# CUTTER RINGS WITH NON-UNIFORM NIOBIUM CARBIDE DISTRIBUTION FOR TUNNEL BORING

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## Abstract

Cutter rings made by centrifugal casting out of niobium alloyed steel were developed to be used in tunnel boring machines. The new material has great potential to replace conventional forged tool steel rings for cutting hard rock. Due to applying high centrifugal acceleration forces during the casting process, primary precipitated carbides with MC-structure are concentrated in the most wear affected zone of the cutter ring, thus leading to higher wear resistance of such rings. The carbide distribution across the cutter ring profile can be adjusted by production process parameters and the chemical composition of the melt.

## Introduction

Tunnel boring machines (TBMs) have been used commercially to excavate the full face of tunnels simultaneously for over 100 years. To improve the performance in cutting hard rock, TBMs equipped with disc cutters were developed in the 1950s, and are still predominant for hard rock excavation [1]. These days, the working parts of disc cutters are high wear resistant cutter rings, mostly made of forged hot working tool steel, of up to 20 inches in diameter.

Replacing worn cutter rings is time consuming and so catastrophic failures of such cutters, under loads of up to 300 kN per ring, can lead to huge downtime costs [2]. Therefore, the tunnel boring industry is looking for new cutter rings, with higher wear resistance leading to lower maintenance.

To match these requirements, cutter rings were developed having a high amount of hard NbCs in the wear affected zone of the ring, and an inner, tough microstructure, with far fewer carbides, patent pending AT300/2013.

## Production

The production of such cutter rings is based on the limited solubility of NbCs in an iron base melt, and in the segregation of such carbides to the outer diameter during centrifugal casting.

In order to form primary NbC particles in the melt, the quantity of niobium and carbon should exceed the solubility product of NbC in the melt. Because the solubility of NbC in an iron melt at normal melting temperatures is very small, the formation of primary carbides already starts with quite small quantities of niobium. The density of the formed particles is a little higher than the density of the iron melt, and this leads to their outward migration under the influence of high centrifugal acceleration forces, applied during spin casting, Figure 1. The movement of the carbide particles stops if they get into a loose network with each other, resulting in a relatively homogeneous carbide rich layer at the outer surface of the casting. For best economic use of material and to reduce machining costs, the mold has been designed to enable net shape casting in the outer part of the ring.

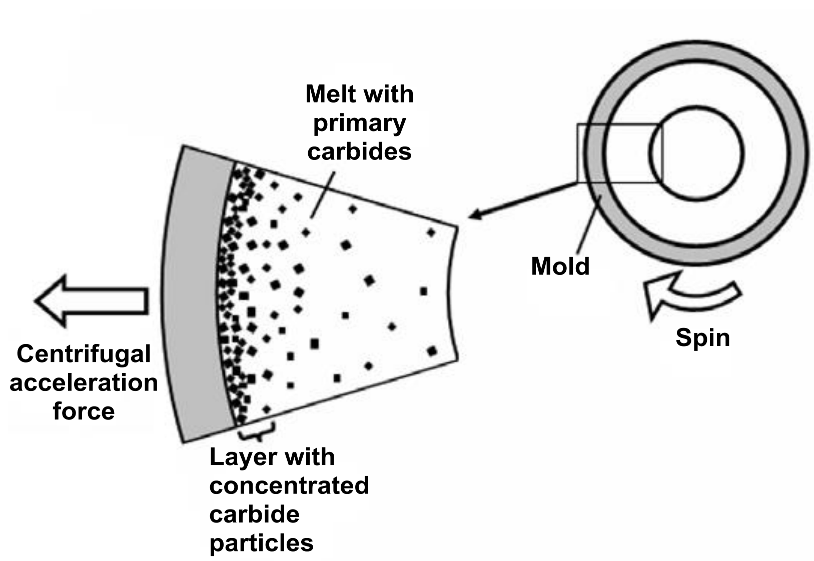


Figure 1. Formation of a layer with concentrated carbide particles during centrifugal casting.

The primary NbC can be formed in the iron base melt by adding carbon, or carbon containing alloys, to a niobium containing melt. It is also possible to add NbC directly into the melt, eg. in the form of Fe-NbC. The whole process must be controlled in such a way that the primary carbide particles, which are slightly heavier than the melt, have enough time to segregate outwards and to form the carbide rich layer, before they get stuck in the solidifying melt. Rapid cooling at the surface of the mold always leads to a layer containing less NbC next to the mold surface. The microstructure of the inner part of the ring consists of solidified residual melt with only a few primary and eutectic NbC particles. Depending on the chemical composition of the melt and on the subsequent heat treatment, other carbides can exist in this area or in the whole casting.

