Development and Production of Advanced Reinforcing Steel

D. Russwurm
Dr.-Ing. habil.

Introduction
Purpose and Development of Reinforcement
Delivery forms
Properties of Reinforcing Steel
Current Grades of Reinforcing Steel
Quality Control
Summary

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1. Introduction

Independently from climatic or geographical situation reinforced concrete is world-wide the mostly used construction method.

It consists of three elements

- concrete
- reinforcement
- scaffolds

This technology is really very old. The romaine used it first in famous constructions as the Pantheon in Rome and some other outstanding buildings as the “Thermes of Caracal and Hadrian”.

Even for simple applications as slabs covering sewage channels and water reserve containment reinforced concrete at that time called “Opus cementitiae” was used.

![Figure 1: Sewage Channel](image_url)
Simpler forms of reinforcement are the additions of cried hay to bricks made of day: A process, which is still used nowadays in underdeveloped countries.

The antique romaine technology got lost for more than 1500 years and became reinvented in the 19th century and perfected and constantly improved during the 20th century.

A large number of inventions were made among than the predominant ones are

- high performance cement and
- a specific reinforcing steel.

By that a technology was created which

- permits to establish all possible constructions above soil, in water in earth, with
  - highest safety and
  - extremely high economy.

The consequences in economic terms are an annual consumption of

- 1500 Million tons of cement
- 100 Million tons of reinforcement.

This means per year and capita

- 250 kg cement and
- 15 kg reinforcing steel

as I believe, very impressive figures.
The development of reinforced concrete is not at its end. The driving force in this case is economy. Particularly in those countries where large amount of investments have to be performed for infra-structure, as traffic, energy-production and housing for the citizens.

I hope, that my colleagues and me can show you which degree of perfection, reliability and economy the reinforced concrete technology has reached in European states which as you know are in a process of unification which is also tackling design codes and product standards.

2. Purpose and Development of Reinforcement

One of the reasons why reinforced concrete has reached its outstanding success is the perfection of the main products involved, steel and cement.

The predominant contribution of steel to the compound system “reinforced concrete” is the ability to sustain tensile forces.

Figure 3 shows in principle how reinforcement influences the behaviour of concrete: Without concrete at point ① a brittle rupture would occur and a collapse of the construction is inevitable.
At the very beginning of the modern technology of reinforced concrete the way of interaction between steel and concrete was not recognized in scientific terms.

Rather soon it was clear that the tension strength of the steel was of highest importance even taking into account that the concrete at that time was very poor.

In the years between 1905 and 1915 the first design codes appeared in Europe and the United States. The consequence was a better understanding of the function of steel.

This brought the experts to the conviction that a specifically designed steel for reinforcement was necessary.

At the very beginning of the technology simple rounds and squares are used. Some time later rails and profiles are used.
Figure 4: Historical Reinforcing Steel

Very ingenious people than designed reinforcing steel which seem to be a multipurpose element serving not only as tension element but also as shear-resisting part of the reinforcement.

Figure 5: Rebar with Stirrup (Kahn-Steel)

The begin of specific reinforcing steel was in the 30ties of the last century. Particularly US-American researches as Menzel have realized the beside the tensile strength also bond – that means the interaction between steel and concrete in terms of load transfer – plays an important role.

Mutual load transfer between steel and concrete theoretically can be obtained by different means as figure 6 shows.
The optimum under this aspect is a continuous load transfer over the whole length of the reinforcement.

Parallel to this progress in knowledge the steel technology advanced too. At the very beginning safety of steel was dramatically influenced by impurities, rolling defects, casting defects as segregation and all this ugly parameters which influence quality of steel products. Starting of in the middle of the last century steel technology permitted a reliable production of products.

For long time bars in as rolled condition were the mainly used elements. Hot rolling of simple Carbon-Manganese steel reached yield strength of 350 to 400 MPa. The Carbon content was about 0.35 %; Manganese depending on size of the final bar between 0.90 % up to 1.45 %.

You might imagine that in using ingot casting segregation of Manganese took place and locally Manganese-content raise up to values > 2.0 %.

The consequence was brittle steel caused by Martensite appearing during final cooling.
Parallel to the hot rolled bars cold deformed wires were used which logically got in this additional process higher yield strength.

The problem with cold deformed wires was that the wires remained plain and therefore bond was insufficient.

After world-war 2 it became more and more usual that all reinforcing steel got a surface with continuous extrusions which worked as a perfect load transfer mean which we call bond.

