Assessment of Concrete Reinforcing Bars made by the Tempcore Process [1]

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Ribbed reinforcing steel manufactured by the Tempcore process was tested for suitability by means of comprehensive investigations. The steel was tested not only with regard to the conventional properties envisaged, for example, in German Standard DIN 488, part 1 Table 1, but other material characteristics not normally the subject of investigation were also included. It can be stated that ribbed reinforcing steel manufactured by this process has the properties required by DIN 488, part 1, for steel grade III and that further investigations of a more far-reaching character give no indication that this new manufacturing process adversely affects the service properties; the steel also possesses suitable weldability for the flash, MMA and resistance methods.

Betrachtungen über nach dem « TEMPCORE »-Verfahren hergestellte Betonstähle. *In einer umfassenden Studie wurden die Anwendungsmöglichkeiten für nach dem « TEMPCORE »-Verfahren hergestellte Rippenstähle untersucht, wobei nicht nur die normalen Eigenschaften wie in der Normvorschrift DIN 488, S. 1, Tabelle 1, festgelegt Gegenstand der Studie waren, sondern darüber hinaus vorab auch andere Eigenschaften von Werkstoffen behandelt wurden, die im allgemeinen nicht untersucht werden. Man kann sagen, dass nach dem TEMPCORE-Verfahren hergestellte Rippenbetonstähle die nach Normvorschrift 488, Seite 1, für die Klasse III geforderten Eigenschaften aufweisen und dass ergänzende Untersuchungen keinerlei Anzeichen dafür erbracht haben, dass dieses neuartige Herstellungsverfahren die Gebrauchseigenschaften nachteilig beinflussen könnte. Desweiteren ist die Eignung dieser Stähle für Schweissungen nach dem RA-, E- und RP-Verfahren ausgewiesen.*

Considérations sur les aciers à béton fabriqués selon le procédé « TEMPCORE ». *Dans une vaste étude, on a examiné les possibilités d'utilisation de l'acier crénelé pour béton fabriqué selon le procédé « TEMPCORE ». L'étude n'a pas seulement visé les caractéristiques normales fixées par exemple dans la norme DIN 488, p. 1, table 1, mais on s'est aussi préoccupé d'autres caractéristiques du matériau qui ne sont pas généralement étudiées. On peut dire que l'acier crénelé pour béton, fabriqué par le procédé TEMPCORE, présente les caractéristiques exigées par la norme DIN 488, page 1, pour la catégorie III, et que les examens complémentaires n'ont pas donné d'indications selon lesquelles ce nouveau procédé de fabrication pourrait porter préjudice aux propriétés d'utilisation; on démontre également l'aptitude au soudage pour les procédés par étincelage, manuel et par résistance.*

Overwegingen over TEMPCORE betonstaal. *In een omvangrijke studie werden de toepassingsmogelijkheden van het geribde TEMPCORE betonstaal onderzocht. Deze studie was niet beperkt tot de gewone karakteristieken, b.v. volgens norm DIN 488, bl. 1, tafel 1; bestudeerd worden ook andere eigenschappen die gewoonlijk buiten beschouwing blijven. Het mag gezegd worden, dat het geribde TEMPCORE betonstaal de door norm DIN 488, bl. 1, van klasse III gestelde eisen bezit, en dat aanvullende onderzoekingen geen aanwijzing gegeven hebben, waarnaar deze nieuwe vervaardigingswijze nadeling zou kunnen zijn voor de aanwendingseigenschappen. Ook is de lasbaarheid gegeven voor het handbooglassen, het weerstandkruislassen en het stomplassen.*

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1. — Introduction

A new method to make steel rebars has been added recently to the classical processes as hot rolling and cold forming.

What is known as the Tempcore process, developed by the C.R.M. Liège in collaboration with some iron and steelmakers, takes advantage of the residual heat of the rods after hot rolling to achieve a controlled heat treatment which results in an increase of the material strength.

A somewhat near method had already been experienced by Dick [1], but not really used.

The new process seems to be reliable, so that it is possible to use it on a large industrial scale [2].

A number of works such as ARBED, Forges de Thy-Marcinelle et Monceau, and Métallurgique et Minière de Rodange-Athus (1), intend now to put on the market rebars obtained by this process. At first it is planned to produce a weldable steel of the 42/50 class and later of the 50/55 class, also weldable.

2. — The Tempcore process

Several methods are available for increasing the strength of steel. For steel reinforcements according to DIN 488, sheet 1, two processes have been used up to now. In the case of bars in the as hot rolled conditions (RU) the strength is due to the nature of the microstructure and eventually to a precipitation hardening of the grains while in the cold deformed bars, near the same structural mechanisms a further increase of the strenght comes from the cold deformation.

Steels subjected to a special heat treatment, for example quenching and tempering, up to now have not been used as reinforcement for concrete. High final strength can be achieved by means of heat treatment even for low alloyed steels; however the expenditure involved in this additional operation, related to the maximum useful strength in reinforced concrete construction, exceeds that of the additional alloying elements or that of the cold forming. However, all steels are at austenisation temperature at the hot rolling stage, it is attractive to take advantage of the heat in the hot rolled product for a subsequent heat treatment. In order to achieve a useful heat treatment, it is necessary to quench the material after the last rolling stand and — in order to obtain favourable material properties — to follow with a tempering phase. The Tempcore process operates according to this idea.

