase in strength if water is not sufficient, as the bar cooled by 1 pump and 1 unit has the same strength of 420 Mpa to that cooled by 1 pump and 3 units.

The obtained hardness and microstructures as stated in Fig.13.a and 13.b compare well to the predicted microstructures from Fig. 12. The yield/ultimate tensile strength for both conditions is 738/848 and 734/868 Mpa and the ductility is 5.8 and 8.8% for carbon equivalents 0.38 and 0.39 respectively. Again, the predicted microstructures compare well with those values and can explain the relatively small ductility obtained for the condition 13.a as the surface contains more martensite.

From fig.13.c it is obvious how the microstructure and hardness varied from surface to core for a 12 mm bar cooled by 3 units and 3 pumps, the significant change in hardness is clear and attributed to the different microstructures from surface to core, namely M on the surface followed by M + B and finally F + B in core.

Several authors [4-9] have discussed the benefit of increasing strength, at a good toughness level, of re-bars by accelerated cooling. The ability of obtaining different microstructures from tempered martensite on the surface to ferrite and pearlite in the core, as well as the grain refinement is the key factor for the optimisation of strength and toughness. The chemical composition, finishing temperature and cooling rates are the major three parameters that affect the properties of the rebars produced by accelerated cooling.

of the out fitting points are of much higher or lower carbon equivalents than the well-fitting ones. It is also worth noticing how different cooling conditions such as 1 unit with three pumps produced a similar strength level of 640 MPa to that obtained by 2 units and one pump, while the calculated equalising temperature is almost similar.

Figure 10 shows the inter-relation between the determined equalising temperature and the surface hardness of the cooled bars for bar sizes 13 and 16 mm Ø. Again, it is clear that lower equalising temperatures are related to higher surface hardness. Higher carbon equivalents cause an abrupt increase in hardness for the same predicted equalising temperature.

Figures 11 and 12 show the predicted cooling curves for some of the tested cooling conditions, on which isothermic TTT cooling curves are incorporated. Thus one can predict that, for example, the 13-mm diameter bar when cooled with the 3

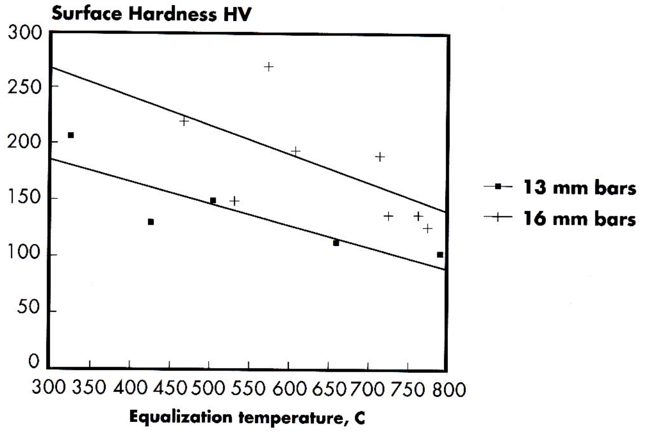


Figure 10: Relation between predicted equalising temperature and obtained surface hardness