In the case of the bars for some years in Europe a combined process of hot rolling and twisting was the dominating process route. The so-called Rippentorstahl – translated as twisted-ribbed-steel – was initially produced in grade 360 and later in grade 400.

In some countries (but at very low extent) also as grade 500 MPa. The Rippentorstahl was partially weldable. This was a new aspect for reinforcing steel even if weldability was limited to butt to butt welding (with gas heating and electric resistance) and spot welding with covered electrodes for non-bearing cross welds.

The production of reinforcing steel must be cheap, because it is a mass product.

This is the reason why the expensive Rippentorstahl disappeared more and more being displaced by purely hot-rolled steel of the same grade, mainly 400 MPa. The grade differed slightly between the different states in a range of 380 to 460 MPa.

During the 70ties of the past century in Europe the idea of weldable steel for reinforcement appeared. The reason behind was also economically based because prefabrication of reinforcing cages became attractive. In order to get stiff and manoeuvrable cages at the points of intersection spot welds were more appropriate than ties.

At that time micro-alloyed reinforcing steel entered the stage and initiated a big step forward.
Companies as Halmstads Järnverk in Sweden and Lech-Stahlwerke in Germany promoted generally weldable reinforcing bars.

The metallurgical basis was micro-alloying with Nitrovan or Ferrovanadium due to the fact that the rebar plants mostly are mini-mills with EAF-technology based on scrap.

These activities joined by some scientific work were the starting point of a development towards generally weldable rebars which at least in Europe is currently the mainstream.

Some plants were testing micro-alloying with element like Niobium and Titan, but without success. Particularly Titan-alloyed steel presented no constant high quality so that all these companies stopped their activities.

Parallel to micro-alloying the existing large integrated steelworks based on iron or realized their disadvantages versus the scrap smelters. The reason for their disadvantages was the benefit of using scrap which contains some content of Manganese, Chromium and Nickel. This enabled the scrap smelters to reduce the amount of Manganese.

These companies invented a new technology – the heat treatment of rebars – known as “Tempcore” or “Thermex” process. Bars are quenched after the last stand superficially and than self-tempered by the heat of the core. In this case the plants are able to produce also weldable reinforcing steel: Tempcore has become meanwhile the leading process route for rebars in Europe.

The competition between both is still going on. The technical reasons which demand for this or the other process route I will explain later. In economical terms the following is important:

Pre-assumed a mill with 1 Million tons per year intends to switch over from normal hot rolled Carbon-Manganese steel to a weldable rebar the decision has to be made between
Page 10

- an investment of 3 to 4 Millions $ for Tempcore installations, heat control systems stronger scissors and a constant amount of water processing

or

- an immediately change without any additional investment using micro-alloying with Vanadium alloys.

I have to mention that in some cases a combination between both processes is optimal i.e. for large sizes of bars (> 40 mm) and products in coils.

The reasons why steel in general is the favourite reinforcement of concrete are listed up in figure 7 and figure 8.
1. Load transfer has to be performed from concrete to reinforcement and vice versa over a limited development length.

2. The reinforcement has to have a high modulus of elasticity in order to gain a high degree of stiffness for the construction as a whole.

3. The interaction between concrete and reinforcement must be in terms of chemical and physical phenomena free of disadvantages.

4. The reinforcement must have the appropriate delivery forms, shape and length which fit with the various constructions.

5. Spacious interfaces, e.g. sheets are less suitable in comparison with rod-formed elements which are offered in a great variety and a large range to match the calculated values of reinforcement section.

6. The reinforcement has also to match with the shape of the construction; it must be flexible and easily bendable.

7. The reinforcement must be capable to be joint, either by overlap or particular joining techniques as welding, forming mechanical connections.

**Figure 7: Reasons for Steel as Optimal Reinforcement for Concrete**

8. The reinforcement has to resist without significant deterioration of damage the rough conditions during transport, storage, bundling and placing on job site. Minor damages should not reduce significantly the performance characteristics.

9. The reinforcement of prestressed constructions (prestressing steel) has to assure that no sudden and brittle collapse due to corrosion attack takes place.

10. The reinforcement has to provide to the construction a sufficient fatigue resistance because concrete is not resistant to dynamic loading.