The Tempcore process can be described as follows : The steel rods have a temperature of, for example, 1,000° C in the last rolling stand. After passing this stand, the steel enters a water quenching zone, in which the outer layers of the rod are cooled so intensively that martensite is formed here; the core of the rod remains at a higher temperature. At the end of this first process stage, the steel has — down to a controlled depth — a predominantly martensitic outside layer and a core which is still austenitic, within which the nonsteady temperature field will naturally lead to a series of intermediate microstructures from martensit to ferrite. The microstructures as well as the proportion of the different layers in the cross rod section can be controlled by selecting the cooling intensity in relation to the rolling temperature, rod diameter and rolling speed. The rod is cooled further at the ambiance after leaving the water cooling region. Owing to the temperature distribution the outer layer of the rod is treated once again. Hence the martensitic outer layers are subjected to a "self tempering process", provided that sufficient heat is still available in the core of the rod to provoke a sufficiently high tempering temperature of approximately 600° C. This second process stage is considered as complete when the outer layer has run through the maximum temperature value, which is caused by the residual heat in the centre "core" and the cooling condition in air (surface area, thermal conductivity).

During the third process stage — the rod is now already on the cooling bed — the material cools down normally in quiescent air.

The final microstructure, depending on :

— chemical composition,
— rod diameter,
— rolling end temperature,
— cooling intensity (in phase 1),

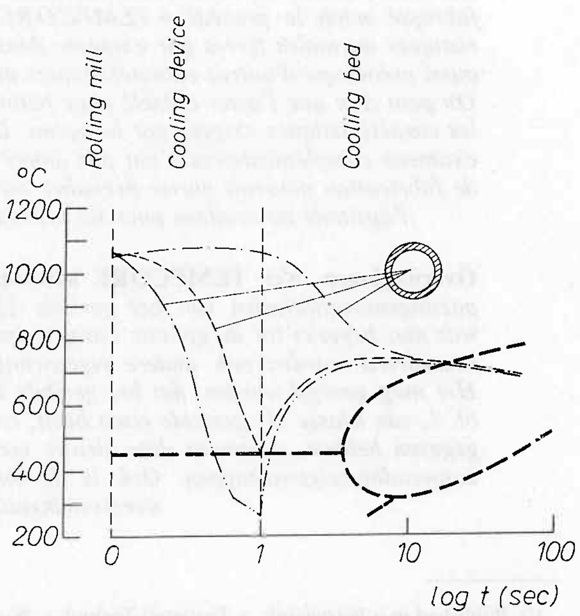

Fig. 1. Schematic representation of heat treatment in the TTT diagrams.

(1) N.B. : and recently Hoogovens B.V.

is a mixture of ferrite and pearlite in the core, a bainitic microstructure in the transition zone and tempered martensite in the outer layer.

The overall process can be traced on a well known TTT diagram (Fig. 1); for simplicity, only the curve for "martensite start" (M_S) as well as the ferrite curve and the bainitic microstructure zone are plotted. In addition the cooling paths for surface and center are given. Hence — on viewing over the cross section — the final product must have different strength values according to the considered layer and this in the following manner :

- a high value in the outer layer;
- this is followed by a transition zone in which the strength gradually decreases to the value in the core.

This situation is represented in Figure 2.

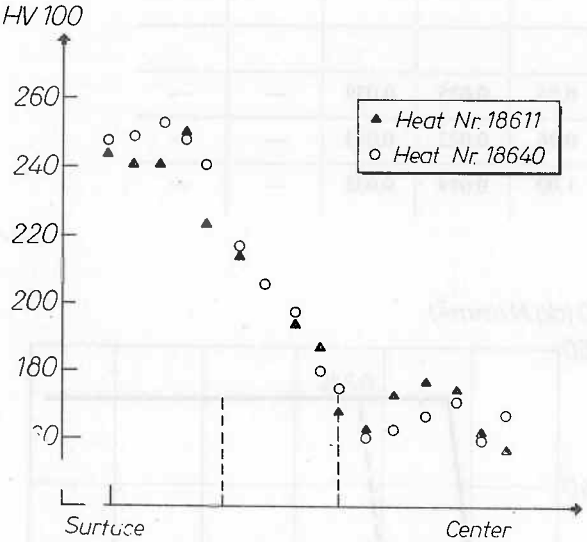

FIG. 2. Distribution of hardness values through the cross-section of Tempcore steel.

To depict further the situation, some tensile tests were carried out on machined specimens which gave the following results :

Rod diameter mm	Heat 1 (18611)		Heat 2 (18640)	
	β_s da N/mm²	β_s da /Nmm²	β_s da N/mm²	β_s da N/mm²
16	49.0	56.5	46.3	54.2
14.5 [a]	47.1	56.2	45.5	54.0
10.0 [a]	37.0	48.0	37.1	48.4
8.05 [a]	35.7	46.9	36.7	48.2
> 14.5	57.7	(68.6)	50.0	(70.8)

[a] turned specimen.

The figures in the lines 1-4 are measured values; the strength of the outer layer (>14.5) was evaluated by calculation; the yield point values are primarily of interest here.

The nonuniform microstructure over the cross section can also be seen especially clearly in Figure 3.

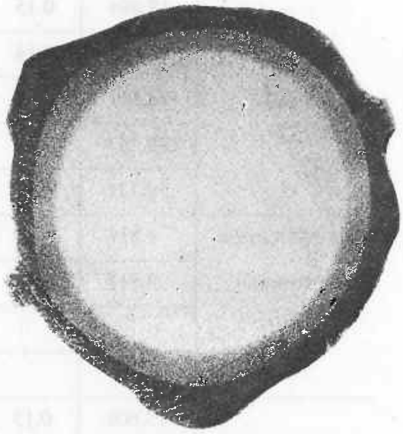

FIG. 3.

