Evaluation of the chip breakability after machining of Bearing steels based on Weight Distribution Methods

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Abstract:

It is well known that a modification of non-metallic inclusions (NMIs) to create especially many smaller inclusions is an important way to improve the machinability of steels. The main focus of this study is the use of a REMs element (Ce) in the liquid steel to modify the NMIs, in order to improve the chip breakability and thereby the machining performance. In evaluating the success of this procedure, a newly developed evaluation method to determine the chip breakability based on chip measurements, which is called the method of weight distribution of chips (WDC), was used. Two similar steel grades were studied, where one was REM treated and the other was a reference. The chips obtained in this study during machining of these two steel grades were classified into three types: i) type I chips having the shape of one arc and a weight of less than 0.08 g, ii) type II chips having the shape of two arcs and weighing between 0.08 g and 0.15 g, and iii) type III chips having a shape consisting of more than three arcs and weights larger than 0.15 g. In order to get the best chip breakability which is good for a fast machining, as many as possible of the chips should be small type I chips. The results show that at a lower feed rate (f_n = *0.4 mm/rev*), 80 % of chips belong to type I small chips for the reference 157C steel and 65 % of chips belong to type I small chips for the

modified 157REM steel. At a higher feed rate ($f_n = 0.5$ *mm*/*rev*), the fraction of type I chips is 14 % but it is 40 % in the Ce treated steel grade. Thus, at the lower feed rate the reference 157C steel resulted in the best machinability, but at the higher feed rate, the Ce-treated 157REM steel resulted in the best machinability. This is due to a lower feed rate of 0.4 *mm*/*rev* and a lower temperature in the local cutting zone the presence of many MnS inclusions in the reference steel is beneficial to obtain a good chip breakability. However, at the higher feed rate of 0.5 *mm*/*rev* and the higher temperature in the local cutting zone, the MnS Inclusions become too soft while the undeformed Ce-containing inclusions remain hard, which enables them to contribute to an improved chip breakability.

Keywords： Steel, Cerium modification, machinability, chip formation, weight distribution, non-metallic inclusions, 3D extraction

1. Introduction

The steel quality has been remarkably improved during the last decades. A considerable amount of new steel grades, so-called clean and ultra-clean steels with low levels of impurities, have been designed to improve the mechanical properties of steel. However, these clean steels have resulted in increased machining times, energy consumptions and costs during the machining operation. This is due to that it is more difficult to form chips during the machining operation, which lead to a reduced cutting tool life. [1] In this case, the addition of sulphur and calcium to modify the inclusions system to create smaller and softer inclusions is a significant way to improve the machinability of steels. [2] However, the machinability is a complex concept that is influenced by the non-metallic inclusion characteristics as well as the structure of the steels. The most important parameters that have an influence on the machinability are the tool life (TL), tool wear (TW), cutting force (CF), and chip characteristics (CC). [1]

Overall, the non-metallic inclusion (NMI) characteristics play an important role with respect to the final properties of steel as well as the machinability of steels. [3,4] During machining, differences in hardnesses and thermal expansions between the steel matrix and NMIs, cause a formation of the chips. The NMIs could act as stress concentration points or play roles as hard particles, which increases the tool wear. [1,2,5-7] Specifically, sulphide inclusions could affect the mechanical properties of steel in different ways. Some reports show that sulfide (MnS) inclusions can improve the machinability of steel. [8,9] However, when the sulphur content of steels reach levels in the range of 0.03 mass % to 0.07 mass %, there will be an important difference in an increased processability. This is mainly due to changes of the lubrication conditions, which correspond to the presence of sulphide inclusions (MnS) in the steels. These MnS inclusions will protect the cutting edge of the tool and contribute to the starting point of cracks during the formation of a chip. Specifically,

sulphide inclusions contribute to improving the machinability in mainly two ways. First, as the source of stress concentrations where the sulphide inclusions could improve the chip breakability and decrease the cutting force during the machining operation. Second, the sulphides inclusions can form protective layers that could prevent the formation of abrasive tool wear and protect the chemical wear of the tool as well as serving as lubricants between the cutting tool and the metal surface. [10-12]

