Reprint from „MPT-Metallurgical Plant and Technology" issue No. 3/84, pages 80–93
Nachdruck verboten Verlag Stahleisen mbH, Düsseldorf

TEMPCORE, an economical process for the production of high quality rebars

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In the present paper, we shall first analyse the consumer's requirements concerning the properties of rebars; this will lead to the standard profile of an up-to-date concrete reinforcing steel. To follow, the different production processes of high quality rebars will be reviewed and the Tempcore process will be described. Finally the economic aspects of the different processes will be analysed in detail and the savings resulting from the implementation of the Tempcore process in typical bar mills will be described.

Analysis of the consumer's requirements

For many years, a strong and definite trend towards high quality rebars is observed in the market; the main concerns of the consumer are economy and safety. We shall hereunder review the properties requested in this respect.

Economy. First of all, economy implies *high yield strength* rebars: when the guaranteed yield strength of the rebars is increased, the weight of rebars to be used for a given construction is reduced and, consequently, the reinforcing costs are cut down. This evolution is also illustrated by the tendency observed in the standards to prescribe higher yield strength. The 400 MPa grade is very common while there is already a market for the 500 MPa grade and, in some countries, for the 600 MPa grade.

Additional cost savings are obtained by the use of prefabricated reinforcements: three–dimensional reinforcing structures are manufactured in workshops and transported directly to the building site. This procedure asks for assembling techniques ensuring the required dimensional accuracy and keeping it during several handlings until the final positioning in the construction. In many cases, tied connections are not strong enough while mechanical splices are not always applicable. Welding becomes then a must and it is well known that *weldability* of rebars requires a low-carbon content (<0.25% or even <0.22% for the tack resistance process) and a low-carbon equivalent (<0.45%) in the steels.

Another important property is the *bendability*; rebars displaying a good bendability will make possible the use of an optimum design and, hence, bring a further reduction of the production costs. On the other hand, the presence of connecting reinforcements requires a good *rebending ability*. In fact, some standards prescribe that rebars have to succeed in bending and rebending operations and this on small diameter mandrels (down to 3 or 4 times the rebar diameter) or in cold weather (−20 °C).

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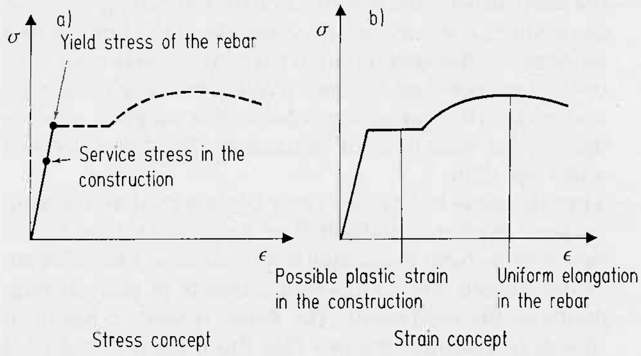
Safety. For many decades, the design of a concrete construction was based on a stress concept, i.e. on the assumption that the loads which normally appear in service induce only elastic stresses in the reinforcing steel. In such a case, the safety of a construction can be defined in terms of a stress ratio, e.g. the ratio between the service stress and the yield stress of the rebar **(figure 1a)**. However, recent research work has led to the conclusion that a stress based calculation of the reinforced concrete is not sufficient because, in some cases, local plastic deformations of a given extent have to be absorbed without failure of the rebars (for instance, when tamping occurs). In such circumstances, the safety of a concrete construction is expressed in terms of a strain ratio, e.g. the ratio between the local plastic deformation which can occur and the uniform elongation of the rebar **(figure 1b)**. Such a way of design is now adopted in many countries; it requires *ductile* rebars and a guaranteed uniform elongation of up to 4% is prescribed for as-received rebars and for welded rebars.

Another important aspect for the safety of concrete constructions is to prevent the loss of ductility after rebending. This again emphasizes the necessity of a good *rebending ability*.