11. The reinforcement has to attribute to the construction a sufficiently high ductility behaviour.

12. The reinforcement has to resist shear forces as well as tension and compression forces.

13. The relaxation of prestressing elements has to be suitable low.

14. The reinforcement must offer its performance characteristics in a sufficient range of temperatures (-60 °C to +80 °C). In case of extreme low or high temperatures (fire) the behaviour of the reinforcement must be predictable.

15. The quality level of the reinforcement has to be usually such to be able to compensate minor imperfections in the execution of the construction.

**Figure 8: Reasons for Steel as Optimal Reinforcement for Concrete**

**Delivery Forms**

My short survey of the history of reinforcing steel covered mainly the rebars.
It is evident that bars are the mostly used product in this field. Nevertheless some other products are offered which also play an important role.

The first to mention are **wire fabrics**. This two-dimensional reinforcing element is produced in panels and consists of two rectangular crossing rows of wires electro resistance welded at each point of interaction. The constituent wires are cold worked, have normally a ribbed or inducted surface and are produced in grade 500 MPa.

This element is the predominant reinforcement for slabs up to a thickness of 40 cm, used as ceilings in all building for housing, offices, hospitals etc.

Another important delivery form is coils.

Coils are produced either in hot rolling of ribbed wires which are finally stretched or cold rolled. The big success of these coils is their benefit in producing continuously stirrups in automatic bending machines and of various lengths in straightening devices.

A less important but in few countries widely spread product are **lattice girders**. This is a three-dimensional element mainly used in slabs. It consists of an upper chord and one or two lower chords which are linked with diagonals which act as shear reinforcement.

The range of bars normally is extended between 6 to 40 mm. Coils are produced from 6 to 16 mm size; wire fabrics and lattice girders from 5 to 16 mm wire size.

For particular applications basis up to 65 mm are in use; fabrics up to 20 mm are hand-welded.

These four different delivery forms cover all possible applications of reinforcing steel in concrete, as

- tensile reinforcement
- compression reinforcement
• shear reinforcement
• reinforcement for crack with control
• minimum reinforcement

Properties of Reinforcing Steel

In the next chapter I want to show you in detail the requirements for the performance characteristics which form an advanced reinforcing steel.

The basic equation which describes safety in reinforced concrete reads

\[ S \cdot \gamma_F = \frac{R}{\gamma_R} \]

"R" represents the resistance of the product against stress "S".

In a semi-probabilistic safety philosophy R is the state or dynamic resistance, in other words either yield strength or fatigue resistance.

The equation makes clear that the higher the resistance R is the higher the loading of a construction can be. Another solution of the equations is: The higher the resistance is the smaller is the amount of the product to be used is because

\[ R = f_y \cdot A_s \]

with \( A_s \) as section of the applied product
Main Performance Characteristic

\[ \text{Yield Strength } f_y \]

\[ S \cdot \gamma_F = \frac{R}{\gamma_R} \]

\[ R = f_y \cdot A_s \]

Figure 9: Main Performance Characteristic

This is the main reason why in the past a strong tendency to higher yield stress was on the run.

But the yield strength can not be regarded isolated: A high yield has to be joined by a necessary high ductility and deformability in bending and rebending.

All that has to be accompanied by a sufficient bond which is given by extensions on the surface.

Taking all into account the properties of advanced reinforcing steel are given by the mutual interaction of different properties which endorses or weakens themselves mutually.

To make it clear figure 10 shows these dependences
Page 15

- the higher the yield strength
- the higher bond
- the higher yield
- the higher bond
- the higher yield

- the lower ductility and bendability
- the higher notch effects at the ribs which lower ductility and bendability as well as fatigue resistance
- the higher bond is necessary
- spalling effects occur in anchorages and joints
- the greater the deflections of the construction

Main Interactions of Properties

<table>
<thead>
<tr>
<th>High yield strength</th>
<th>low ductility and bendability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>greater deflections</td>
</tr>
<tr>
<td></td>
<td>better bond necessary</td>
</tr>
<tr>
<td>High bond</td>
<td>high notch effects at extrusions (ribs) lower ductility, bendability and fatigue</td>
</tr>
<tr>
<td></td>
<td>spalling effects (longitudinal cracks in concrete) at joints and anchorages</td>
</tr>
</tbody>
</table>

Figure 10  Main Interaction of Properties

The reinforcing steel is therefore the result of an optimization between all necessary performance characteristics.
In which way these performance characteristics interact with the design rules and the structural analysis my colleagues will show you.

