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# The metallurgy of roller-bearing steels

Ever greater demands made by roller-bearing users have resulted in consistent further development and refinement in all stages of production, from the starting material up to and including the finished product. Roller-bearing rings and balls are nowadays produced at rational cost and with an excellent quality using new and highly efficient processes. A decisive precondition for these advances was the development at Hüttenwerke Krupp Mannesmann GmbH (HKM) of an Al-free process route, which permits production of roller-bearing steel with ultra-high oxide cleanness. The fruit of all these efforts is a roller bearing which possesses a significantly longer service life than competing products.

Roller-bearing users, and the aerospace and automotive industries in particular, expect ever increasing service-lives from the bearings they use, and demand corresponding guarantees from the manufacturers. The requirements made on the quality of the steels increase correspondingly. In addition to good hardenability and adequate chip-removing machinability, the most important quality characteristic of a roller-bearing steel is its resistance to fatigue under exposure to rolling loads. Not only the steel's structure properties and homogeneity are decisive for this, but also various metallurgical influencing factors, such as non-metallic inclusion content and the chemical composition, geometry, size and distribution of any inclusions present. Non-metallic inclusions are frequently the starting point for fatigue fractures.

Recent decades have witnessed continuous improvement in the cleanness achieved in steel production around the world, with various paths having led to this target. The microscopic cleanness of well-known steelmakers' products has now reached a high level. Macroscopic cleanness, on the other hand, remains a challenge, since complete production certainty appears not to be achievable except in the case of remelted materials, and detection presents a statistical problem [1...5]. In view of the demanding standards set for its service and working properties, roller-bearing steel is, with certainty, one of the most – and best – researched of all the families of grades of steel. A large range of publications in which steel properties and their adjustment are discussed exists. It is no exaggeration to state that roller-bearing steel has itself decisively co-influenced the development of metallurgical processes for the production of other homogeneous ultra-clean steels. This steel is, therefore, particularly suitable for the examination and discussion of the large and diverse range of metallurgical control methods. Other steel grades used in heavily loaded components have also benefited decisively from these developments.

**The history of roller-bearing steel.** The first references to a *roller-bearing steel* originate from Professor Richard Stribeck who, in 1901, was the first to formulate the requirements for a material for roller-bearings [7]. He considered

| steel grade | chemical analyses of common bearing steels % C | % Si | % Mn | % P max | % S max | % Cr | % Mo | % Ni | % V | % W | Cu max |
|---|---|---|---|---|---|---|---|---|---|---|---|
| full hardening steels | | | | | | | | | | | |
| 100 Cr 2 | 0,90-1,05 | 0,15-0,35 | 0,25-0,45 | 0,030 | 0,025 | 0,40-0,60 | - | max. 0,30 | - | - | 0,30 |
| 100 Cr 6 | 0,90-1,05 | 0,15-0,35 | 0,25-0,45 | 0,030 | 0,025 | 1,35-1,65 | - | max. 0,30 | - | - | 0,30 |
| 100 CrMn 6 | 0,90-1,05 | 0,50-0,70 | 1,00-1,20 | 0,030 | 0,025 | 1,40-1,65 | - | max. 0,30 | - | - | 0,30 |
| 100 CrMo 7 | 0,90-1,05 | 0,20-0,40 | 0,25-0,45 | 0,030 | 0,025 | 1,65-1,95 | 0,15-0,25 | max. 0,30 | - | - | 0,30 |
| 100 CrMo 7 3 | 0,90-1,05 | 0,20-0,40 | 0,60-0,80 | 0,030 | 0,025 | 1,65-1,95 | 0,20-0,35 | max. 0,30 | - | - | 0,30 |
| 100 CrMnMo 8 | 0,90-1,05 | 0,40-0,60 | 0,80-1,10 | 0,030 | 0,025 | 1,80-2,05 | 0,50-0,60 | max. 0,30 | - | - | 0,30 |
| case hardening steel | | | | | | | | | | | |
| 17 MnCr 5 | 0,14-0,19 | max. 0,40 | 1,00-1,30 | 0,035 | 0,035 | 0,80-1,10 | - | - | - | - | 0,30 |
| 19 MnCr 5 | 0,17-0,22 | max. 0,40 | 1,10-1,40 | 0,035 | 0,035 | 1,00-1,30 | - | - | - | - | 0,30 |
| 16 CrNiMo 6 | 0,15-0,20 | max. 0,40 | 0,40-0,60 | 0,035 | 0,035 | 1,50-1,80 | 0,25-0,35 | 1,40-1,70 | - | - | 0,30 |
| 17 NiCrMo 14 | 0,15-0,20 | max. 0,40 | 0,40-0,70 | 0,035 | 0,035 | 1,30-1,60 | 0,15-0,25 | 3,25-3,75 | - | - | 0,30 |
| heat treatable steel | | | | | | | | | | | |
| Cf 54 | 0,50-0,57 | max. 0,40 | 0,40-0,70 | 0,025 | 0,035 | - | - | - | - | - | 0,30 |
| 44 Cr 2 | 0,42-0,48 | max. 0,40 | 0,50-0,80 | 0,025 | 0,035 | 0,40-0,60 | - | - | - | - | 0,30 |
| 43 CrMo 4 | 0,40-0,46 | max. 0,40 | 0,60-0,90 | 0,025 | 0,035 | 0,90-1,20 | 0,15-0,30 | - | - | - | 0,30 |
| 48 CrMo 4 | 0,46-0,52 | max. 0,40 | 0,50-0,80 | 0,025 | 0,035 | 0,90-1,20 | 0,15-0,30 | - | - | - | 0,30 |
| stainless steel | | | | | | | | | | | |
| X 45 Cr 13 | 0,42-0,50 | max. 1,00 | max. 1,00 | 0,040 | 0,030 | 12,5-14,5 | - | max. 1,00 | - | - | 0,30 |
| X 102 CrMo 17 | 0,95-1,10 | max. 1,00 | max. 1,00 | 0,040 | 0,030 | 16,0-18,0 | 0,35-0,75 | max. 0,50 | - | - | 0,30 |
| X 89 CrMoV 181 | 0,85-0,95 | max. 1,00 | max. 1,00 | 0,045 | 0,030 | 17,0-19,0 | 0,90-1,30 | - | 0,07-0,12 | - | 0,30 |
| steel with a high degree of hardness at elevated temperatures | | | | | | | | | | | |
| 80 MoCrV 4216 | 0,77-0,85 | max. 0,25 | max. 0,35 | 0,015 | 0,015 | 3,75-4,25 | 4,00-4,50 | - | 0,90-1,10 | - | - |
| X 82 WMoCrV 654 | 0,78-0,86 | max. 0,40 | max. 0,40 | 0,030 | 0,030 | 3,80-4,50 | 4,70-5,20 | - | 1,70-2,00 | 6,00-6,70 | - |
| X 75 WCrV 1841 | 0,70-0,78 | max. 0,45 | max. 0,40 | 0,030 | 0,030 | 3,80-4,50 | max. 0,60 | - | 1,00-1,20 | 17,5-18,5 | - |