From the above review of consumer requirements, the specifications to be fulfilled by an up-to-date concrete reinforcing steel appear clearly:
— high yield strength,
— weldability,
— bendability and rebending ability,
— ductility.



Stress concept

$$\text{Safety} = \frac{\text{Service stress}}{\text{Yield stress}}$$

Strain concept

$$\text{Safety} = \frac{\text{Plastic strain}}{\text{Uniform elongation}}$$

Figure 1. Safety concepts

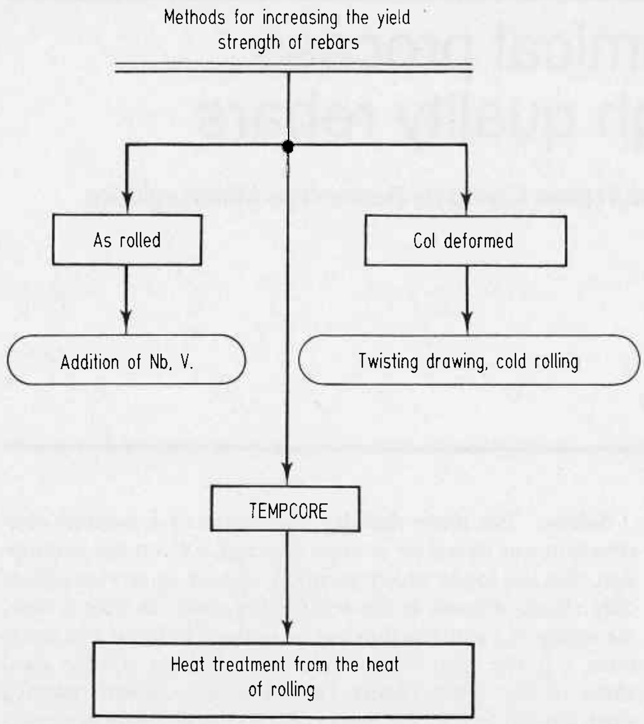


Figure 2. Methods for increasing the yield strength of rebars

Production of high quality rebars

Conventional processes. Before describing the Tempcore process, we shall make a brief survey of other processes which can be used for the production of high strength weldable rebars. These methods can be classified into two distinct categories **(figure 2)**:

— rebars used in as-rolled condition after slow cooling in air. For these bars, the yield strength can be increased by modifying the chemical composition but the C and Mn contents have to be kept low in order to avoid a significant decrease in weldability. The problem is solved by microalloying, i.e. by adding appropriate quantities of microalloying elements such as Nb or V;

— rebars submitted to a strain hardening after hot rolling, for instance by cold deformation. For such bars, the yield strength can be increased by increasing the extent of straining. This method enables the production of high strength weldable rebars from low C and Mn steels.

Tempcore process (principle). The Tempcore process has been thoroughly described elswhere[1][2]. Therefore, we shall only summarize its principle **(figure 3)**:

— the rebar leaving the last stand of the hot rolling mill passes through a special water cooling section. The cooling efficiency of this installation is such that a surface layer of the bar is quenched into martensite, the core remaining austenitic. The quenching treatment is stopped when a determined thickness of martensite has been formed under the skin;

— when the rebar leaves the drastic cooling section, the temperature gradient established in its cross section causes heat to flow from the center to the surface. This increase of the surface layer temperature results in the self-tempering of the martensite. The name Tempcore has been chosen to illustrate the fact that the martensitic layer is TEMPered by the heat left in the CORE at the end of the quenching stage;

— finally, during the slow cooling of the rebar on the cooling bed, the austenitic core transforms into ferrite and perlite or into bainite, ferrite and perlite.