Some things have to be clarified:

First of all the properties which define the ductility of a rebar:

In figure 11 the load-elongation line of a rebar is shown.

![Load Elongation Line of Rebars](image)

**Figure 11 Load Elongation Line of Rebars**

Ductility in the sense of the design codes is defined by two parameters

- the relation

\[
\frac{R_s}{R_e} \left( \frac{f_t}{f_y} \right)
\]

and

- the elongation \( \varepsilon_{su} \) at maximum load.
The first value describes the ability of steel to offer an increase of resistance beyond the yield point. The second parameter gives a value for the possible elongation before necking or constriction takes place.

In design both values are needed for moment redistribution and plastic design.

In any case for design these parameters are more appropriate than the elongation after rupture which has been used in the past.

Regarding ductility in general another term is of importance: bendability.

Nearly all rebars – predominantly small sizes – are being bent. Bending is a cold working process may cause strain aging effects. In many cases additional rebending of the prior bent bar in the bent area is necessary for various reasons. Also this very hard treatment modern reinforcing steel has to withstand. This process is very often used in continuity sets. A well experienced choice of metallurgy and rib pattern is necessary to avoid failures of bars.

Particularly in bridge constructions a good fatigue resistance of rebars is of highest importance.

Fatigue resistance is generally described by a so-called SN-line which gives the dependency of load cycles and stress. Figure 12 shows this coincidence. The SN-line has two branches with a point of intersection in between.
For the different design approaches either Palmgreen-Miner or the equivalent stress method the whole SN-line is necessary. That means that the knowledge of the SN-line is an essential part of an advanced rebar. For earthquake situations low cycle fatigue is of importance. How it is tested is shown in figure 13 and 14.
Figure 13: Specimen for low cycle tests
Weldability is another property of rebars. They usually should be weldable for various welding techniques as well as for various types of joints. Figure 15 shows which variety in this context is demanded by current design-codes.
Permitted welding methods and examples of application
(see EN ISO 17760)

<table>
<thead>
<tr>
<th>Loading case</th>
<th>Welding method</th>
<th>No.</th>
<th>Bars in tension</th>
<th>Bars in compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predominantly static</td>
<td>flash-welding</td>
<td>24</td>
<td>butt joint</td>
<td></td>
</tr>
<tr>
<td></td>
<td>manual metal arc welding</td>
<td>111</td>
<td>butt joint with • 20 mm, splice, lap, cruciform joints, joint with other steel members</td>
<td></td>
</tr>
<tr>
<td></td>
<td>metal arc welding with filling electrode</td>
<td>114</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>metal arc active welding</td>
<td>135</td>
<td>splice, lap, cruciform joints &amp; joint with other steel members</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>friction welding</td>
<td>42</td>
<td>butt joint with • 20 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>resistance spot welding (with one-point welding machine)</td>
<td>21</td>
<td>lap joint, joint with other steels</td>
<td></td>
</tr>
<tr>
<td>Not predominantly static</td>
<td>flash-welding</td>
<td>24</td>
<td>butt joint</td>
<td></td>
</tr>
<tr>
<td></td>
<td>manual metal arc welding</td>
<td>111</td>
<td></td>
<td>butt joint with • 14 mm</td>
</tr>
<tr>
<td></td>
<td>metal arc active welding</td>
<td>135</td>
<td></td>
<td>butt joint with • 14 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>136</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Only bars with the same or similar nominal diameter may be welded together.
2. Permitted ratio of mixed diameter bars • 0.57
3. For bearing joints • 16 mm
4. For bearing joints • 28 mm

Figure 15: Welding methods

Weldability of rebars is defined according to IIW and the so-called Carbon-equivalent. This value originally describes the hardening ability of steel.

Concerning rebars this value alone is not sufficient. Additionally to a value $C_{equ,max}$ limitations for some important elements are specified. I mention the complete definition which in Germany is demanded (mass %):
The current definition of weldability by the European rebar standard is shown in figure 16.

### Definition of Weldability

<table>
<thead>
<tr>
<th></th>
<th>Carbon (max)</th>
<th>Sulphur (max)</th>
<th>Phosphorus (max)</th>
<th>Nitrogen (max)</th>
<th>Carbon Equivalent Value (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast analysis</td>
<td>0.22</td>
<td>0.05</td>
<td>0.05</td>
<td>0.012</td>
<td>0.50</td>
</tr>
<tr>
<td>Product analysis</td>
<td>0.24</td>
<td>0.055</td>
<td>0.055</td>
<td>0.014</td>
<td>0.52</td>
</tr>
</tbody>
</table>

a Max 0.80% by mass Cu permitted
b It is permitted to exceed the maximum values for carbon by 0.03% by mass, provided that the carbon equivalent value is decreased by 0.02% by mass.
c Higher nitrogen contents are permissible if sufficient quantities of nitrogen binding elements are present.