3. — INVESTIGATIONS OF THE TEMPCORE REBARS

3.1. — *Principles and aims.*

It was intended to find out whether steel rods made by the Tempcore process could be used as concrete reinforcement, i.e. whether they were fitting all the requirements of DIN 488, sheet 1, Table 1, for the steel class III U and whether the weldability was ensured for all welding procedures used in reinforced concrete construction. It is obvious that it was also necessary to test all the other properties in use, such as sensitivity to corrosion, susceptibility to brittle fracture and sensitivity to temperature. Of great importance was the investigation of the consistency of the production method, i.e., to which extent the production process accurately could be controlled ensuring a uniform quality of the product.

3.2. — *Experimental material.*

In this general investigation to test the suitability of the rebars made by the Tempcore process, altogether 23 melts were used from 3 steel mills within the dimension range varying from 8 to 28 mm. The rods were ribbed in the same way as for the steel class III U, according DIN 488.

4. — EXPERIMENTAL RESULTS

4.1. — *Chemical composition.*

The chemical compositions for individual heats are shown in Table 1. In comparison with the

TABLE 1. Chemical composition of examined heats.

Origin	Heat No.	C	Si	Mn	P	S	Nb	N
		Composition in weight per cent						
ARBED	18,894	0.15	0.06	0.97	0.022	0.013	—	0.0037
	18,640	0.14	0.03	0.92	0.015	0.012	—	0.0031
	18,611	0.18	0.04	0.98	0.021	0.013	—	0.0025
	198,357	0.19	0.03	0.78	0.036	0.022	—	0.010
	19,121	0.14	0.05	1.01	0.017	0.016	—	0.003
Thy-Marcinelle et Monceau	3,811	0.11	0.05	0.52	0.020	0.028	—	0.011
	3,817	0.15	0.04	0.66	0.029	0.027	—	0.011
MMRA	15,606	0.15	0.08	0.95	0.025	0.039	—	—
	15,609	0.15	0.07	0.96	0.022	0.033	—	—
	15,162	0.15	0.08	1.00	0.019	0.033	—	—

conventional chemical composition of the steel class III U, the considerable reduction of the carbon and also of the manganese contents will be noticed.

4.2. *Tensile strength characteristics.*

For each melt, at least 15 specimens were tested and the following tensile characteristics measured: yield stress (β_s), tensile stress (β_z), fracture elongation (δ_{10}) and partly uniform elongation (δ_g). The characteristic values are entered into Tables 2 and 3. The results of the tensile tests with a very precise strain measurement for determining the E. modulus and of the 0.01 % proof stress are shown in Tables 4 and 5.

The main features of the tensile properties are as follows:

— the material has a marked yield point;
— the ratio of the yield point to the tensile strength is on the average 0.85 (III U, usually about 0.65);
— in spite of the fact that some strength values are high for a III U steel class, extraordinarily good uniform and ultimate elongations are always observed;
— the average E modulus is $2.05 . 10^4$ da N/mm²;
— the stress-strain curve (example Fig. 4) has a linear rise;
— the ratio $\beta_{0.01}/\beta_{0.2}$ is in the average 0.98, i.e. the 0.01 % proof stress coincides with the yield point.

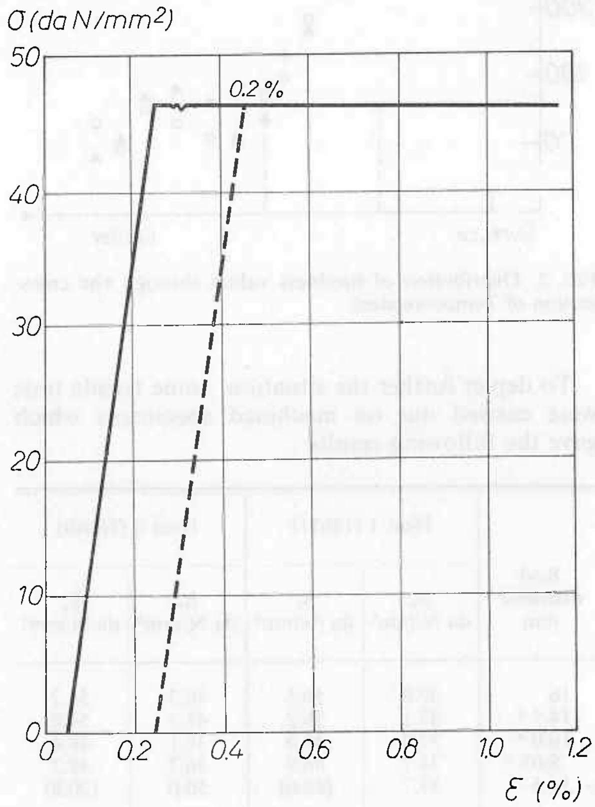

FIG. 4. Stress-strain diagram.

TABLE 2. Characteristic results of tensile tests on "Tempcore" specimens.
($\beta_s + \beta_z$ in da N/mm², δ_{10}, δ_g in %).