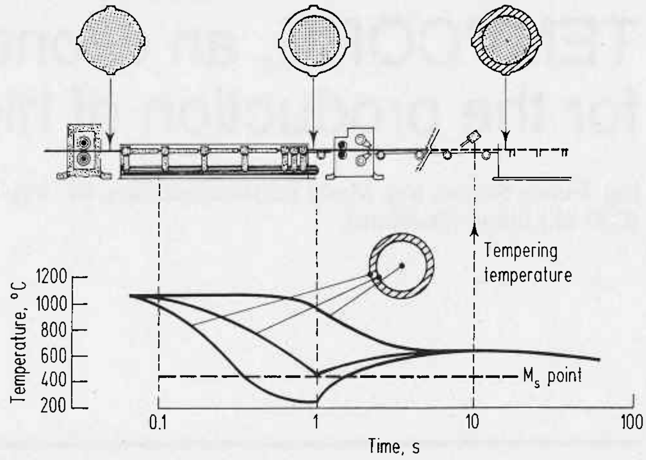


Figure 3. Schematic representation of the Tempcore process

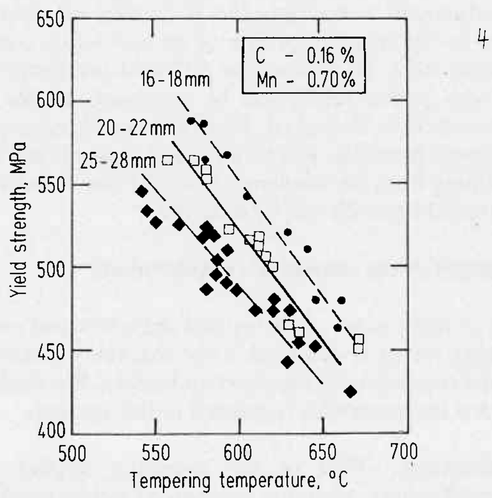


Figure 4. Example of yield strength/tempering temperature relationships

The temperature time history of the rebar is shown in figure 3. The three stages of the Tempcore process clearly appear:

— quenching of the surface layer;

— self-tempering of the martensite;

— transformation of the core.

The process, properly applied, leads to an increase of the yield strength of 150 to 230 MPa, depending on the cooling intensity.

Properties of Tempcore rebars. **Figure 4** shows an example of yield strength/tempering temperature relationships for a given chemical composition and different rebar diameters.

For a given chemical composition, thanks to the flexibility of the Tempcore process, it is possible to cover a large range of yield strengths by acting only on the cooling power of the quenching installation. In this example, it appears that grades III S and IV S can be produced by using the same chemical composition (0.16% C and 0.70% Mn) for all diameters.

Figure 4 also confirms that, for a specified chemical composition and diameter, there is an unequivocal relationship linking the mechanical properties to the tempering temperature. This unequivocal relationship is the key to the control of the Tempcore process: to achieve the required mechanical

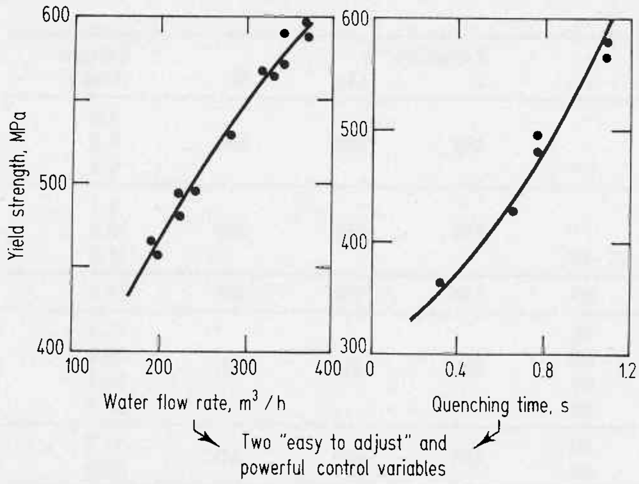


Figure 5. On line control of Tempcore

properties, it is sufficient to maintain the tempering temperature within a predetermined range. The obvious control variables are the length of the quenching line and the cooling water flow rate: they are easy to adjust during rolling and they have a strong effect on the yield strength of the rebars **(figure 5)**. The validity of this process control method is proven by experience: for the production of a mill during one year (about 300 000 tons), the standard deviation in the yield strength (average 480 MPa) was lower than 30 MPa, including the scatter of process and chemistry.