Figure 16: Chemical composition and weldability

Another wide-spread technique to join rebars are mechanical couplers. The mainly used type is shown in figure 17.
I have shown you the most important properties of an excellent rebar. What I will show you now are in which way these characteristics can be obtained using micro-alloying with Vanadium.

Micro-alloying with Vanadium has two outstanding mechanisms

- Increase of yield by grain refining
- Increase of yield by precipitation hardening

Of importance is also that the structure is homogenous over the cross-section of the product.

The consequences are:

- in rebars yield strength up to 550 MPa can be obtained
- in case of fire accident the yield strength drops significantly at temperatures beyond 700 °C; cold worked products loose yield
already dramatically beyond 450 °C and heat treated bars of 580/600 °C.

- fine grain guarantees high ductility values:
  \[ \frac{R_m}{R_e} > 1.15 \] is usual on all sizes
  \[ \varepsilon_{su} > 8.0 \% \] is common

- fine grain guarantees extreme bendability even at low temperatures (0 > -20 °C)

- fine grain is softening notch effects at the bottom of the extrusions (ribs) whereby bendability and fatigue resistance is optimized

- no strain hardening takes place which is important for rebending

- due to the homogenous structure machining of threads is possible without loss of resistance: this is important for mechanical couplers which are more and more used in advanced design.

- homogenous structure avoids failure in welding because no loss of resistance takes place in heat affected zones.

- fine grain is a presumption for good impact resistance of rebars which is needed in earth quake design and in military applications.

Let's take a look to a chapter of reinforced concrete which is still unsolved: corrosion.

Everybody knows the impression of corrosion in concrete caused either by atmosphere corrosion or additionally induced by Chlorides. In the first case corrosion of steel is the consequence of imperfections in the concrete cover, either to small width or poor concrete or both. In the second case de-icing by salt is the reason used on bridges, in tunnels, parking houses etc.

None of the usually used steels have reduced susceptibility to corrosion attack. We all know that cold worked and heat treated rebars have an
accelerated corrosion rate in the air where only oxygen and humidity is present. Corrosion of steel is an electro-chemical process based on cells which form anode and cathode. In a usual structure the grain forms the cathode and the grain boundary the anode where dissolution takes place. If an inhomogeneous structure is present – decarboration and Perlit or Martensite and Bainit atmospheric corrosion is accelerated by additional voltage differences which form battery effects.

In case of micro-alloyed steel we find a homogenous structure with fine grains and we can show a some better corrosion resistance against atmospheric corrosion. With regard to Chloride-attack till now no difference is found. I can only recommend to the research in micro-alloyed steel to keep in mind this problem because it is an important one for concrete but also in other constructions.

In which war the requirements of the designers interact with the performance characteristics of rebars are shown in figure 18.
<table>
<thead>
<tr>
<th>Basis of Demands</th>
<th>Resulting Requirements of Reinforcing Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competitiveness of reinforced concrete</td>
<td>Yield as high as possible</td>
</tr>
<tr>
<td>Structural analysis:</td>
<td></td>
</tr>
<tr>
<td>linear elastic and moment redistribution</td>
<td>high yield</td>
</tr>
<tr>
<td>plastic methods</td>
<td>high yield and ductility</td>
</tr>
<tr>
<td>non linear</td>
<td>high yield and high ductility</td>
</tr>
<tr>
<td>earthquake design</td>
<td>sufficiently high yield in combination with</td>
</tr>
<tr>
<td></td>
<td>highest ductility requirements</td>
</tr>
<tr>
<td>fatigue</td>
<td>high yield and fatigue resistance</td>
</tr>
<tr>
<td>Serviceability limit state</td>
<td>Yield strength adjusted to crack control and</td>
</tr>
<tr>
<td></td>
<td>acceptable deformations</td>
</tr>
<tr>
<td>Sustainable constructions</td>
<td>Corrosions resistance</td>
</tr>
<tr>
<td>Handling of reinforcement</td>
<td>Bendability, Rebending, Weldability</td>
</tr>
</tbody>
</table>