**Table 1:** Chemical composition of widely used roller-bearing steels

necessary for this application a steel containing 0.8 to 1.0 % carbon, which must, in addition, be free of harmful extraneous constituents. The use of alloyed steel had also been successfully tried. Stribeck pointed out the need for good hardenability of the balls as an important property, a process which must be accomplished without generating stresses. In addition, the balls would be required to be extremely homogeneous and possess adequate toughness. The 100Cr6 with approx. 1 % carbon and 1.5 % chromium now used worldwide was adopted for the first time by Fichtel & Sachs, of Schweinfurt, in 1905, and became established on a commercial scale for the production of roller-bearings within a few years. When, in the mid-1930s, the hardenability of 100Cr6 no longer sufficed, due to the development of ever larger bearing dimensions, the manganese variant, 100CrMn6, was developed in Sweden and Germany, specifically to achieve improved hardenability. After the Second World War, series of steels with molybdenum contents ranging from 0.15 to 0.55 % were developed, again to achieve even better hardenability, and to permit the production of large rolled or forged rings. Increasing cost pressure in the roller-bearing industry resulted from the 1970s onward in a rationalization of the range of grades used. Attempts to reduce the chromium content of these steels have even now not been accepted in the bearing-using industries. A diminution of impurities contents in 100Cr6 had been under discussion since the 1990s. The target of more stringent specifications is the achievement of improved roller-bearing operating performance, at elevated operating temperatures or under contaminated lubrication conditions. **Table 1** provides an overview of the commonly used roller-bearing steels.

Recent developments coming increasingly into use in the production of roller-bearing steels include:

- ♦ production of bearing rings directly from continuous-cast material and near-net-shape cast hot-tubular components, followed by turning;
- ♦ aluminium-free melting of roller-bearing steels.

The development of these technologies is examined below.