The excellent properties of Tempcore rebars have been discussed in many papers[3)–7)]. As a consequence, in the present paper, we shall not detail this point but only give a few examples. **Figure 6** illustrates the good weldability and ductility of Tempcore rebars, while **table 1** shows their excellent bendability. In the above examples, the Tempcore rebars have been compared to classical as-rolled C/Mn rebars.

Technology. The implementation of a direct heat treatment in a rolling mill has to comply with numerous, and sometimes conflicting, production and lay-out constraints. Without going into details, we list some of these constraints:

- low water flow rate availability;
- necessity of rapid changes of products, grades and sections;
- installation of the quenching lines in difficult areas.

These constraints have been overcome by technological improvements in the design of the cooling installations; it has thus been possible for certain applications:

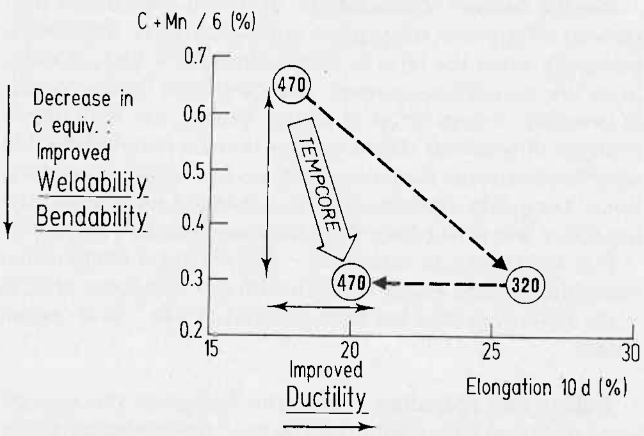


Figure 6. Weldability and ductility properties of Tempcore rebars

Table 1. Bendability

Bending tests	Typical D values Conventional $C_{eq} = 0.61\%$	Tempcore $C_{eq} = 0.30\%$
180° bending	3	0.5
90° bending and rebending after ageing	6	3.2
90° bending after electrical butt welding	15	4.0
90° bending after electrical cross welding	>20	7.0

Bendability expressed in terms of minimum bending diameter D (D is the ratio of the minimum possible bending diameter to the rebar diameter)

- to reduce the required cooling water flow rate by a factor of 2 to 3;
- to change production from Tempcore to non-Tempcore products in 3 to 5 minutes, without using a crane;
- to install quenching lines in areas already crowded with other mill equipment; for example, in two strand-mills where the finishing mills are not located side by side, the quenching line of one strand is located very close to some of the equipment of the other strand (shafts, gear boxes, motors, etc.)[8)].

This clearly shows that the expansion of the Tempcore process has been supported by an important development work for the cooling devices proper as well as for the detailed design of the quenching installation itself. From a technological point of view, its implementation is feasible in practically all bar mills.

Detailed economic comparison of Tempcore with other processes

Though in total Tempcore has superior properties to any other rebar, we shall in a first approximation consider that the other processes (microalloying and cold deforming) produce high strength rebars of acceptable properties. In this case, the differences will only arise from the economics.

As explained earlier, for cold deformed rebars, the yield strength is increased by straining. This additional operation of cold deformation is expensive, the manpower costs involved beeing particularly high in the case of small diameter bars. As a consequence, it becomes evident that the cold deforming process is non-competitive compared to Tempcore and microalloying; therefore our detailed economic comparison will be restricted to these two processes.

A survey has been made in 4 mini-mills in order to determine the advantages and drawbacks of both Tempcore and microalloying processes. The 4 plants had all used the microalloying route before implementing the Tempcore process on their bar mill; this obviously gives a good basis for our comparison. All plants are using electric furnaces to produce continuously cast billets from scrap. In these mills, the annual production of rebars is between 90 000 to 180 000 tons. The rebar diameters varies from 8/12 mm to 28/40 mm, while the minimum guaranteed yield strength generally ranges from 400 to 500 MPa.

The following factors have been taken into account for the comparison of the production costs of the Tempcore and microalloying processes:

- alloying elements;
- off-grades;
- other steelmaking factors;
- rolling mill operation.