Figure 18: Interaction with Properties

As a consequence rebars have to fit with all these demands. How perfect a micro-alloyed rebar matches these requirements is given in figure 19.
## Performance Characteristics

<table>
<thead>
<tr>
<th>Performance Characteristics</th>
<th>Favourable Reasons to Use Micro-Alloyed Reinforcing Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>Perfect way of increasing yield by precipitations and grain size</td>
</tr>
<tr>
<td>Ductility $R_{m}/R_{e}$ $A_{gt}$</td>
<td>$R_{m}/R_{e} \geq 1,15$ independent form size</td>
</tr>
<tr>
<td></td>
<td>Elongation at maximum load $\geq 10%$</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Reduction of notch-effect at rib-basis due to fine grain</td>
</tr>
<tr>
<td></td>
<td>improvement due to homogenous structure – no embedded martensite / ferrit</td>
</tr>
<tr>
<td>Weldability</td>
<td>Improved particularly at butt-welds due to homogenous resistance across the section</td>
</tr>
<tr>
<td>Safety</td>
<td>Coefficient of variation small due to smaller standard deviation: leads to higher safety</td>
</tr>
<tr>
<td>Bendability</td>
<td>Lower notch effects at ribs results in smaller mandrels for bending</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Amount of corrosion before concreting and later is small due to rather dense layer of mill scale on the surface</td>
</tr>
<tr>
<td>Behaviour in case of fire</td>
<td>Smaller decrease of yield depending of temperature</td>
</tr>
<tr>
<td></td>
<td>(significant $\geq 700$ °C; cold worked 400 °C; heat treated: 550 / 600 °C)</td>
</tr>
<tr>
<td>Machining and mechanical splices</td>
<td>Machining (lathe operating) possible; splices with threads do not reduce resistance</td>
</tr>
<tr>
<td>Mechanical defects on surface</td>
<td>No influence on resistance, notches are softened by fine grain size</td>
</tr>
</tbody>
</table>

Figure 19: Advantages of micro-alloyed Vanadium Steel
Current Reinforcing Steel

Being a German Engineer but plenty of European spirit I start with this survey with the European design code.

The yield strength covered by the design rules has a range between 400 and 600 MPa.

Concerning ductility one has established three classes, called low, normal and high.

<table>
<thead>
<tr>
<th>Type of steel</th>
<th>$R_m/R_e$ [-]</th>
<th>$A_{gt}$ [%]</th>
<th>Type of steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal ductile steel</td>
<td>1,05</td>
<td>2,5</td>
<td>cold worked</td>
</tr>
<tr>
<td>High ductile steel</td>
<td>1,08</td>
<td>5,0</td>
<td>hot rolled (heat treated, micro-alloyed)</td>
</tr>
<tr>
<td>Earth-quake steel</td>
<td>$1,15$</td>
<td>$8,0$</td>
<td>hot rolled (heat treated, micro-alloyed)</td>
</tr>
</tbody>
</table>

| $R_e,act/R_e,c < 1,3) |

Figure 20: Ductility classes

The low class has been chosen to the fact that wire fabrics and some rebars in coils are cold worked and are unable to meet the "normal" requirement. This is to be understood as a transition time. The "normal steel" covers all possible applications and the earthquake steel is particularly for those countries which suffer from seismic accidents.

This Euro-Code can be regarded as a master-issue for the European member states. Consequently the various states are challenged by that code to join this mainstream.

It is a pity to tell you that the relevant European standard for Reinforcing steel called EN 10080 does not follow this rules. The authorities in Brussels claimed that all existing rebars should all be covered by that standard. In consequence the standard would look like a shopping list of
round about 45 products or a liberal standard without clearly defined steel grades. The latter will take place. As chairman of this European Committee I regret this deeply.

But what will happen in Europe in future.

Due to the fact that EN 10080 will not contain classes (grades) of steel the various European states will establish for the future steel grades of their own. A survey is given in figure 21 an 22.