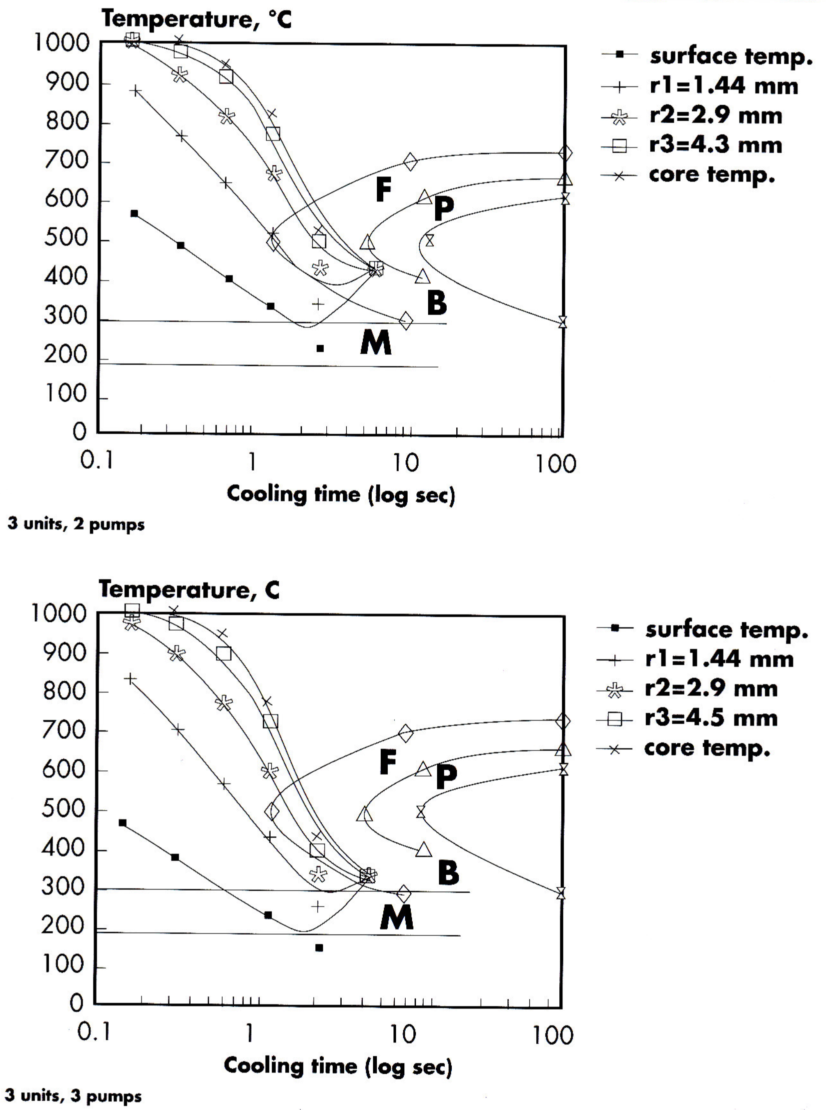


Figure 11: Cooling curves predicted by the model from which the microstructure of 13 mm bars could be predicted

units and 3 pumps would contain a surface layer of martensite up to about 1.4 mm and the remainder will be bainite and ferrite. Similarly one can predict that for the 16 mm diameter bar cooled by 3 units and 3 pumps, a surface layer of martensite up to about 1 mm below the surface is expected while the remainder is ferrite and pearlite.

The analysis of these results indicates the great effect of cooling parameters on controlling the obtained microstructure of cooled bars and accordingly on their mechanical properties. The encorprorated TTT curves are for steel of composition 0.2%C - 0.85% Mn, using the equation %C + Mn/5.9 + Mn/17 [2]. The carbon equivalent is 0.35, obviously different compositions and carbon equivalents would mean different microstructures obtained for various cooling conditions. Also, the hardness and strength obtained depend greatly on the carbon equivalent of the re-bar steel.

From Fig. 11, it could be predicted that the microstructure of the 13 mm bar cooled by 3 units and 2 pumps is M + B + F + P on the surface versus F + P in the core. The hardness of 13 mm bars cooled using such condition and of carbon equivalent 0.25 was almost the same from surface to core and approssimatly equal to 140 ± 5HV. On the other hand, the hardness of the 13 mm bar cooled by 3 units and 3 pumps and of carbon equivalent 0.34 changed abruptly from 205 HV on the surface to 150 HV in the core indicating the respective change in microstructure, which is predicted by the model to be M on the surface and F + B in the core. Comparing cooling conditions in fig. 12 it is noted that though the cooling time is less with 2 units and 3 pumps than three units and three pumps a full martensitic surface layer on the surface of the former is expected against a mixed microstructure of M + B + P on the surface of the latter. However, the