Table 2. Alloy savings with Tempcore

Grades	W*)	Microalloying**) C	Mn	Si	V	Tempcore**) C	Mn	Si	Savings (DM/t)
Fe B 400	No	340	950	325	–				8,0
DIN 488-III RU	No	395	1200	225	–	180	600	200	8,5
DIN 488-III RU	No	415	600	225	25				9,2
ASTM 615-60	No	425	950	400	–				8,1
ASTM 615-60	No	450	1300	325	–	230	750	200	10,6
ASTM 615-60	Yes	275	1200	400	48				27,7
BS 4449	Yes	255	1000	400	50	230	750	200	25,8
Fe B 400 S	Yes	200	950	400	45				25,4
Fe B 400 S	Yes	160	975	275	50	180	600	200	23,9
DIN 488-III RUS	Yes	195	1025	300	60				28,7
DIN 488-III RUS	Yes	150	900	400	50				26,4
DIN 488-IV RUS	Yes	215	1400	450	60	180	600	200	37,7
DIN 488-IV RUS	Yes	225	1000	350	90				39,9
KS 60 S	Yes	275	1200	400	150				61,7
KS 60 S	Yes	220	1300	400	110	275	800	200	49,4
KS 60 S	Yes	260	1450	425	105				50,3

*) Weldable according to the mentioned standard.
**) Chemical compositions in 10^{-3}%.

Alloying elements. **Table 2** gives typical chemical compositions used for different rebar grades and for both processes. The savings listed in the last column have been based on the following costs (end 83/beginning 84):

- MN: 1,30 DM/ton for 0.1%;
- Si: 2,75 DM/ton for 0.1%;
- V: 34,00 DM/ton for 0.1%.

They represent the cost to increase by 0.1% the alloy content in the rebar, taking into account the price of the ferroalloys, the yield of the latter and the metal losses from liquid steel to rebar.

On average, the savings in alloying costs brought by the Tempcore process compared to microalloying are:

- 8,50 DM/ton for the production of grade III RU (420 MPa) according to DIN 488 (In the revised standard, due to come into force during 1984, this grade will be suppressed.);
- 8,00 to 10,60 DM/ton (or 3 to 4 US$) for the production of grade 60 according to ASTM 615 with high carbon/manganese contents; if lower carbon/manganese contents are favoured, i.e. for avoiding brittleness, vanadium has to be added and this brings the savings to 27,50 DM/ton;
- 26,00 DM/ton for the production of grade 460 (weldable) according to BS 4449;
- 26,00 DM/ton for the production of grade III RUS (420 MPa) according to DIN 488;
- 39,00 DM/ton for the production of grade IV RUS (500 MPa) according to DIN 488;
- 54,00 DM/ton for the production of grade KS 60 S according to SIS 142168.

Off-grades. We call *off-grade heat*, a heat which, due to its actual chemical composition, is considered unsuitable for its initially planned destination. As a consequence, such a heat has to be rerouted (diverted to another product, i.e. another diameter within the same grade or another grade) or, in some very unusual cases, scrapped.

In this regard, compared to microalloying, Tempcore displays several advantages:

- the chemical composition range beeing simpler (no Nb or V, lower Mn content) the percentage of off-grade heats is lower;
- the rerouting is simple and cheaper. With the microalloying process, when off-grade heats are on the low side (low C, Mn, Nb or V) a part of them has to be downgraded to lower qualities, which can be costly. With the Tempcore process, most of these off-grade heats can be maintained within the initially planned grade by adjustment of the cooling power of the installation.

The percentage of off-grade heats, their reduction with the Tempcore process, and the cost of the rerouting procedure, vary largely from plant to plant, depending on local conditions such as product mix, steelmaking plant practice, market possibilities, etc.

In some plants, the utilisation of the Tempcore process has brought a reduction of the percentage of the off-grade heats by a factor of 2 to 5. This, together with the cheaper rerouting costs linked to the flexibility of the Tempcore process, has led to savings varying from 1,00 to 13,00 DM/ton.