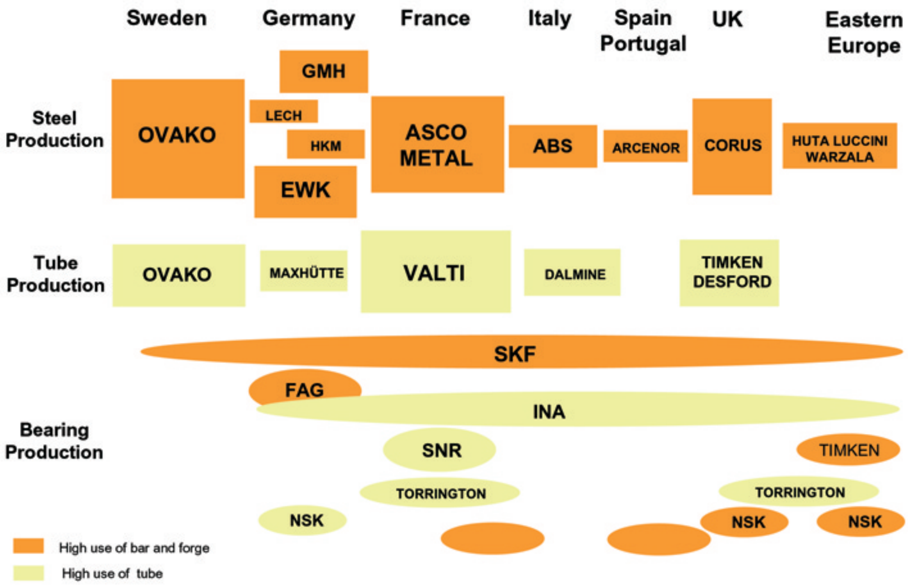


**Fig. 1:** Market coverage with 100Cr6 in Europe [25]

## Market volume and market shares

Annual world production of 100Cr6 roller-bearing steel is currently around 3.0 million t. Roller-bearing steel thus makes up only a small percentage of the world's total steel production of some 900 million t. It can, nonetheless, justifiably be regarded as a "tonnage" steel, since other special structural steels are produced in much smaller quantities. The large roller-bearing steel producers can be found in North America (Timken and Republic), and Japan (Daido, Sumitomo and Sanyo). In Europe, practically every steelmaker is attempting to produce this grade, alongside the specialist producers Ovako Steel and Asco Metal, leading to a heavily disputed market, **fig. 1.**

The situation in the production of pipes is similar. Ovako, Maxhütte, Valti and Dalmine are European suppliers who compete globally with the Japanese (Sanyo and Sumitomo) and the North Americans (Timken). Also worthy of mention is the production of 100Cr6 by Vallourec & Mannesmann do Brazil, who are unique in South America in possessing their

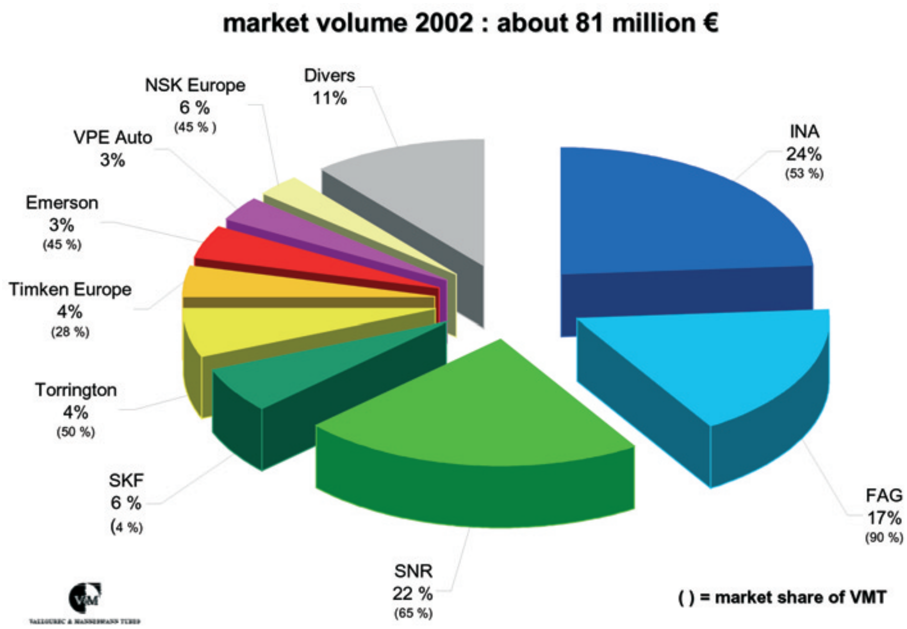


**Fig. 2:** Market shares for 100Cr6 in Europe [25]

own pipe-making mill. Even more fragmented is the market breakdown in the roller-bearing industry itself. A study completed in 2002 indicates that pipe-manufacturer Valti, with a 50 % market share in Europe, supplies its material to ten internationally active roller bearing producers, **fig. 2.**

## The processing of roller-bearing steel

**The production of roller-bearing balls.** After primary solidification, the raw strand is diffusion annealed and cogged with an extremely large per-pass reduction rate during rolling. The blanks generated in this production stage are billets with a square cross-section of the most diverse dimensions. The objective of diffusion annealing and cogging is that of achieving the greatest possible deformation of the material in order, on the one hand, to reduce the centre porosity inevitably associated with the continuous casting process and, on the other hand, to break down the extremely brittle primary carbides formed during primary solidification. A compact billet with a low primary carbides content and small primary carbide size can be assumed as the result of this operation. These billets are rolled and/or drawn to wires of varying diameters on rolling lines. Wire production involves a further very great deformation of the material in a large number of individual passes. Any primary carbides present

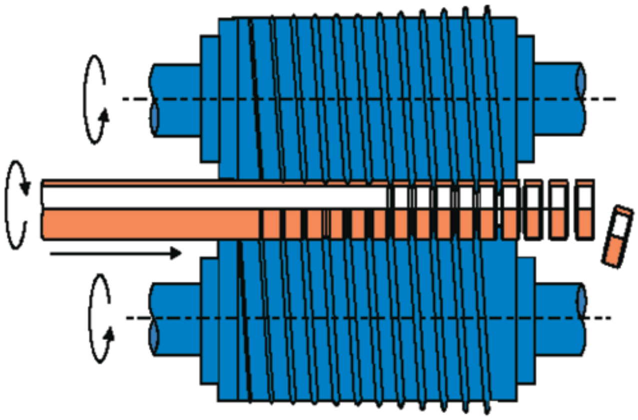

**Fig. 3:** Production of ring blanks using the Trenpro process [6]

are further mechanically disintegrated. The rolled wire is then GKZ (spheroidizing) annealed. This annealing process is intended to achieve further homogenization of the material and the formation of uniform spherical carbides. The bone-shaped carbides produced from the primary carbides cannot, on the other hand, be broken down. The rolled wire is supplied in annealed condition for ball production.