After casting, a heat treatment has to be applied in order to achieve the best properties of the matrix. Due to the high thermal stability of NbC, the formed particles are not affected by the treatment. Small additions of vanadium or titanium lead to mixed Nb-V-Ti carbides, resulting in different morphologies and properties of the primary carbide particles.

## Microstructure and Properties

Figure 2 shows the principal design of commonly used cutter rings and their cross section. During boring, the outer cutting edge of the ring is pressed against the hard rock and breaks it into small pieces, which fall and grind onto the outer surfaces next to the edge. So the whole outer zone is the wear loaded part of the ring. A cross section of a cast cutter ring is shown in Figure 3. Due to etching of the polished sample surface, the carbide enriched zone is visible with the naked eye. It can be seen that the concentrated carbides are situated exactly in the wear affected area. A typical microstructure of the carbide rich area can be seen in Figure 4(a), while the inner zone is shown in Figure 4(b). The carbide volume fraction in the outer part lies typically between 20% and 40%, depending on the chemical composition of the melt and the production specifications. In this example, the angular carbide particles are pure NbC. The particles still have the structure that they had in the Fe-NbC, an alloy of iron and NbC, used as the NbC source to the base melt. Additions of vanadium or titanium lead to rounder carbide appearances, as shown in a deep etched sample containing Nb-V carbides, Figure 5 [3]. The carbides are connected to each other three-dimensionally, forming a robust network. Varying concentrations of niobium and vanadium in the carbides result in different brightness in the SEM picture.

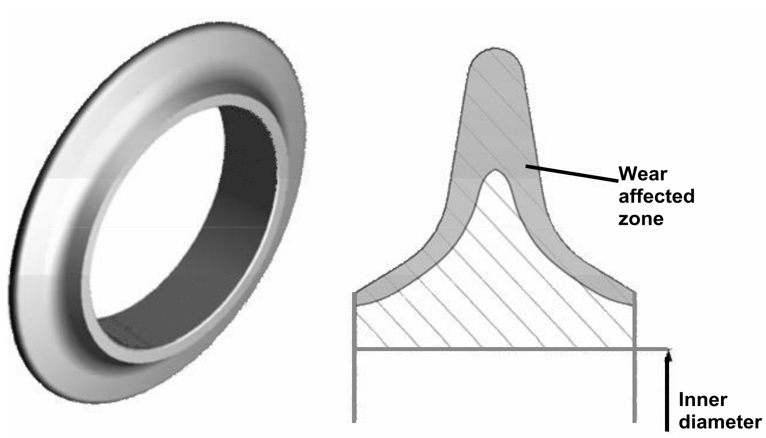


Figure 2. Design and cross section of commonly used cutter rings.

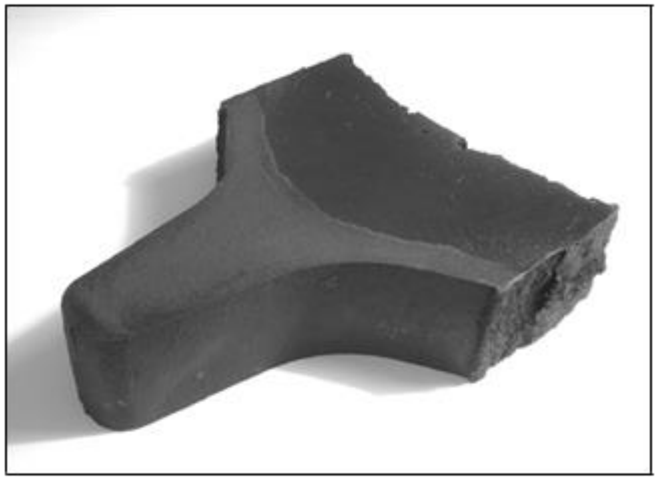

Figure 3. Cross section of cast cutter ring with carbide enriched layer.