For both process – Tempcore and microalloying –, correct billet analysis normally leads to a suitable product. In certain cases, it may however happen that the actual mechanical properties of the rolled product are found outside initially planned specifications. Such an *off-grade product* has then to be diverted to another grade or scrapped.

It has been observed that the flexibility of the Tempcore process (adjustment of the cooling power of the installation) allows a better control of the yield strength of the product than microalloying; in some cases, the reduction of the percentage of off-grade products has brought additional savings of 0,7 DM/ton.

Electric furnace steelmaking. It is well known that high carbon, silicon and manganese contents lead to brittleness, especially when the level of tramp elements is high. Thanks to its low manganese content, the Tempcore process could, in principle, accept scrap of poorer quality, i.e. with higher contents of residuals. However, for reasons mainly linked to reliable electric arc furnace operations and quality considerations, Tempcore licensees have not changed their scrap buying policy when switching from microalloying to Tempcore.

It is interesting to note that – the chemical composition being simpler and easier to reach with the Tempcore process – the tap-to-tap time has been reduced by 4 to 7% in certain plants.

Rolling mill operation. With the Tempcore process, the same chemical composition can be used for producing all the diameters of a given grade. Moreover, different grades (e.g.

grades III S and IV S according to DIN 488) can also be produced by using the same chemical composition. As a consequence, the number of steel qualities, defined by a range of composition for each alloying element, is strongly reduced with respect to microalloying.

Moreover, as the flexibility of the Tempcore process enables an easier recovery of the off-grade heats, it is possible to process these heats faster and thus to avoid an expensive stock piling.

Reductions of billets stock level from 1 000 to 20 000 tons have been observed, which corresponds to a reduction of tied-up capital of 400 000 to 8 000 000 DM. Taking into account the annual rebar production and an interest rate of 12% per year, this has led to savings ranging from 0,4 to 10,7 DM/ton.

Let us also recall that hot charging of continuously cast billets steadily increases. The efficiency of microalloying elements depends on the temperature evolution of these billets; there is no doubt that variations in the thermal path linked to the hot charging practice may lead to more off-grades or to higher alloying costs. Studies are under way to quantify this factor.

As far as cooling is concerned there is an advantage for microalloying, as no water is needed. The operating costs of the Tempcore process (water, energy, maintenance, wear of equipment, etc). vary from 0,50 to 1,50 DM/ton.

Table 3 summarizes the results of our detailed economic comparison between the Tempcore and the microlalloying processes; it shows in all cases a net advantage for the Tempcore route.

Example of economic evaluation

Hereunder we shall make a detailed evaluation of the economics of the implementation of the Tempcore process in bar mills which, at the present time, are using the microalloing route. Two examples pertaining to the situations in Europe and the U.S.A. will be given.

Case A (Europe). This mill is supposed to use billets made by the electric furnace-continuous casting route for the production of 100 000 tons per year. We have also supposed that it will produce 8 to 28 mm weldable rebars of the following grades:

— 70% of grade DIN 488 – III RTS (420 MPa);
— 30% of grade DIN 488 – IV RTS (500 MPa).

It should be noted that:

a) the III RTS grade includes the equivalent grades (Fe B 400, Ks 40 S, etc);
b) the IV RTS grade includes the equivalent grades (Fe B 500, KS 50 S, etc.);
c) the "extra" savings brought by the possible production of a small percentage of grade KS 60 S rebars have been disregarded.

The following investment and operating costs have been estimated for the Tempcore process:

— investment costs: these costs vary largely from plant to plant (1 to 6 000 000 DM), according to the capacity of the installation, to the water system installed and to the possible necessity to install a new dividing shear capable of cutting the cooler and stronger Tempcore rebars. We have considered a total investment cost of 4 000 000 DM (including license fees, cooling equipment, new dividing shear, water system, process control equipment, miscellaneous, etc.). On the basis of 20% per year (amortization and interest), this corresponds to a cost of 8,00 DM/ton of rebar;
— operating costs: 1,00 DM/ton;

Total costs: 9,00 DM/ton.