Lengths of approx. 220 mm are cut fully automatically from the rolled wire and cold pressed to ball-making blanks. The ends of the wire produce on the surface of the balls characteristic faces, which are referred to as poles (90°). A ring, which corresponds to the separation plane of the matrix halves, remains in the middle of the ball blank during the cold-pressing process. This projecting ring is removed in a downstream grinding process in a ball mill. Fibers thus also leave the ball in this sector. This zone is referred to below as the Equator (0°). Hardening of the balls is performed by means of austenitization (840 °C), quenching in oil (60 °C) and subsequent tempering (180 °C). Cold hardening of the surfaces is achieved by means of drum tumbling. The balls are ultrasonically inspected before use, in order to eliminate any cracks possibly present under the surface before the balls enter practical service.

**Production of roller-bearing rings.** The starting material for the roller bearing ring takes the form of a seamless tube, **fig. 3.** Seamless 100Cr6 tubes produced by means of conventional hot rolling are normally soft (GKZ) annealed, in order to assure, on the one hand, trouble-free machining and, on the other hand, to generate an initial structure advantageous for subsequent hardening of the soft rings. The development of thermomechanical rolling now makes it possible to omit soft annealing of the tubes, since they already possess, on the cooling bed, a structure with finely distributed spherically shaped cementite particles [6].

The introduction of this technology was the precondition for further processing of the tubes to ring blanks using the Trenpro process. This operation is a highly efficient cutting and section-rolling process (up to 1000 rings per minute). It can, in terms of temperature level, be classified as a semi-hot forming process. The cutting and rolling tools of identical geometry located in a rolling stand parallel to the axis of the tube set the tube to be machined in a co-rotating synchronous rotating motion. The cutting tools take the form of helical cutters contacting on the external shell surfaces, which continuously gain in cutting height from the infeed side. The tube is conveyed through the cutting/rolling stand in the axial direction as a result of the continuous rotating motion and is cut into individual rings in the process. The tubes are fed automatically in a push-push motion synchronously to the cutting process, by means of MF induction furnaces, and continuously processed. Particular importance attaches in this process to careful temperature control since, on the one hand, the structure properties previously generated during TM rolling may not be impaired but, on the other hand, the service lives of the cutting tools must be kept as high as possible. Appropriate tool design makes it possible to impart certain sectional geometries (e.g. ball races) on the outer diameter of the rings simultaneously to the cutting process, see fig. 3.

Chip-removing machining is necessary after cutting and profiling of the rings, in order to remove from the ring blanks the internal burring typical of mechanical cutting. CNC-controlled automatic multi-station rotary machining centres, functioning with a stationary workpiece and rotating cutting tools, are used for this purpose. The high level of automation permits machining times of less than 4 s for a 47 mm ring. Particular importance attaches during machining to process certainty and product quality. These are assured by means of integrated tool breakage monitoring and in-process measuring systems. Adherence to all important drawing data is verified and the geometrical accuracy of the finished rings 100 % checked by these systems.

## The production of roller-bearing steel

The property requirements for roller-bearing steel are extremely high in every respect. As a consequence of the global competition situation, the industries which use this steel are also, conversely, subject to enormous pressure to rationalize production processes. It is, therefore, readily apparent that the economic benefits of mass production of steel ultimately also become established in the production of roller bearing steel. The following discussion of the metallurgical process route for the production of 100Cr6 at Hüttenwerke Krupp Mannesmann GmbH is intended to illustrate that the production of highly sensitive grades is also possible in large, non-specialized steelplants, and to examine the special provisions associated with such production. With its two LD converters, the Duisburg-Huckingen steelplant nowadays produces some 5.6 million t of crude steel. Production is 80 % slabs, which are cast on three casters. Two casters, with a total of eleven strands, are available for the production of some 1.2 million t of round continuously cast products with dimensions of between 180 mm and 406 mm. Production of roller bearing steel at HKM in the 2003 trading year was approx. 30000 t/a, i.e., 0.5 % of total production, or 2.5 % of round product output. Although production of this grade is therefore not part of HKM's core business, the company's presence in this market segment, with all its implications, is regarded as a continuous provision for the further development and refinement of quality standards for all other grades. Only the production of ULC/IF steels possesses no comparability with the demands made on roller bearing steel in HKM's quality program.