Heat No. Workshop	Diameter mm	Measured Value	Results				
			Average	Scattering	Minimum Value	Maximum Value	5 % Brittle
T 3,811	8	β_s	46.3	0.8	44.8	47.7	44.9
		β_z	54.6	0.7	53.6	55.6	53.4
		δ_{10}	25.4	1.8	22.5	28.8	22.4
		δ_g	16.7	—	13.1	18.1	—
T 3,817	8	β_s	50.9	2.1	48.1	54.3	47.4
		β_z	59.6	2.5	58.1	63.6	55.5
		δ_{10}	24.4	3.5	17.5	30.0	18.7
		δ_g	14.6	—	11.3	18.8	—
A 16,894	16	β_s	47.2	2.1	44.5	51.2	43.8
		β_z	55.1	1.8	52.7	58.9	52.1
		δ_{10}	23.2	1.9	19.1	25.4	20.0
		δ_g	12.1	—	12.8	16.0	—
A 18,611	16	β_s	48.4	2.1	46.3	51.3	44.9
		β_z	56.4	2.0	53.7	59.1	53.2
		δ_{10}	21.7	1.6	19.3	24.4	19.0
		δ_g	12.4	—	11.9	12.9	—

4.3. — *Reliability of production (scatter of the strength values).*

A good survey of the reliability of a production process is obtained by means of the standard deviation. This was evaluated for the yield point, tensile strength and fracture elongation in relation to melts and individual rods. The number of specimens per melt was, as a rule, 15; but for some melts, it was up to 50. The individual values per melt are given in Tables 2 and 3. From these, the following average values are calculated :

— Yield point : 1.37 da N/mm²,

— Tensile strength : 1.29 da N/mm²,

— Fracture elongation : 1.82 %.

For one melt, groups of different numbers of specimens were investigated for the purpose of studying the influence of the number of specimens. The following results were found :

Heat	Yield point		Tensile strength		Elongation at fracture	
	n	scatter da N/mm²	*n*	scatter da N/mm²	*n*	scatter %
1	15	0.8	15	0.7	15	1.8
	35	0.9	35	0.7	35	1.9
	50	0.7	50	0.8	50	2.4
2	15	2.1	15	1.8	15	1.9
	32	1.5	32	1.8	31	1.8
	47	1.9	47	1.6	47	1.8

TABLE 3. Characteristic Results of the tensile tests on "Tempcore" specimen. ($\beta_s + \beta_z$ in da N/mm², δ_{10}, δ_g in %.)

Heat No. Workshop	Diameter mm	Measured Value	Results Average	Scattering	Minimum Value	Maximum Value	5 % Brittle
A 18,640	16	β_s	46.5	1.8	43.1	49.0	43.5
		β_z	54.1	1.1	51.5	55.4	52.3
		δ_{10}	22.4	1.5	19.6	25.3	19.9
		δ_g	13.6	—	11.7	16.0	—
A 18,640	28	β_s	47.9	0.9	46.3	49.4	46.3
		β_z	57.2	1.2	54.8	59.4	55.2
		δ_{10}	20.5	1.5	16.9	22.3	18.0
		δ_g	12.0	—	11.5	12.9	—
A 18,894	28	β_s	50.6	0.9	48.9	52.0	49.1
		β_z	59.4	1.0	57.8	60.9	57.8
		δ_{10}	20.0	1.1	17.6	21.8	18.2
		δ_g	11.0	—	11.7	14.0	—
A 18,611	28	β_s	50.7	1.1	49.1	53.1	48.8
		β_z	60.1	1.1	58.3	61.9	58.2
		δ_{10}	19.4	1.4	17.8	22.1	17.0
		δ_g	12.3	—	11.7	13.0	—
R 15,606	14	β_s	46.5	1.3	44.6	47.6	44.4
		β_z	56.7	1.0	55.5	59.2	55.1
		δ_{10}	22.5	2.1	19.3	27.8	19.1
R 15,609	14	β_s	46.4	1.8	44.5	51.4	43.4
		β_z	56.1	1.4	54.4	59.8	53.8
		δ_{10}	23.7	1.7	20.7	26.4	20.9
R 15,612	14	β_s	48.9	0.6	48.0	49.7	47.9
		β_z	58.9	0.4	58.2	59.2	58.2
		δ_{10}	20.3	1.0	18.6	21.4	18.7

TABLE 4. Results of tensile tests with precise measurement of elongation.

Diameter of bar mm	Heat No.	Characteristics of the diagram stress strain			
		$\beta_{0,01}$ da N/mm²	$\beta_{0,2}$ da N/mm²	β_z da N/mm²	Modulus E (.10³) da N/mm²
8	A I	47.1	47.1	56.2	20.3
16	A 18,894	46.6	46.3	54.0	21.0
		46.9	46.8	54.6	20.3
		45.2	45.2	53.4	20.7
		48.3	48.4	55.1	20.7
16	A 18,611	48.9	48.9	56.0	20.4
		48.7	48.7	56.2	21.0
		49.1	48.9	56.4	20.4
		51.2	51.2	56.7	21.1
		50.0	50.0	55.9	20.9
		48.1	47.4	55.4	20.6
16	A 18,640	—	45.8	52.5	20.4
		45.6	46.6	53.2	20.5
		44.2	43.3	50.9	21.1
		47.4	46.1	52.8	20.9

TABLE 5. Results of tensile tests with precise measurements of elongation.