Table 3. Production costs (1 US$ = 2,7 DM)

Cost factor	Tempcore-Savings DM/t	Tempcore-Savings US$/t
Alloying element	8,0 to 54,0	3,0 to 20,0
Off-grade heats	1,0 to 13,0	0,4 to 4,8
Off-grade products	0 to 0,7	0 to 0,3
Scrap quality	*)	*)
Tap-to-tap duration	*)	*)
Level of billets stock	0,4 to 10,7	0,15 to 4,0
Rolling costs	−0,5 to −1,5	−0,2 to −0,6

*) In favour of Tempcore but not quantified.

The following gains have been estimated compared to microalloying:

— alloying elements: 29,90 DM/ton (26,00 DM/ton for the III S and 39,00 DM/ton for the IV S: see table 2);
— off-grade heats and rerouting: 4,00 DM/ton (average of the 4 plants examined);
— off-grade products: it has been assumed that there was no off-grade products, for both processes;
— tap-to-tap duration: those savings have not been credited;
— level of billets stock: it has been supposed that the amount of stock reduction was of 2 to 3 weeks of mill production, i.e. about 4 800 tons. This corresponds to a tied-up capital of 1 920 000 DM or, for an interest rate of 12%, to 2,3 DM/ton.

Total gains: 36,20 DM/ton.

These calculations lead to the conclusion that, for case A, the implementation of the Tempcore process brings *net savings* of 36,20 − 9,00 = 27,20 DM/ton or 2 720 000 DM/year. The corresponding pay-back period is about 15 months.

Case B (U.S.A.). This mill is similar to the mill of case A; it is supposed to produce 100 000 tons per year of grade 60 according to ASTM 615.

The cheapest solution (as far as alloying costs are concerned) for this grade is to produce hot rolled bars with about 0.45% C and 1.25% Mn, which corresponds to a high carbon equivalent (about 0.65%). As said above, when the contents of residual elements are high, this high carbon equivalent can lead to brittleness, which means a costly downgrading or scrapping of part of the production.

To avoid this risk, it is theoretically possible to make a scrap selection in order to avoid high residual elements contents but this is also costly and not feasible in all cases. This is the reason why certain mini-mills perfer to use lower C or Mn contents and to compensate by microalloying.

The investment and operating costs estimation for Tempcore is the same as in case A, i.e. a total of 9,00 DM or 3,33 US$ per ton.

As explained above, there are different possibilities to produce the ASTM 615 grade 60 with the conventional process. As a consequence, the gains vary from plant to plant and is is difficult to estimate the average savings. Therefore we have performed the economic calculations in two extreme cases: high C/Mn steel and microalloyed steel.

1st hypothesis: replacement of high C/Mn steel by Tempcore.

In this case, the alloying savings are of 9,00 DM or 3,33 US$ per ton (see table 2). We have considered a gain of 4,00 DM or 1,48 US$ per ton for the off-grades. In fact, due to the brittleness problem mentioned earlier, the percentage of off-grades – and particularly the costly off-grade products – is probably larger than for the 4 mini-mills examined in our survey and 4,00 DM/ton constitutes a bottom limit. With a gain of 2,30 DM or 0,85 US$ per ton for the lower billet stock, we reach minimum total savings of 15,30 DM or 5,67 US$ per ton. The calculations lead to the conclusion that the implementation of the Tempcore process brings *net savings* of minimum 630 000 DM or 233 300 US$ per year.

2nd hypothesis: replacement of microalloyed steel by Tempcore.

In this case, the gains have been estimated to:

— alloying elements: 27,50 DM or 10,19 US$ per ton (see table 2);
— off-grade heats and rerouting: 4,00 DM or 1,48 US$ per ton;
— lower billet stock: 2,30 DM or 0,85 US$ per ton.

The total gains are of 33,80 DM or 12,52 US$ per ton. The implementation of the Tempcore process brings *net savings* of 2 480 000 DM or 918 500 US$ per year. The corresponding pay-back period is comparable to case A.