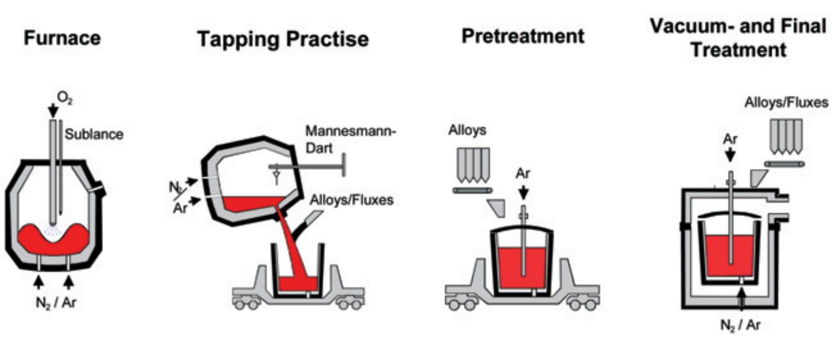


**Fig. 4:** The roller-bearing steel production route at Hüttenwerke Krupp Mannesmann

**Melting and secondary metallurgy.** The state-of-the-art for the production of low-alloy continuous casting stainless steel grades is similar at all German and European steelplants. The crude steel is melted in the primary metallurgy stage via either the BOF or the electrical steelmaking route. Secondary metallurgy comprises the working operations of deoxidation, stirring using an inert gas, treatment in the ladle furnace and subsequent vacuum tank or recirculating vacuum degassing of the liquid crude steel. Cleanness bubbling after treatment of the liquid steel is *de rigueur* on the basis of present-day knowledge. Deoxidation practices can be differentiated into processes using metallic aluminium and aluminium-free processes, depending on individual producer [8...20]. After comprehensive testing, Hüttenwerke Krupp Mannesmann has decided in favour of the Al-free production route, which permits the attainment of a significantly superior oxide cleanness. **Fig. 4** shows an overview of the metallurgical production route in the liquid phase.

Consistent adherence to an Al-free production route necessitates special efforts at minimizing importation of Al. The first step is the selection and careful preparation of the steel pouring ladles in the production sequence. Repeatable slag carry-over at tapping of the primary metallurgical plant must be assured, in order to achieve an optimum treatment sequence. A combination consisting of the Mannesmann slag stopper and automatic termination of tapping by means of an infrared camera system has proven very effective at HKM. Careful selection and analysis of alloying elements, particularly in terms of their Al and Ti contaminant contents, is also of special importance. Both the formation of $Al_2O_3$ and of titanium carbon nitrides are undesirable, due to their detrimental effects on bearing service life. The slagging agents and a large portion of the alloying elements are added directly to the tapping stream at tapping, in order to achieve good homogenization. $SiO_2$ and carbon monoxide are generated as deoxidation products at this point. After homogenizing bubbling of the heat using an argon lance, a low-viscosity, lime-silicatic top slag, which possesses an extremely good absorption capacity for the $SiO_2$, will have formed. Ultra-fine deoxidation products nonetheless remain in the heat after preliminary bubbling. HKM applies a vacuum treatment to remove these. Under ultra-low vacuum in the vacuum-tank degassing installation, the deoxidation potential of the carbon present is sufficient to reduce the fine $SiO_2$ particles with certainty, **fig. 5.**

The result is a significant reduction in the quantity of extremely finely dispersed deoxidation products and, therefore, an extremely good microcleanness. Such removal of ultra-

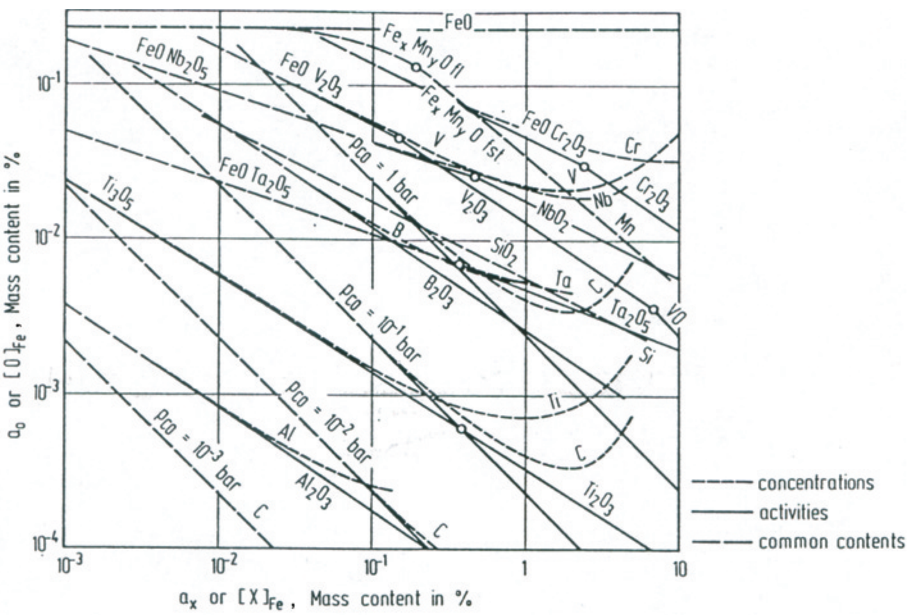


**Fig. 5:** Deoxidation potential of carbon at reduced ambient pressure [26]

fine deoxidation products is not possible in principle if Al-deoxidation is used, due to aluminium's greater affinity for oxygen.

Fine alloying and vacuum treatment is followed by cleanness bubbling. The feeding of low flows of gas through bottom bubblers is intended to remove ultra-fine remnants of emulsified top slag, in a process similar to flotation.