Diameter of bar mm	Heat No.	Characteristics of the diagram stress-strain			
		$\beta_{0,01}$ da N/mm²	$\beta_{0,2}$ da N/mm²	β_z da N/mm²	Modulus E (.10³) da N/mm²
25	A II	47.6	49.9	62.7	20.4
28	A III	46.0	50.8	60.0	20.5
28	A 18,640	46.5	46.5	56.5	20.3
		46.6	47.1	56.3	20.3
		46.2	46.4	55.3	20.4
		44.7	45.5	55.2	20.4
28	A 18,894	47.9	49.1	59.1	20.5
		47.6	48.2	57.8	20.3
		46.8	49.3	57.3	20.2
28	A 18,611	48.2	48.8	59.5	20.3
		47.1	49.0	58.4	20.5
		46.6	49.8	58.6	20.5
		48.2	50.4	59.3	20.3

Three different dimensions were examined on individual values, the standard deviations are :

Bar diameter	Specimen total	Yield stress da N/mm²	Tensile strength da N/mm²	Elongation at fracture %
8 mm	12	0.7	0.5	1.6
10 mm	12	0.5	0.7	2.8
20 mm	30	0.5	0.5	1.4

A slight increase is observed on comparing these values with those in DIN 488 sheet 6, which are considered as basic figures, or with those found for conventional reinforcing steels [3].

The homogeneity of the product is however to be considered as very good : especially no wide deviation is found for individual values in any experimental group. The high average level of the quality characteristics has a favourable effect on the characteristic value corresponding to the 5 % fractile calculated from the standard deviation.

4.4. — *Formability.*

The favourable values of the fracture elongation and especially of the uniform elongation have already been mentioned. They lead to the general conclusion that the formability is good. This represents one of the most important conditions for an easy workability.

For each melt, 10 bend- unbend tests and also 10 bend tests (around half the bending mandrel diameter of the bend-unbend test) were carried out. All tests ran according to the requirements.

In an additional series of tests, the minimum values of the mandrel diameter allowing a correct bending (folding up to 180°) and a correct bend-rebending operation (bending to 90° and unbending to 70°) were determined for some heats.

However, bend-unbend tests at —20° C, with D = 1 de were carried out for one melt; even in this case, the material withstood the test.

On summarising, the following can be said about the formability.

- The formability (in spite of a harder outer layer) of the Tempcore concrete reinforcing steel rod is to be considered as extraordinarily good (Fig. 4);
- A damaging aging effect could not be observed;
- For the bend test, the critical limit of the bending mandrels is approximately 1. de (independent of the diameter), in the bend-unbend test it is about 1.5 de for diameters 8 and about 2.5 for diameters 28;
- When a fissuration occurred (for example D = 0.5 de) and bending was continued, the fracture was not brittle but a ductile propagation of the crack in the material was observed (Fig. 5).

FIG. 5.

4.5. — *Fatigue strength.*

The fatigue strength was evaluated according to DIN 488 part 3, section 3.2 for a constant amplitude loading of 20 da N/mm², for the dimensions 16 and 28 mm. Rods of 8 mm diameter were used for the bracket reinforcements.

The results were statistically evaluated commonly according to diameters, because the number of the existing results did not fit the simplified testing system of DIN 488.

In Figure 6 clearly can be seen that the tested Tempcore rebars meet the requirements of DIN 488. No unusual incidents were encountered in the tests; the appearance of the fracture corresponds to that of conventional steels.

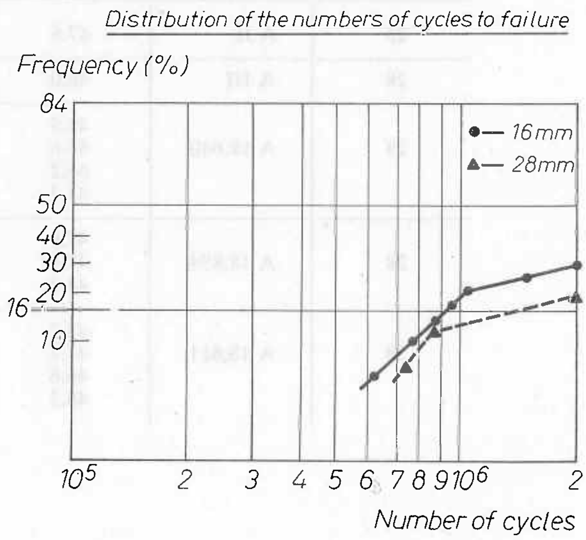

FIG. 6. Distribution of the number of cycles to failure.

The analysis of results gave for the amplitude $2\sigma_A = 20$ da N/mm² the following characteristic values :

Characteristic value	Diameter 16 mm	Diameter 28 mm
10 % fractile	0.81×10^6	0.7×10^6
Average value	2.0×10^6	2.0×10^6

4.6. — *Weldability.*

The demonstrations for the weldability of the Tempcore concrete reinforcing steel rods were carried out for the following processes :

— flash butt welding (RA);
— manual metal are welding (E);
— resistance tack welding (RP);

according to DIN 488, part 5, DIN 4099, sheet 1 and for the resistance tack welding according to DIN 4099, part 2. For the manual metal arc welding in addition to the required tests on overlap joints and on deposited weld bend specimens, all other joining methods such as :

— butt weld with X joint;
— overlap joint (centered);
— cross joints (load bearing);

were also tested.

The production and the testing of the welded joints were carried out according to the prescriptions. Attention was paid on testing especially to any decrease of strength and embrittlement. The investigation of the weldability was carried out on a total of 10 melts of dimensions 8-28 mm.

The main results of these extensive investigations are as follows :

— the Tempcore steel is to be considered as weldable with respect to the three above mentioned processes;
— no additional precautions are to be considered apart from the well known recommendations given in the standards for carrying out welding.