The above calculations show that, in the case of ASTM 615 grade 60, the net savings brought by the Tempcore process lay between 6,30 and 24,80 DM per ton (2,33 to 9,19 US$ per ton). The true savings depend on:

— the actual quantity of the off-grades and their costs;
— the percentage of high quality rebars produced. In fact, if the U.S.A. market follows the tendency towards high quality rebars described in the first part of this paper, this percentage will rapidly increase.

Conclusions

In the technical part of this paper, we have shown that the Tempcore process consistently produces high quality rebars which meet the consumer's requirements and that its implementation is easy. From the economical point of view, the calculations performed in the case of typical bar mills demonstrate the superiority of the Tempcore process. In comparison to the microalloying route, the savings are of:

— 2 700 000 DM per year when producing 100 000 tons per year of weldable rebars (European market);
— 630 000 to 2 500 000 DM per year (230 000 to 900 000 US$) when producing 100 000 tons per year of ASTM 615 – grade 60 rebars (US market).

Therefore, it can be concluded that Tempcore is the answer to the present and future rebar market, as well for the consumer as for the rebar producer.

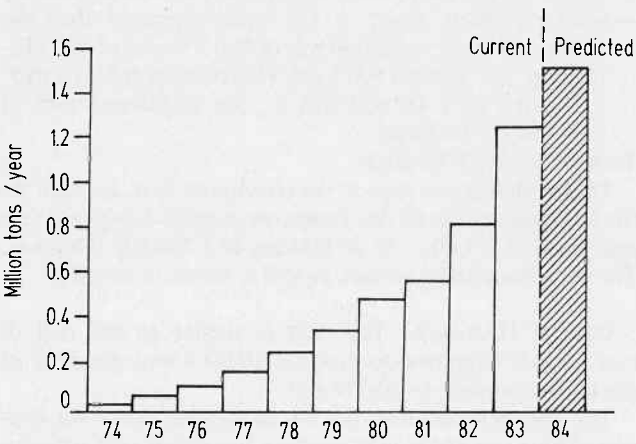


Figure 7. Tempcore production

Table 4. Tempcore installations

In operation	
Arbed S.A., Luxembourg Schifflange plant	Broken Hill Proprietary Co Ltd Australia, Port Kembla plant
S.A. Metallurgique et Miniere De Rodange-Athus, Luxembourg Rodange plant	Broken Hill Proprietary Co Ltd Australia, Newcastle plant
Cockerill-Sambre S.A., Belgium, Marcinelle plant	Badische Stahlwerke AG, Germany Kehl plant
Hoogovens-Ijmuiden B.V. The Netherlands, Ijmuiden plant	Hoesch Hüttenwerke AG, Germany Dortmund plant (2)
Alpa, France Porcheville plant	Max Aicher KG, Germany Annahütte plant
Manufer, France Montpon plant	Eisenwerk-Gesellschaft Maximilianshütte mbH, Germany Haidhof plant
Sacilor, France Homécourt plant	Arbed Saarstahl GmbH, Germany Völklingen plant
Sheerness Steel Co. Ltd., UK Sheerness plant	Von Moos Stahl, Switzerland Emmenbrücke plant
North Star Steel Co, USA Monroe plant (1)	Norsk Jernverk a/s, Norway Mo-I-Rana plant
	Stahl- und Walzwerke Marienhütte GmbH, Austria Graz plant
Under construction or planned	
Sidenor, Greece Thessaloniki plant	Lech-Stahlwerke GmbH, Germany Meitingen plant
Elkem a/s, Norway Christiana plant	The Tata Iron & Steel Co Ltd India, Jamshedpur plant
Voest-Alpine AG, Austria Donawitz plant	Rashtriya Ispat Nigam Ltd. India, Visakhapatnam plant

(1) Not for rebars but for cooling plain carbon and alloy bars.
(2) Production to be discontinued.

This conclusion is supported by **table 4** which shows that, at the present time, 19 installations are in operation all over the world and that 6 more installations are planned or will start operation in the near future. Moreover, **figure 7** shows the growth of the production of Tempcore rebars during the recent years and the forecast for 1984.

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