Calcium (Ca) modified oxides are also considered to be beneficial to reach a good machinability, as has been reported by many authors. [7,13,14] Specifically, the results showed that by adding Ca, an adhering layer on the cutting tool surface could be formed. This is due to that the inclusion system of CaO-Al_2O_3-SiO_2-MnS has a spherical shape, which significantly will improve the machinability when machining Ca-S free cutting stainless steels. [7,13] The chip formation will be improved when the microcrack is initiated at the interface between the metal and the Ca inclusions. This effect is combined with that chips are heavily deformed in the shearing zone and due to a slight deformation of the spherical shape of Calcium oxides occur during the machining operation. Also, the cutting force could be reduced because of the combined effect of the presence of a stress concentration as well as due to a reduction of the actual anti-shearing zone. [7] N. Ånmark et al. [6,13] studied the influence of the inclusion composition on the tool wear during hard turning of carburised steel by using a Polycrystalline Cubic Boron Nitride (PCBN) cutting tool. The result shows that after the Ca treatment, the machinability of the carburising steel was doubled and the cost of cutting tools was reduced by 50%. [13]

Another way of modifying inclusions in some clean steel grades is by using additions of rare earth elements (REM) to reach an improved machinability. [3,4,15,16] Sulfide inclusions are considered as being positive for the machinability of these steels, as also was the case for calcium-treated steels as discussed previously. However, it is also well

known that sulfides, especially large elongated MnS, can negatively affect the mechanical properties (anisotropy, fracture toughness, tensile strength, etc.) of the final steel products. [17,18] Therefore, to improve machinability without decreasing mechanical properties, the preferred characteristics of sulphide inclusions are small size spherically shaped inclusions, which are evenly dispersed in the steel. Due to a high affinity to oxygen and sulphur, the added REMs elements will react with these dissolved elements to form non-metallic inclusions. As a result, the contents of harmful dissolved elements could be reduced in the steels. [19] Luo et al. investigated the effect of adding the REM element Cerium to 20CrNiMo steels to modify the inclusion composition. The result shows that without using a Ce addition, the main inclusions that are formed in the steel are Al_2O_3, MnS and complex Al_2O_3 - MnS oxy-sulphides. After adding Ce, the dissolved O and S react with the dissolved Ce. As a result, inclusions having the compositions of Ce-Mn-S and Ce-O-S were formed when the Ce content is increased to levels up to 77 ppm. When Ce content is lower than 0.1 % (mass percent), the inclusion transformation occurs in the following manner: $Al_2O_3 \rightarrow CeAlO_3 \rightarrow Ce_2O_2S \rightarrow Ce_2O_2S + CeS$ with increasing Ce contents. [19]

The most common methods to evaluate the breakability of chips is by making chip breaking curves based on visual inspections or the longitudinal turning operation as well as by making a chip chart using photos of collected chips. [10] However, in order to obtain more quantitive comparisons between steel grades such as between reference steels and modified steels or to evaluate the results when modifying the machinability of steels by applying various cutting parameters, these methods are less accurate. In a previous study [10], a sensitive and quantitative evaluation method was developed to measure the weight distribution of chips (WDC). However, more studies needs to be carried out in order to test the method on more steel grades as well as to ensure

that the accuracy of the results to quantify the chip breakability of steels during machining is further improved.

In this study, the REM element cerium was added to modify the system of inclusions in the steel to significantly improve the chip breakability as well as to increase the tool life. In doing this, the chip breakability was determined by measuring the chip weight using the above mentioned WDC method. [10]

2. Materials and methods

Workpiece Materials

This study investigated one reference bearing steel (157C) sample where no Ce treatment was used and one Ce modified steel (157REM) sample, where both samples had been gathered during industrial trials. Specifically, a Ce addition was made to one ingot mould for the 157REM sample while the sample for the reference steel (157C) was taken from a mold where no Ce addition was made. The chemical compositions are given in **Table 1**.