4.7. — *Temperature dependence of the strength values.*

Since the Tempcore ribbed concrete reinforcements are subjected to a heat treatment, the question about the temperature dependence of the strength values therefore has a special meaning. The steel behaviour under these conditions was assured by means of two series of tests :

— tensile tests at room temperature after previous heat treatment up to 900° C;
— tensile tests at temperature of −60° C, +300 and 500° C.

Tensile tests at room temperature after previous heat treatment.

These experiments were carried out in such a manner that three or two specimens per heat were held in the laboratory furnace at temperatures between 250 and 900° C for half an hour, subsequently cooled slowly to room temperature and then subjected to tensile testing; three melts with specimen diameter 8 mm and one melt with specimen diameter 28 mm were examined in this way.

An evaluation of the data has been carried out as in Figure 7 which demonstrates the following :

— up to temperatures of about 500° C a slight increase of strength occurs, associated with a reduction in elongation;
— a significant drop in strength starts at about 550° C; accordingly the values of the fracture elongation increase;
— the yield point and the tensile strength decrease in the same way up to a temperature of about 600° C, but at 700° C, already the decrease of the yield point runs ahead of that of the tensile strength,
— at 900° C the yield point is on average 21 da N/mm² and the tensile strength has decreased

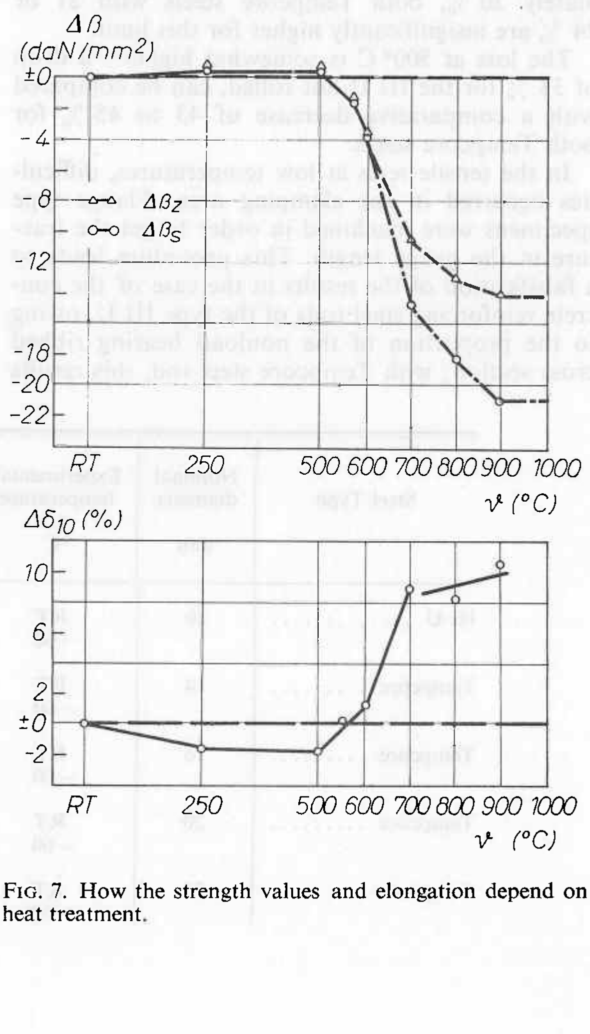

FIG. 7. How the strength values and elongation depend on heat treatment.

by about 14 da N/mm²; the ratio β_s/β_z is about 0.63 for specimen heat treated at 900° C which is the same as for the normally hot rolled material.

Comparing the data found here with those of the conventional reinforcing steel rods for concrete, a difference to those of the hot rolled steels becomes apparent; the relation to the steel III K, however, is situated at higher temperatures for the start of the strength decrease in Tempcore steel : the steel III K will considerably have lost in strength from 350° C [4] onwards.

Tensile tests at temperatures different from room temperature.

In contrast to the investigations described in the previous section, isothermal tensile tests now are considered :

— hot tensile tests at 300° C and 500° C;
— tensile tests at −60° C.

Four different diameters have been used in the investigations and a steel III U was also tested for comparison purposes. The following results were obtained in hot tensile tests :

Steel type	Diam. mm	$\beta_{0.2}$ (da N/mm²) RT	300° C	500° C	$\beta_{0.5}$ (da N/mm²) RT	300° C	500° C	β_z (da N/mm²) RT	300° C	500° C
III U	16	45.5	36.9	30.5	45.5	39.2	31.4	66.6	63.6	46.8
Tempcore	20	45.6	34.5	25.2	45.7	35.7	26.5	54.5	52.2	38.3
Tempcore	20	51.2	40.6	29.4	51.5	42.2	30.3	61.6	58.9	41.5

The decrease of the $\beta_{0.2}$ proof stress limit at 300° C for the steel III U (hot rolled) is approximately 20 %, both Tempcore steels with 21 or 24 % are insignificantly higher for this limit.

The loss at 500° C is somewhat higher : a drop of 33 % for the III U hot rolled, can be compared with a comparative decrease of 43 to 45 % for both Tempcore steels.

In the tensile tests at low temperatures, difficulties occurred in the clamping area. Flange type specimens were machined in order to get the fracture in the gauge length. This procedure leads to a falsification of the results in the case of the concrete reinforcing steel rods of the type III U, owing to the proportion of the nonload bearing ribbed cross section; with Tempcore steel rod, this results in an additional modification of the strength, because a part of the high strength region is machined.

In order to obtain a rough assessment of the material behaviour at low temperatures, tensile tests were carried out on hot rolled and Tempcore rods at −60° C; the naturally hard reinforcing steel rod was machined from 20 mm down to 10 mm (within the gauge length); the Tempcore steels were machined by turning only by 0.7 mm so that the major part of the hard external zone was still present.