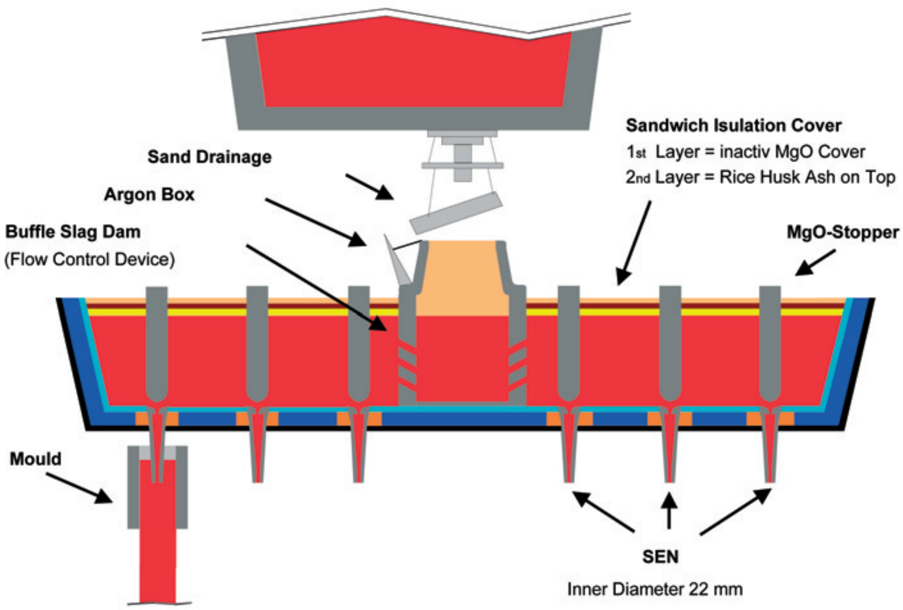


**Fig. 6:** Schematic view of Hüttenwerke Krupp Mannesmann's roller-bearing steel casting process

The ladle surface is covered with insulating fluxes, in order to avoid excessive temperature losses.

All suppliers currently known dispense with calcium treatment of the liquid steel to improve castability in the continuous casting process, although this treatment is successfully applied for a large range of other grades.

**Casting.** After ladle treatment, the teeming ladle is positioned in the turret of the continuous caster. The steel is fed into the tundish via a ceramic shielding tube into a casting box which is continuously flooded with argon, **fig. 6.**

The flow of steel from the ladle is regulated by means of a hydraulic slide gate system. In the tundish itself, the steel's direction of flow is manipulated by means of various internal elements in such a way that short-circuit currents towards the tundish outlets can be prevented with certainty. Special internals are used to generate directional flows towards the bath surface, which assure the removal of any non-metallic constituents still entrained in the steel, **fig. 7.**

Continuous-caster tundishes nowadays feature multiple sealing and insulating layers consisting of fast-melting slags and insulating casting fluxes for the purpose of absorption of the separated slag particles, thermal insulation of the bath of metal and avoidance of reoxidation effects. The level of steel in the tundish is controlled using the ladle slide-gate; only narrow fluctuations in level (approx. ± 50 mm) are permissible.

From the tundish, the liquid metal passes via submerged entry nozzles into the moulds. The surface of the pool of steel is sealed airtight with casting powder slag. The casting powder has not only a covering and sealing function, but also a lubricating action between the interior faces of the mould and the shell of the strand. The moulds oscillate in a sinusoidal vertical motion, in order to ensure a uniform withdrawal movement. Below the moulds, the strands are guided through a circular arc. The thickness of the strand shell increases during passage through this arc, from around 20 mm at the outlet from the mould up to the point of complete solidification. Removal of heat via the surface of the strand is accelerated by means of a spray-water cooling system. After straightening of the strands into the horizontal and complete solidification, the strands are cut to order lengths, conveyed away, systematically cooled, inspected and marked. Following extensive sampling and testing, the shippable strand sections are loaded onto rail trucks and transported to the hot-rolling mills.

## Quality requirements

Roller-bearing manufacturers orientate their demands on steelmakers around the most frequent material related source of roller-bearing failures. Every component exhibits in the vicinity of material inhomogeneities a heterogeneous stress pattern which manifests locally higher stresses than the ho-

**Fig. 7:** Tundish for roller-bearing steel at Hüttenwerke Krupp Mannesmann

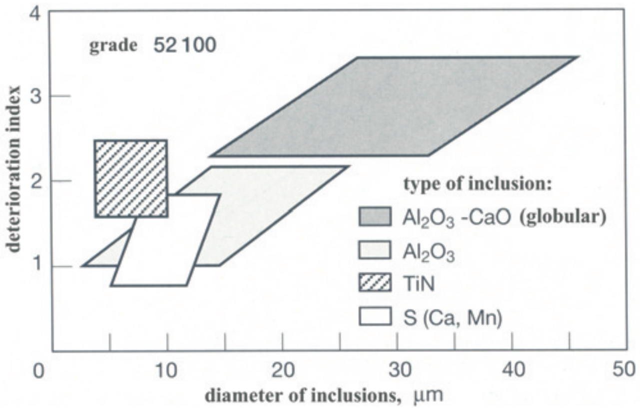


**Fig. 8:** Harmfulness of various inclusion types [24]

mogeneous material. High alternating load cycles, in particular, can cause fatigue cracking at these points, which can then result in premature failure of the component. Every non-metallic inclusion constitutes a material inhomogeneity