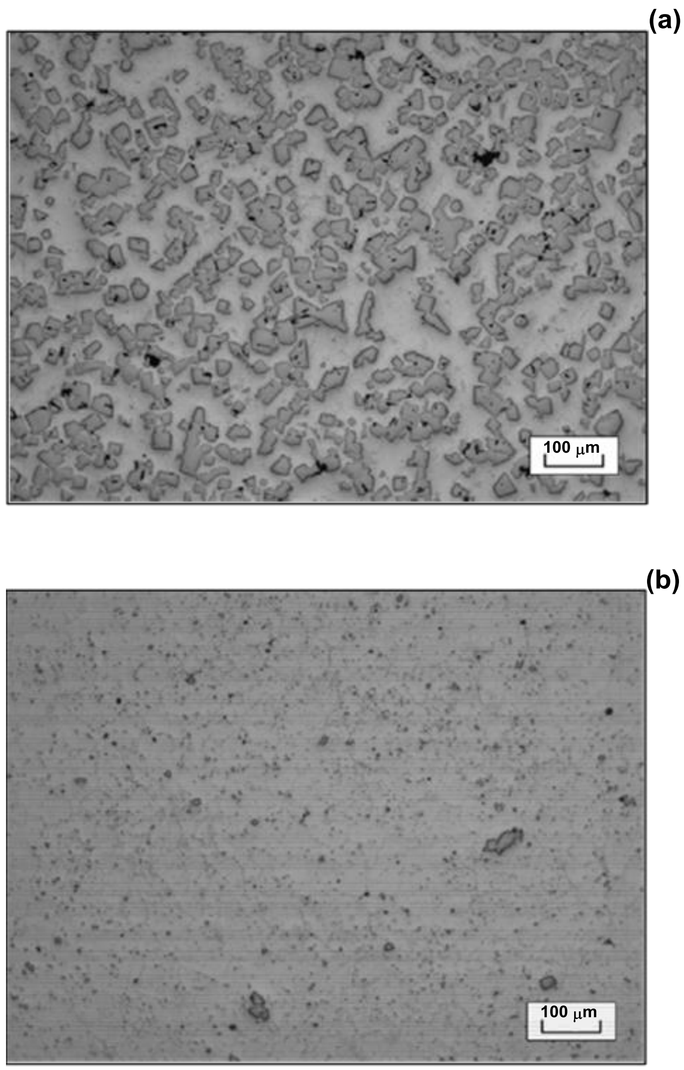


Figure 4. Microstructure; (a) in the carbide enriched layer, (b) in the inner zone.

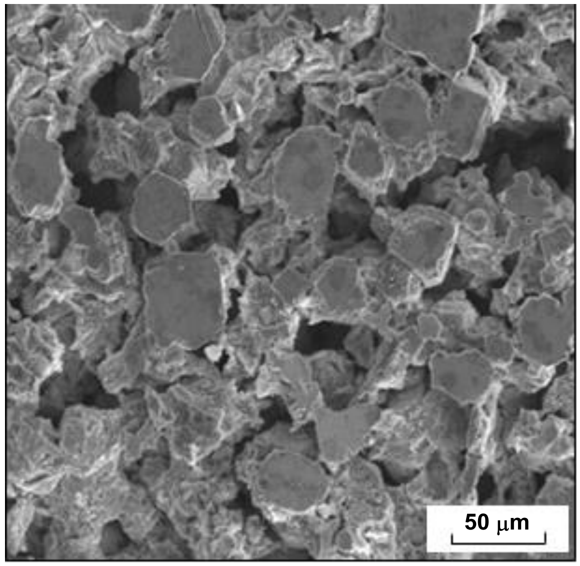


Figure 5. Deep etched sample in carbide enriched layer containing Nb-V-carbides (SEM).

The microstructure of the inner part contains only a small fraction of carbides, Figure 4(b). The carbide volume fraction in this area is typically lower than 5%. The profile of the fraction of carbides in the microstructure from the tip of the cutting edge to the inner diameter of the cutter ring is shown in Figure 6. The first 5 mm were rapidly solidified before the primary carbides were able to separate. This layer consists of the mean chemical composition of the cast melt. Next to this chilled layer, the carbide enriched layer shows a normal homogeneous structure, which is more than 20 mm thick. The thickness of the carbide enriched layer can be adjusted by the amount of niobium and carbon in the melt. Niobium contents of up to 15% in the melt are possible. To the inner side of the carbide enriched zone, a decrease of the carbide content follows to around 3% to 4% in the inner part of the ring.