Table 1. *Chemical compositions of samples of the reference steel (157C (20NiCrMo7)) and the Ce-treated steel (157REM).*

Steel grade	Ce-Treated	C	Mn	Si	Al	Cr	Ni	Mo	Ce	O	S
		(mass %)								(ppm)	
157C*	No	0.20	0.60	0.25	0.025	0.55	1.70	0.24	<0.001	5.3	40
157REM*	Yes	0.18	0.61	0.23	0.025	0.55	1.70	0.25	0.027	5.3	30

*CNMG120408-MM 4325 cemented carbide inserts (Sandvik Coromant, Gimo, Sweden), with CVD coatings (Ti(C, N) + Al_2O_3 + TiN), were used for the machining testings.

As shown in **Figure 1**, samples of an approximate size of 10 × 20 mm in length and width were used for the evaluation of the non-metallic inclusion characteristics in the 157C and 157REM steels. The samples were both taken from the middle zone of the hot-rolled bar (Ø 121 mm) and in the longitudinal direction.

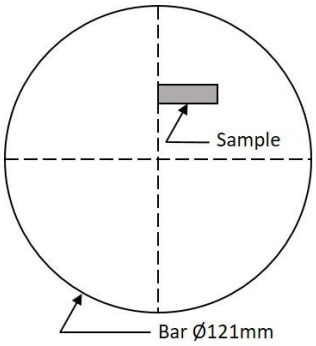


Figure 1. *A schematic illustration of how samples were cut from hot rolled bars made of 157C and 157REM steel grades.*

Conventional Evaluations of Chip Breakability

To make chip breaking curves based on visual inspections, the first six machining operations with different cutting depths (α_p= 0.5, 0.75, 1, 2, 3.5, 5 mm) were used. Thereafter, the following next 30 machining operations were used to make chip charts. Also, the chips obtained from longitudinal turnings with similar sizes and shapes in the chip charts were compared based on their weight.

The operational parameters for visual inspections to make chip breaking curves and chip charts are shown in **Table 2**. Note, that first the data for the chip breakability curve was collected and then directly afterwards the data for the chip chart were collected

Table 2. *The cutting parameters used to determine chip breakability curves and chip charts.*

Test	**Feed rate (f_n)(*mm/rev*)**	**Cutting Depth (α_p) (*mm*)**	**Cutting Speed (*m/mm*)**
Chip breakability curve / Chip chart	0.15, 0.2, 0.3, 0.4, 0.5	0.5, 0.75, 1, 2, 3.5, 5	200

Chip Weight Measurements

The machining parameters that are used for evaluating the chip weight measurements were the following: a cutting speed of 200 m/min and a

cutting depth α_p of 2.0 mm. In addition, two different feed rates f_n (*mm/rev*) having the values 0.4 and 0.5 mm/rev were used for both two steels. For each set of cutting parameters, more than 200 chips were randomly collected and thereafter weighted individually. For measurements, an analytical balance with a yield readability up to four decimals places to the right of the decimal point (up to 0.0001 g) was applied. The chips were classified into three types, based on their weights and shapes, as described in the results chapter. Thereafter, the percentages of the number of each type were calculated.

Investigation of Non-metallic inclusions

The non-metallic inclusions from the two steel samples were extracted using electrolytic extraction. It has previously been reported [20] that many oxides (Al_2O_3, TiOx, MgO, etc.), carbides, sulfides, multicomponent inclusions, etc., have successfully been studied using nonaqueous electrolytes in the EE method. Specifically, the Ce_2O_3 and CeS inclusions were extracted by using a 2 %TEA (2 v/v % triethanolamine-1 w/v % tetramethylammonium chloride-methanol) solution. In this study, both soft 10 %AA (10 % acetylacetone-1 % tetramethylammonium chloride-methanol) and 2 %TEA electrolytes were used for electrolytic extraction of all steel samples. An electric charge of 1000 C was used and the weight dissolved was 0.25 g and the dissolved depth was 165 μm. After finishing the extracting of the inclusions, a filtration of the solution was applied. A 0.4 μm aperture polycarbonate film filter was used for the collection of the inclusions on the film filter as the liquid was drained through the filter. More than 200 NMIs were extracted for both steel samples. After the process was finished, the filter was carefully removed and placed in a dry clean plastic sample box. Finally, the filter was kept in the sample box until the SEM investigations were made.