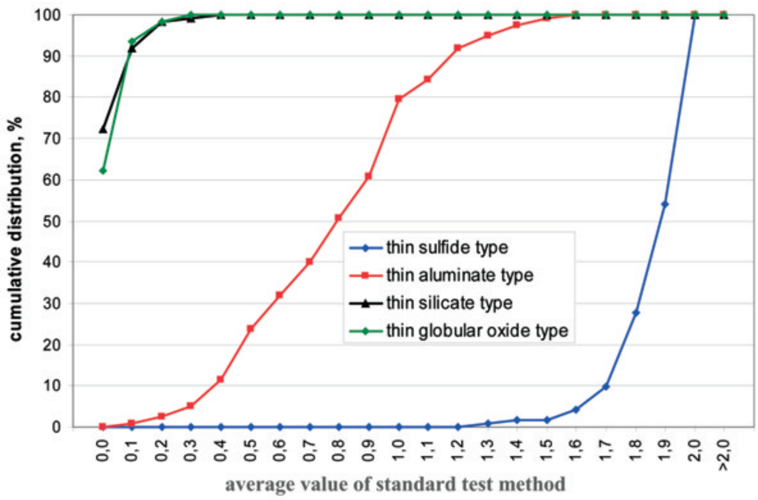


**Fig. 9a:** Average value of standard test method *thin inclusions* per ASTM E45 (A)

and increases the probability of fatigue cracking. The harmfulness of an inclusion is determined by its size and, decisively, by its morphology and deformability, **fig. 8.**

These, then, are the sources of the roller-bearing manufacturers' demands for the fewest possible, smallest possible, and most ductile possible inclusions.

## Quality achieved

It is necessary to differentiate between microscopic and macroscopic cleanness, since the size of non-metallic inclusions has a great influence on the quality achieved. On the basis of the standard (DIN 50602) currently applicable, all inclusions with a surface area of less than 0.03 mm$^2$ in a polished microsection are classified as microscopic inclusions.

As may be anticipated from the description of the company's melting metallurgy, the roller-bearing steel produced at Hüttenwerke Krupp Mannesmann achieves outstanding microscopic cleanness, **figs. 9a, b.**

Macroscopic cleanness at HKM has also been greatly improved in recent years, thanks to a large range of process-engineering innovations. The influence of the submerged entry nozzle used at HKM, with an internal diameter of 22 mm, is shown by way of example in **fig. 10.** The roller-bearing steel produced nowadays is of a level of quality that makes detection of a macroscopic inclusion a statistical problem. Positioning of microsection specimens in the steel would make it necessary to anticipate the finding of a macroscopic inclusion only as from a microsection surface area of an order of magnitude of 100 m$^2$. Isolated occurrences, which can be assigned to process-engineering changes only given an extremely high sampling density, must be assumed. Physical methods for volume inspection are, therefore, nowadays used for determination of macrocleanness. These methods include, for example, the Midas process developed at Mannesmann, and ultrasonic immersion methods, both of which are capable of detecting macroinclusions after deformation of the material. **Figs. 11** and **12** show inspection results for current 100Cr6 production from 2002 up to the present day.

The high level of quality of bearings produced in this way is also reflected in the significantly higher roller-bearing service lives achieved compared to competing products, **fig. 13.**

## Prospects

Although the cleanness of 100Cr6 production at Hüttenwerke Krupp Mannesmann has already reached a level which makes the detection of larger non-metallic inclusions difficult, extensive investigations have nonetheless been performed in order to achieve further improvements. Ultrasonic inspection methods have been used to locate inclusions, which were then exposed by means of pol-

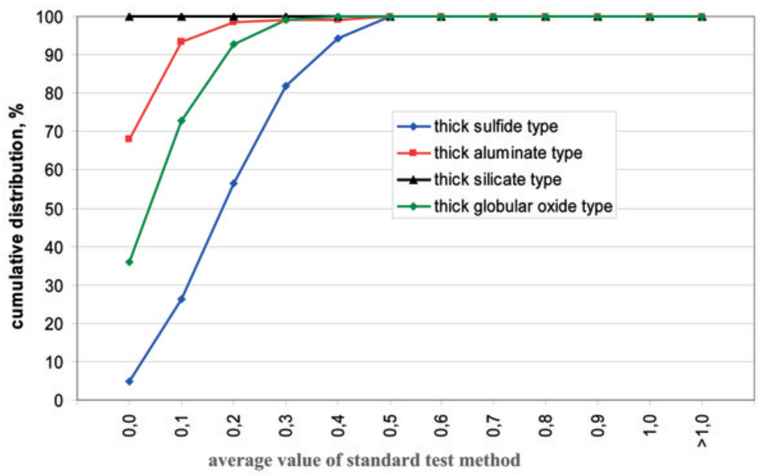


**Fig. 9b:** Average value of standard test method *thick inclusions* per ASTM E45 (A)

ished microsections. Inclusions from a statistically evaluable number of samples were analyzed in this way using the electron beam microprobe. These analyses permit deductions concerning the origin of the non-metallic inclusion. The results of current work are to be published in the near future.