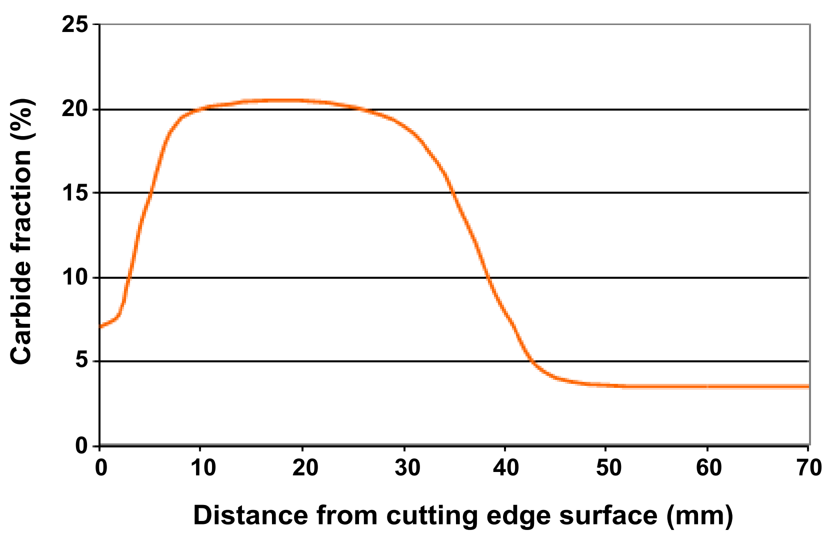


Figure 6. Fraction of carbides in the microstructure from the tip of the cutting edge to the inner diameter of the cutter ring.

Unexpectedly, the carbide enriched layer is not always homogeneous. As shown in Figure 7, it is possible that the layer includes a small ribbon containing less carbide. This behavior needs further investigations in order to be explained.

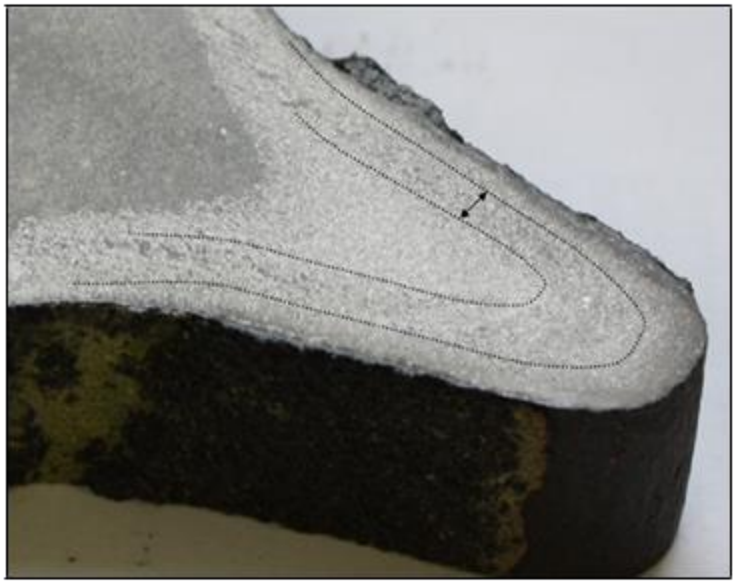

Figure 7. Carbide enriched layer with ribbon containing less carbide.

A specific heat treatment is essential to achieve the optimal properties of the whole ring. Depending on the chemical composition of the base melt, eg. hot-working tool steel, the toughness and hardness of the material can be optimized by the right heat treatment. A hardness of up to 70 HRC in the carbide enriched layer was achieved with a cold-working tool steel base material.

Machining of the carbide enriched zone with any kind of cutting material in the finally heat treated condition is nearly impossible. Only grinding is successful to shape the surface in the area of the cutting edge. Since the rings are mainly net shape cast, the outside surface does not have to be machined. Only the front faces and the inner diameter are machined in the annealed condition.

## Performance

A few cutter rings have already been tested in a tunnel boring site. However, test statistics are currently insufficient to compare their performance to that of cutter rings made of forged hot working tool steel. Nevertheless, it can be said that the toughness of these cast rings can be high enough to fulfil the requirements of tunnel boring operations.

Since mechanical processing is so difficult, we expect a high performance of cutter rings, made of such material, at the working site. Several cutter rings are waiting for tests at different tunnel boring sites.

## Conclusions

Cast cutter rings made out of high niobium containing material have been developed, which present a non-uniform carbide distribution that is repeatable in terms of carbide distribution, carbide content, microstructure and material properties. As these discs are produced mainly by net shape casting and present, therefore, unique properties, these cutter rings could be an economical alternative to the commonly used forged rings made out of tool steel. Performance testing is currently in progress under actual tunnel boring conditions. Also, other applications of this material are possible in mining industries or other technical fields, where high wear resistance and toughness are necessary.

## Acknowledgements

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## References

1. Australian Tunneling Society, "Current & Emerging Rock Cutting Technology," www.ats.org.au, 5th February, 2015.

2. J. Roby et al., "The Current State of Disc Cutter Design and Development Directions," www.therobbinscompany.com, 5th February, 2015.

3. B. Feistritzer, "Erhöhung der Verschleißfestigkeit von Walzenwerkstoffen durch die Verwendung von Niob als Legierungselement" (Ph.D. thesis, Montanuniversität Leoben, 2000).