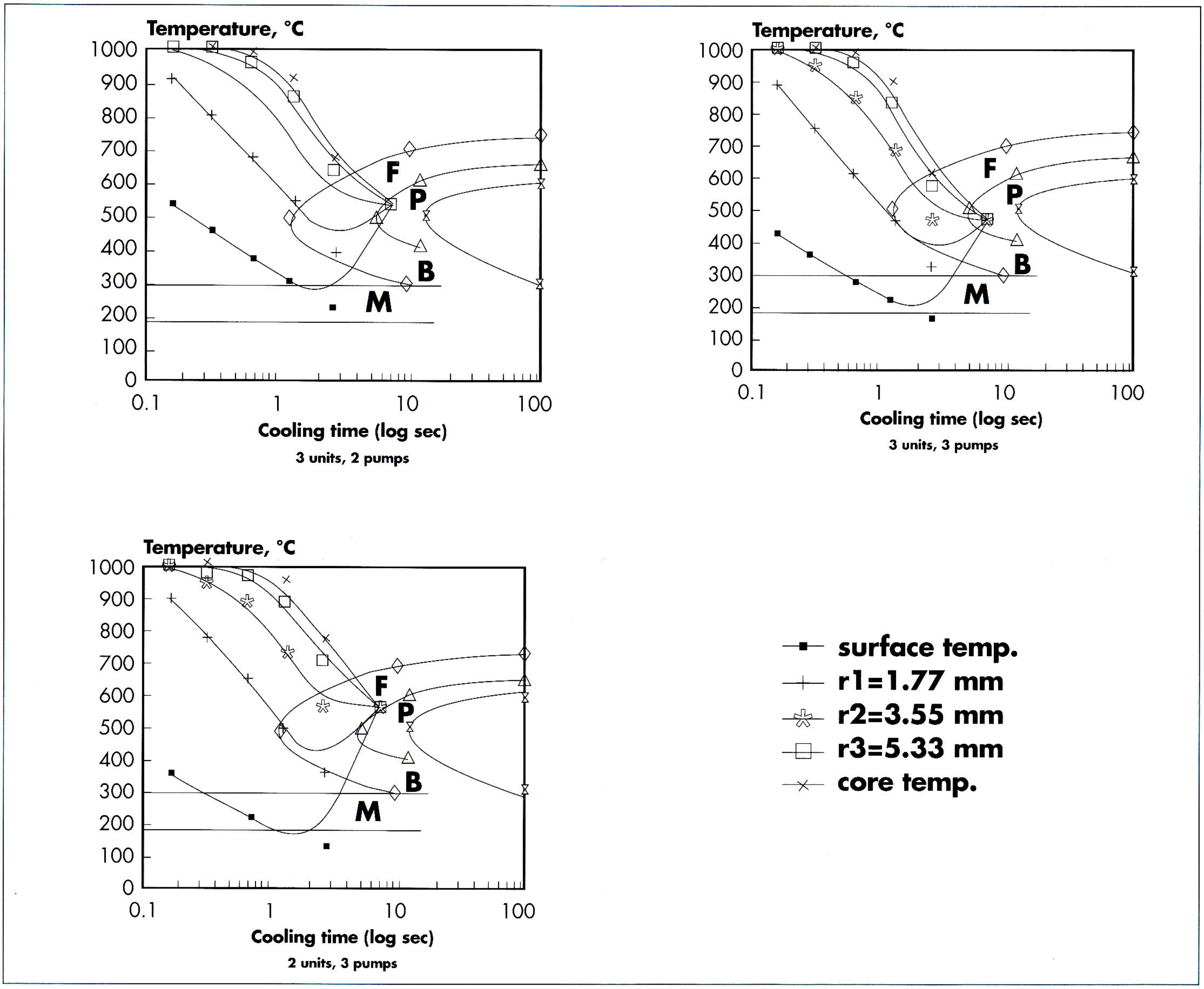


Figure 12: Cooling curves predicted by the model from which the microstructure of 16 mm bars could be predicted