<table>
<thead>
<tr>
<th>Proposer</th>
<th>UK</th>
<th>P</th>
<th>E</th>
<th>TC19/SC1</th>
<th>UK</th>
<th>TC19/SC1</th>
<th>TC19/SC1</th>
<th>E</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel grade</td>
<td>B250R</td>
<td>B400X</td>
<td>B400E</td>
<td>B450C</td>
<td>B460A</td>
<td>B460B</td>
<td>B500A</td>
<td>B500B</td>
<td>B500D</td>
</tr>
<tr>
<td>Yield strength [MPa]</td>
<td>250</td>
<td>400</td>
<td>400</td>
<td>450</td>
<td>460</td>
<td>460</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Ratio $\frac{R_m}{R_e}$</td>
<td>1,15</td>
<td>1,08</td>
<td>$\geq 1,20 \leq 1,35$</td>
<td>$\geq 1,15 \leq 1,35$</td>
<td>1,05</td>
<td>1,08</td>
<td>1,05</td>
<td>1,08</td>
<td>$\geq 1,15 \leq 1,35$</td>
</tr>
<tr>
<td>Elongation at max. force [%]</td>
<td>5,0</td>
<td>5,0</td>
<td>9</td>
<td>7,5</td>
<td>2,5</td>
<td>5,0</td>
<td>2,5</td>
<td>5,0</td>
<td>8</td>
</tr>
<tr>
<td>CEV (cast) % by mass</td>
<td>$\leq 0,42$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
<td>$\leq 0,50$</td>
</tr>
</tbody>
</table>

Figure 21: Future European Steel Grades
You can recognize that all rebars are ribbed, with fatigue resistance and a given weldability.

Coming to different countries.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Yield Strength N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM 615</td>
<td>400</td>
</tr>
<tr>
<td>ASTM 706</td>
<td>550/420</td>
</tr>
<tr>
<td>BS 4449</td>
<td>460</td>
</tr>
<tr>
<td>DIN 488</td>
<td>500</td>
</tr>
<tr>
<td>Europe (general)</td>
<td>400 to 700</td>
</tr>
</tbody>
</table>

Weldable steel (generally in Europe) Fatigue resistant (generally in Europe)

Germany is revising its national standard on rebars - DIN 488.

Germany has a tradition with steel grade 500 MPa and will maintain it. The steel must be ribbed and weldable with appropriate fatigue resistance. The ductility requirements are as in the European design code.

In United Kingdom the relevant standard is BS 4449.
The main grade is a 460 MPa class, weldable, ribbed and with fatigue resistance.

Austria's mostly used rebar is a grade 550 MPa furnished with the usual performance characteristics.

Switching over to United States I have to state that this country is concerning reinforcement not so advanced as expected. The main grade is produces according to ASTM 615 in grade 60, that means a yield strength of 415 MPa. No fatigue resistance, no weldability is granted. In some of the states, where earthquakes are common (California) a slightly modified grade is used which also fits weldability requirements.

**Quality control**

The users expect from high performance rebars more or less a zero-defect production.

By that the low degree of probability of collapses can be obtained and additional – so called – hidden safety can be activated in case of extreme overloading.

The basis for all safety is a severe quality control system at the producer combined with an appropriate quality management system.

The question is: What can a micro-alloyed Vanadium rebar contribute to these demands?

The answer is quite simple:

- A very low standard deviation of all properties in the production unit

These small standard deviations of all properties have a twofold consequence:

- The release tests in the plants lead to a higher probability of refusing units with a high portion of defectives
The partial safety factor is smaller than that one which is used in design.

Let me try to explain these facts.

Before a production unit i.e. a heat leaves the plant it has to pass successfully the factory production control.

From each heat a certain number of test pieces have to be taken and the results must be assessed according statistic rules.

Regarding the most important property, the yield strength, we find in a heat a standard deviation – independently of the grade – in a range between 8 to 12 MPa. The figures for Tempcore-steel are 15 to 20 MPa.

Product units are accepted if the average value of the tests is higher than nominal value plus a given factor A and if all individual values of the test are higher than the nominal value plus a factor B. These acceptance criteria result in a so-called operation characteristic which is the more severe the smaller the standard deviation is.

By the way: A producer has benefits from that because he is able to lower the average value of the total production without running into a risk of quality and saving money by that.

**Attributive Values**

Sampling plan

\[ n = N, \quad c = M \]

**Variable Values**

Sampling plan based on average value

\[ \bar{x} \geq x_c + A \]

Sampling plan based on average value and minimum value

\[ x_1 \geq x_c + B \]

Figure 24 : Sampling plans
The second advantage results in an improvement of safety.