Tensile tests were carried out also at room temperature with the specimens of the same kind for comparison purposes.

The results are as follows :

Steel Type	Nominal diameter mm	Experimental temperature °C	Strength values β_s daN/mm²	β_z daN/mm²	δ_{10} %	β_s, −60° / β_s, RT
III U	20	RT −60	44.2 52.4	65.0 73.8	26.6 25.3	1.18
Tempcore	14	RT −60	56.8 64.2	64.4 71.3	24.5 23.5	1.13
Tempcore	16	RT −60	50.3 56.0	56.0 64.2	32.7 31.0	1.11
Tempcore	20	RT −60	44.5 50.2	51.3 58.0	32.5 31.5	1.13
Tempcore	28	RT −60	51.8 61.3	60.8 67.3	26.0 23.0	1.18

The results show that the behaviour of the Tempcore steel basically is not different from that of hot rolled steels; the strength values increase while the elongations slightly decrease.

4.8. — *Time dependence of the strength values.*

It was indicated to check the constancy of the strength characteristics along the time. In the conventional concrete reinforcement steel rods, a time variation of the strength values is to be taken into account. Hence in the first two weeks after rolling the hot rolled concrete reinforcing steel approximately loses 1-2 da N/mm² of its yield strength and it gains a few percent in elongation at fracture. On the other side, the yield strength of a cold deformed steel rod (which subsequently has not been tempered) increases and its elongation falls.

This matter was investigated also for eight melts of Tempcore concrete reinforcing steel rods. The steel rods were tested at least after three different periods of time. Table 6 shows the collection of data. The constancy of the data is clearly recognised; a slight deviation from this behaviour is indicated only by rods of diameter 10 mm, in which a loss of the yield strength occurs at the start, while in comparison with this, the tensile strength is not changed.

Probably this particular observation was caused by the normally existing scatter and by the selection of the testing time.

Thus it can be assumed that no significant change of the strength as a function of time occurs which could affect the usefulness of the Tempcore steel.

4.9. — *Behaviour of the Tempcore steel under compressive loading.*

In the committees responsible for problems of reinforcing, the compressive loading of the concrete reinforcing steel rods in recent times frequently has been discussed. Hence it appeared useful to investigate also the steel rods produced by the Tempcore process with regard to the behaviour under compressive loading.

For this purpose two compressive tests were carried out according to DIN 50 106. The specimen length was 30 mm for the diameter 16 mm, and also for the diameter 28 mm, because the standard testing apparatus does not allow any greater length of the specimen. The steel rods were not machined, so that the whole cross section was examined.

Test no.	Rod nom. diam. mm	Heat no.	Characteristic values, Tensile test $\beta_{0.01}$ da N/mm²	Tensile test $\beta_{0.2}$ da N/mm²	Compressive test $\beta_{d0.2}$ da N/mm²
1	16	59123	47.5	48.3	49.4
2	28	18894	47.2	48.8	52.2

Thus a ratio of $\beta_{d0.2}$ to $\beta_{0.2}$ is found varying on average from 1.02 and 1.06.

The compressive loading capacity, up to the yield strength in compression, is the same as for tensile loading.

4.10. — *Sensitivity to corrosion.*

In conventional concrete reinforcing steel rods no damage as stress corrosion cracking or delayed fracture has been observed (exception : especially low carbon steels or steels with decarburized surface layer). Extensive damage occurred, however, in steel rods which obtain their final strength by a heat treatment, for example prestressed concrete reinforcements.

As the Tempcore steel is a heat treated steel too, it seemed absolutely necessary to carry out corrosion tests.

Considering the aim of the investigation, it was obvious to select tests prescribed for prestressed reinforcement. One of this test procedures corresponds especially to the anodic stress corrosion cracking and another one allows to assess the sensitivity of the material to hydrogen ("cathodic" stress corrosion cracking).

The test conditions are in detail :

Test type	Test solution	Test temperature	Test stress
I	30 % $Ca(No_3)_2$ solution	boiling	(0.6-0.8) β_s
II	20 % NH_4 SCN solution	35° C	(0.6-0.8) β_s

With these procedures, the following results were obtained :

Rod diameter	Melt No.	Test solution	Test stress	Application time (h)
8	T 3811	$Ca(NO_3)_2$	0.6 β_s	208
16	18 640		0.8 β_s	200
8	T 3811	NH_4-SCN	0.6 β_s	283
16	18 640		0.8 β_s	200

None of the specimens failed before the given testing time, nor appeared were cracks. A metal-

TABLE 6. Effect of time on tensile strength.

Workshop	Diameter mm	Measured Value	Time of measuring 2-4-76	7-4-76	14-4-76	14-5-76
ARBED	16	β_s	46.4		47.2	47.0
		β_z	54.7		55.1	55.2
		δ_{10}	24.0		23.2	23.6
	16	β_s	47.9		48.4	48.4
		β_z	56.5		56.4	56.0
		δ_{10}	22.4		21.7	22.4
	16	β_s	46.2		46.5	46.3
		β_z	54.0		54.1	53.8
		δ_{10}	23.0		22.4	21.2
	28	β_s		48.1	47.9	48.1
		β_z		57.8	57.2	57.2
		δ_{10}		20.4	20.5	21.8
	28	β_s		50.4	50.6	50.5
		β_z		59.5	59.4	59.4
		δ_{10}		19.8	20.0	19.4
	28	β_s		50.7	50.7	50.5
		β_z		60.7	60.1	59.7
		δ_{10}		19.6	19.4	20.4

Workshop	Diameter mm	Measured Value	Time of measuring (1976) 7-4	9-4	12-4	15-4	22-4	3-5	10-5
THY	8	β_s		46.1		45.8			45.9
		β_z		54.6		53.9			54.4
	8	β_s		51.9		51.6			51.4
		β_z		60.8		60.2			60.2
	10	β_s	50.8	48.9	48.6	49.0	49.4	49.1	49.6
		β_z	59.6	59.8	59.8	59.5	59.9	59.6	59.9

lographic investigation of the specimens did not show any decarburised zone, which could have explained the good behaviour.