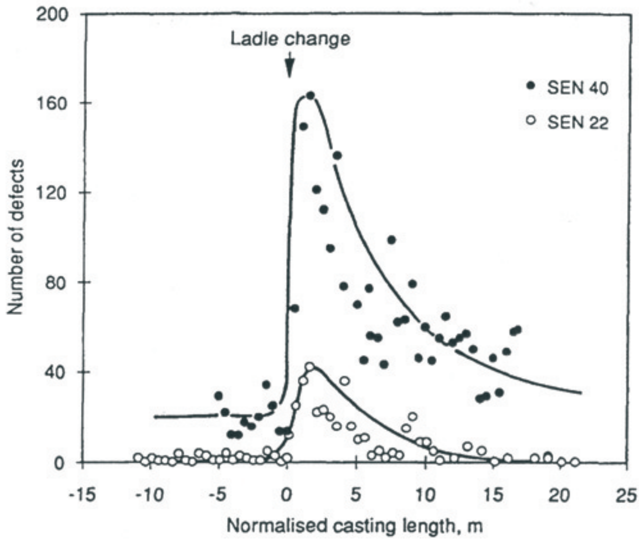


**Fig. 10:** Influence of submerged entry nozzle diameter

## Summary

Ever greater demands made by roller-bearing users on the price and service-life of roller-bearings have in recent decades resulted in innovative developments in production technology and metallurgy. Consistent further development, from the starting material up to the finished product, has now made it possible to produce roller-bearing rings and balls of excellent quality at a rational price using new and highly efficient processes. The decisive precondition for these advances is extremely good cleanness in the roller-bearing steel. An Al-free production route which permits production of roller-bearing steel with ultra-high oxide cleanness has been developed at Hüttenwerke Krupp Mannesmann GmbH. The result of these joint efforts is a roller-bearing with a service-life significantly higher than that of competing products.

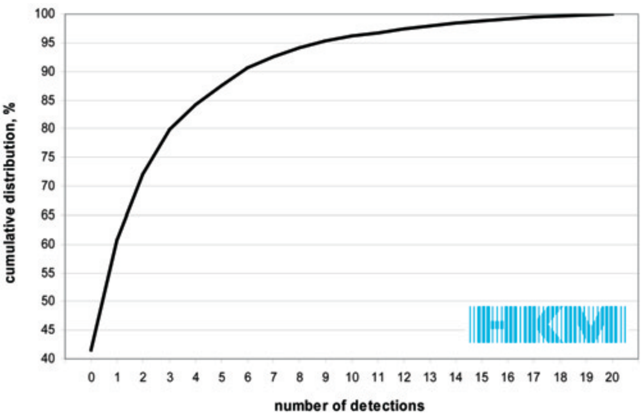


**Fig. 11:** Midas inspection results

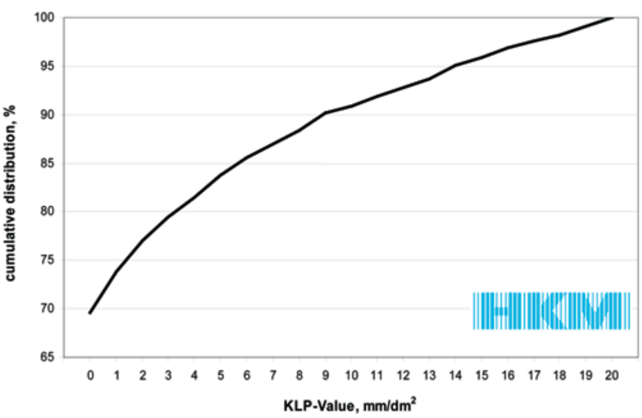


**Fig. 12:** Ultrasonic pipe inspection results

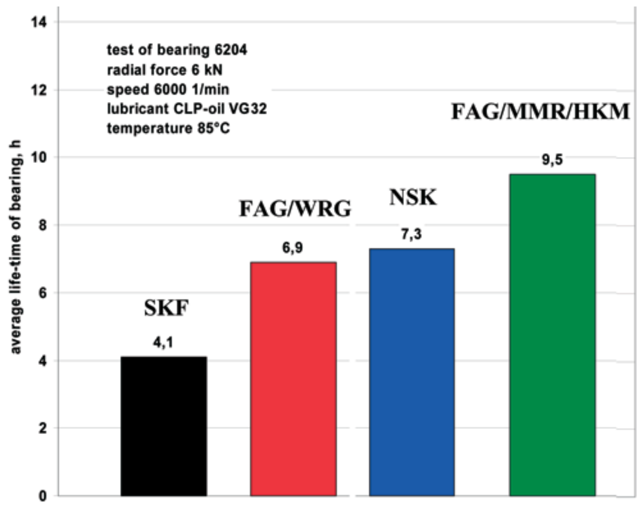


**Fig. 13:** Results of roller bearing inspections [6]

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