The partial safety factor of a product depends among other parameters decisively from the standard deviation. The equation reads for log-normal distributions is shown in figure 26.

\[ \gamma_s = \exp[(\alpha \cdot \beta - v) \cdot k] \]

- \( \alpha = 0.8 \)
- \( \beta = 3.8 \)
- \( k = \) quantile coefficient
- \( v = \) standard deviation / average value

Generally the value of \( s \) is orientated at the average values obtained in the different process routes. If i.e. in the case of yield strength the common value is 1.15 for micro-alloyed steel this value is reduced to 1.11.
What does that mean?

There are two possibilities:

1st A lower real safety factor increased safety of the construction and balances imperfections in the execution of a construction.

2nd If the authorities permit the application of a proved lower safety factor the result is a much better position in the competition with other producer which do not follow the process route of micro-alloying.

Summary and Outlook

I hope that I have shown you in a comprehensive way the development of a technology with reference to the reinforcement. I suppose that I made clear that micro-alloying leads in terms of quality to the most advanced high performance rebar which is currently available.

The reason for that statement is the metallurgy of this type of steel which is supreme to others:

- there are no problems to obtain high yield strength
- the accuracy of the production in terms of quality is extraordinary
- ductility values are outstanding
- the grain structure together with precipitation hardening softens notch effects given by the geometry of the ribs, which are necessary for bond and
- improve bendability and fatigue resistance
- in fire resistance micro-alloyed rebar is optimal as well as in low temperature behaviour
- concerning impact loading the structure offers optimal behaviour.
Concerning the economy there is a strong competition with heat-treated and self-tempered products. Depending on the question of price of micro-alloying there is an advantage for a producer which has no investments to spend and which has to produce alternatively simple grades and high quality products.

Decisions towards a technology must also be taken under the aspect of the future development in this field.

Regarding this issue we have to separate between the development of reinforcement and the concrete technology.

Concerning rebar I am convinced that the tendency towards high-yield steel is strong. The tendency to substitute all grades between 350 and 460 by grades between 500 and 550 MPa is evident.

Another strong tendency is ductility of rebar

\[ \frac{R_m}{R_e} \text{ values of 1.10 to 1.15 and} \]

\[ A_{gl} \text{ values } > 6.0 \% \]

will be usual in future. For seismic design the margin must be greater than 1.15 and \( \varepsilon_{su} \) higher than 8.0/9.0 %.

Of importance will also be which delivery forms will be available.

Bars in sizes between 6 to 40 mm will be usual; an extension to 60 mm can be expected in several cases. It is well known that with sizes above 40 mm the heat treating process route does not fit with.

Another chance where micro-alloying is inevitable is rebar in coils.

Heat treatment does not permit to produce these wires with the speed which is usual for wire rolling mills; the limit is round about 50 m/sec.

In consequence the coils currently are produced on the basis of a Carbon-Manganese steel (0.20 and 0.65) and after cooling the wires are stretched by round about 3 to 5 % to obtain sufficient yield strength.
I can imagine that using the micro-alloying process the additional expensive cold working can be avoided and coils can become cheaper.

A similar development is imaginable with wire fabrics. Currently they are produced by cold working of hot rolled wires (0.10 C / 0.40 Mn). The result of cold working is extremely low ductility values. Using the above mentioned micro-alloyed coils the effect will be a fabric of constituent wires of high ductility.

The same is valid for lattice girders.

So far my remarks on future product grades and process routes.

Concerning delivery forms bars as ribbed rounds are unbeatable. Eventually an optimization on rib pattern will occur: instead of extrusions intrusions may appear which improve fatigue resistance and soften notch effects in bending.

Wire fabric will be dominant in slab and wall reinforcement. In this case quite a lot new configurations are possible presupposed the grade of the wires is changed to good ductility. Panels might be – at least partly – substituted by rolls.

For the time being a high yield high performance rebar with adequate ductility bond, bendability and fatigue resistance is the summit of the development of rebars.

But we have not to regard this isolated.

The driving force in reinforced concrete is the developments in cement and concrete.

The claim to get also ductile concrete is obvious. Beside the improvement in cement and concrete technology steel or plastic fibres are already used. The addition of fibres – length 6 to 80 mm, thickness 0.6 to 1.0 mm in grade 700 MPa and more has become quite common, particularly in the outer layers of concrete. Research is done also on the substitution of traditions stirrups working as shear reinforcement by
fibres. Even the substitution of tensile reinforcement by fibres is in research stage. If these are some success I am convinced that it will happen only in simple applications. In large constructions – there is no doubt – traditional steel reinforcement will be used in future too.