On the basis of these results it can be assumed that the Tempcore steel rods are not more corrosion sensitive than conventional reinforcing steel rods.

4.11. — *Evaluation of the effect of mechanical damage.*

On viewing over its cross section, the Tempcore steel rod possesses a nonuniform strength distribution of such a kind that the zones close to the surface have maximum strength.

On the basis of this the mechanical damage, which is quite unavoidable in general building construction, could lead to a non negligible loss of strength and/or to a local deterioration of the formability.

In order to examine this behaviour notch (impact toughness) and notch bending (impact toughness) tests were used.

Due to the lack of test recommendations for concrete reinforcement steel rods, those valid for the prestressing steel rods were applicated.

The following notch values — independent from the diameter are specified :

— notch depth : 0.50 (1.00) mm (+0.04; −0.01)
— notch radius : 0.25 mm
— flank angle : 45°

Using these dimensions the following approximate form factors for tensile loading have been found according to [5] :

Rod diameter mm	α_k for t = 0.50 mm	α_k for t = 1.00 mm
8	3.0	3.3
16	3.2	3.6
28	3.5	4.2

In the tensile tests the strength values were calculated over the cross section of the non-notched rod. In the bend tests, D = 4 de was selected for diameters 28 mm and D = 3 de for 16 mm rod. The bending was carried out up to 180° of bending angle with the notch in the tensile zone.

An evaluation of the results cannot be carried out quantitatively due to the small number of the specimens; however, it is possible to make clear qualitative statements.

(*a*) Notches up to 1.0 mm depth do not adversely affect the bending behaviour of Tempcore steels of all diameters; the material has such a tough and ductile behaviour that the notch has in no case been torn up;

(*b*) Notches up to 0.5 mm deep do not behave as preferential initiation point for the point of mixture of the specimen in tensile tests; thus the strength values are not influenced;

(*c*) Notches of depth 1.0 mm in tensile tests will nearly always initiate fracture at these points; the tensile strength to be considered here decreases on average by 1.5 da N/mm²; the tensile strength values are above the corresponding yield point values by at least a factor of 1.17; this corresponds exactly to the average value of the ratio β_s/β_z of 0.85 found in the investigations of all melts. A sensitivity to mechanical damage of the hard outer layer does not exist up to the notch depth used in the tests.

(*d*) The average decrease of the fracture elongation is 3.5 % (absolute value); this is mainly explained by the lower elongation of the necked region, while the uniform elongation has remained unchanged.

4.12. — *Dimensions of the ribs.*

The application of the ribs, as demanded in DIN 488, sheet 2, for the ribbed concrete reinforcings of the type U, does not present any specific problems for the new production process. The Tempcore steel rods are to be considered in this respect as hot rolled steel rods. On the other hand, however, the influence of the rib geometry on the properties such as the fatigue strength and bending behaviour etc. is well known.

For this reason attention was paid in all investigations to use experimental materials which correspond to the demand of the DIN 488 for the steel BSt 42/50 RU.

5. — Summarising evaluation

In a very extensive investigation concrete reinforcings made by the Tempcore process were tested to ascertain its usefulness. The testing was not only carried out with respect to the usual properties and those, for example, established in DIN 488, part 1, Table 1, but also material characteristics, usually not investigated were included.

The following can be stated concerning concrete reinforcing rods, made by the Tempcore process :

— the process leads to reliably constant strength values,
— the formability is extraordinarily good in relation to the strength values,
— in spite of the existing harder external zones there is no decrease of the bending possibilities; even notch type damage in this zone does not cause any premature failure,
— the weldability for the flash butt welding process, manual metal arc welding and resistance

welding is ensured within the meaning of DIN 488, sheet 3, and DIN 4099, sheet 1,
— the requirements with respect to the fatigue strength of the reinforcing steel rods of the type III are obtained.
— the stress-strain curve is to be designated as bilinear within the meaning of DIN 1045, because the deviations from the ideal theoretical curve are negligibly small.
— the correction tests do not indicate that this steel is sensitive to stress corrosion cracking mechanism of the kind simulated in tests.
— the Tempcore steel is to be classified approximately midway between conventional qualities with respect to the strength behaviour after a heat treatment; it behaves more favourably than a cold formed steel; however, it does not quite reach the results of the hot rolled class,
— the scatter of the strength properties within a production lot are slightly higher than normally for this reason it is recommended to maintain a somewhat higher level of precautions in the inspection,
— with respect to the additionally examined properties no deterioration of the specified usefulness for concrete reinforcing rods occurred.

Summarising it can be stated that the ribbed concrete reinforcing rods made by the Tempcore process ensure properties demanded by DIN 488, sheet 1, for the type III and on the basis of further investigations no indication was found that the new production process adversely effects the properties in use; the weldability is ensured for the flash butt welding, manual metall arc welding and resistance cross welding process too.

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