CONCLUSIONS

1. A mathematical model is developed to predict the design parameters of the accelerated cooling units used for the production of high strength steel rebars.
2. The design parameters provided by the model were used in installing an accelerated cooling unit at El-Ahlya National Company, which produced high strength rebars of strength values that reached 500-1500 MPa from ordinary steel 37.
3. Design curves are obtained for each group of bar sizes, from which water flow rate and cooling unit length could be determined at various rolling speeds.
4. Cooling curves are obtained by a thermal mathematical model, that could be used to predict microstructure of in-line accelerated cooled bars.
5. The hardness and microstructure predicted by the cooling curves show good agreement with those observed metallographically.
6. The control of cooling conditions to obtain the required equalising temperatures is of great importance if precise control of mechanical properties is required.

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REFERENCES

1. Shunfa Y., L. Kun, S. Zehan, C. Chunze, B. Zhonghao, Z. Guangliang and W. Jianahuan The interrupted accelerated cooling process after hot rolling for deformed reinforcing bars. lntrn. Conf. on HSLA Steels, Beijing, China 4-8 Nov., 1985, 885-891.
2. Forman, K. and C.M. Viad. Mechanical and technological properties of temprimar weldable high strength rebars. ibid, 901-907.
3. Viad, C.M. A comparison between the temprimar and tempcore processes for production of high strength rebars. ibid, 909-912.
4. Jari, M. and U. Tjernquist. Controlled rolling and accelerated water cooling of C-Mn and micro-alloyed bars. ibid, 893-900.
5. Sawada, H., J. Koarai, M. Uemura and T. Ohshiro. Controlled rolling of bars. TMS-Conference on Accelerated Cooling, Pitts Burgh, 19-21 Aug. 1985, 589-599.
6. Kilimore, C.R., J.F. Barrett and J.G. Williams. Mechanical properties of high strength reinforcing bar steels accelerated cooled by the tempcore process. ibid, 541-557.
7. Sjostrom, A. and H. Lonnberg. Control of bar and wire rod temperature with water cooling. ibid, 523-539.
8. Mori, T., H. Kanisawa, T. Banno, T. Waseda and R. Mohri. Development of hot water cooled high-strength steel wire rods for fasteners. ibid, 575-587.
9. Liewellyn D.T. Low carbon structural steels. Steels metallurgy and applications, Butterworth Heinemann, Oxford, 1992 pp 65-73.
10. Carnahan B., H.A. LITHER and J.O.WILKES. Applied Numerical Methods, John Wiley & Sons, 1969.
11. Holman, J. P. Heat Transfer, McGraw-Hill, 1984.
12. El-Koussy, I.S. El-Mahallawi, N. Abdel Rahim and A. El-Kady. Factorial analysis of the effect of C, Mn, Si and V on yield stress of reinforcing steel bars. Proceedings of Mining, Petroleum and Metallurgy Conference, Cairo, Egypt 2-4 Feb.1992, 42-54.

NOMENCLATURE

C	Specific heat (J/kg.°C)
E	Emissivity of the steel bar
h_c	Convective heat transfer coefficient (w/m2. °C)
k	Thermal conductivity (w/m. °C)
L	Length of the steel bar (m)
n	Direction of heat flow
R_o	Radius of the steel bar (m)
r,θ,z	Cylindrical co-ordinates
T_a	Ambient temperature of the air (°C)
T	Temperature at any point (°C)
t	Time (s)
ρ	Density (kg/m^3)
α	Thermal diffusivity ($=\kappa/\rho c$)
σ	Stefan Blotzmann constant.
M	Martensite
B	Bainite
P	Pearlite
F	Ferrite