The depth of the dissolved sample layer (D_{dis}) in mm during EE was calculated as follow:

$$D_{dis} = W_{dis} / (\varrho_{metal} \times A_{surface}) \quad (1)$$

where W_{dis} is the weight loss (in g) of the sample after extraction, $A_{surface}$ is the surface area of reaction (in mm^2) of the steel sample, and ϱ_{metal} is the density of steel (0.0078 g/mm^3).

Scanning Electron Microscope Determinations

The sizes of the inclusions as well as the chemical compositions were determined using Scanning Electron Microscopy (SEM) in combination with Energy Dispersive Spectroscopy (EDS). The typical settings used in the determinations were the following: an 11 mm working distance (WD) and a 15 kV voltage. In addition, the back-scattered electron (BSE) mode was applied to avoid interferences from impurities.

The aspect ratio (AR) was used to determine the deformability of inclusions after deformation. It can be calculated as follow:

$$AR = L/W \quad (2)$$

The number of NMIs per unit volume of a metal sample (N_v) in $mm^{-3}$was also calculated as follow:

$$N_v = n \times A_f / \sum A_{obs} \times \varrho_{metal} / W_{dis} \quad (3)$$

where n is the number of investigated inclusions in the selected size range, A_f is the whole area of the film filter which contains inclusions (=1200 mm^2), and A_{obs} is the observed area on a film filter.

<u>Method 1</u>

In order to investigate the typical NMIs found in each steel sample, Method 1 (M1) was applied. In this method, SEM photos were randomly captured on the film filter to observe the inclusions having both small sizes (less than 10 μm) and large sizes (larger than 100 μm). Also, different SEM magnifications were used depending on the sizes and the morphologies of the typical NMIs, which were found in the samples. Also, the compositions of typical inclusions found in the samples as well as the

different phases in the complex inclusions were determined using energy dispersive spectroscopy.

Method 2

In order to evaluate the characteristics of NMIs more systematically, Method 2 (M2) was used. In this method, a magnification of 1000 was used to determine the fractions of different types of NMIs as well as the number of inclusions per volume, N_v. Typically, 10 to 50 photos of inclusions collected on the film filter were taken continuously. The data was mainly gathered to determine the N_v, values of the inclusions. For each sample, a minimum of 200 inclusions was investigated to obtain a statistically reliable amount of data.

3. Results and discussion

3.1. Conventional Evaluation Methods

Chip breaking curve method

In order to study the chip formations of a 157C bearing steel and a REM modified 157REM steel, a cutting speed of 200 m/mm was applied during the longitudinal turning tests. **Figure 2** shows that the chip breaking curves of these two samples are separated into two parts, namely an accept zone and a no-accept zone. The chip formation with an acceptable condition is located at the right side of these curves. However, it should be noted that an acceptable condition is based on a subjective estimation by an operator. Thus, its values are dependent on the human factor.

As can be seen in **Figure 2**, the only slight differences between these two curves are at α_p values between 1 mm and 5 mm and at f_n values between 0.15 *mm/rev* and 0.45 *mm/rev*. As the cutting depth α_p increases from 0.15 mm to 0.3 mm, the 157REM steel has a slightly smaller acceptance area compared to the 157C steel. Moreover, an increased cutting depth α_p from 0.3 mm to 0.45 mm results in a slightly larger range for the 157REM steel compared to the reference 157C steel. Compared to the results of a previous study [10], the chip breaking curves using a different cutting

speed applied to a Ca treated 316L steel have a wider range of an acceptable area compared to the reference 316L steel. These results show that the use of a Ca treated 316L stainless steels has led to improved chip breakabilities compared to when using a reference 316L steel and using the same cutting condition. However, the current study of the chip breaking curve for Ce modified 157C steel has been performed using a narrow range of α_p values from 0.15 mm to 0.3 mm. This may be explained why it is not possible to judge why the Ce modification of 157C has not resulted in an improvement of the chip breakability compared to the reference case in these experiments.

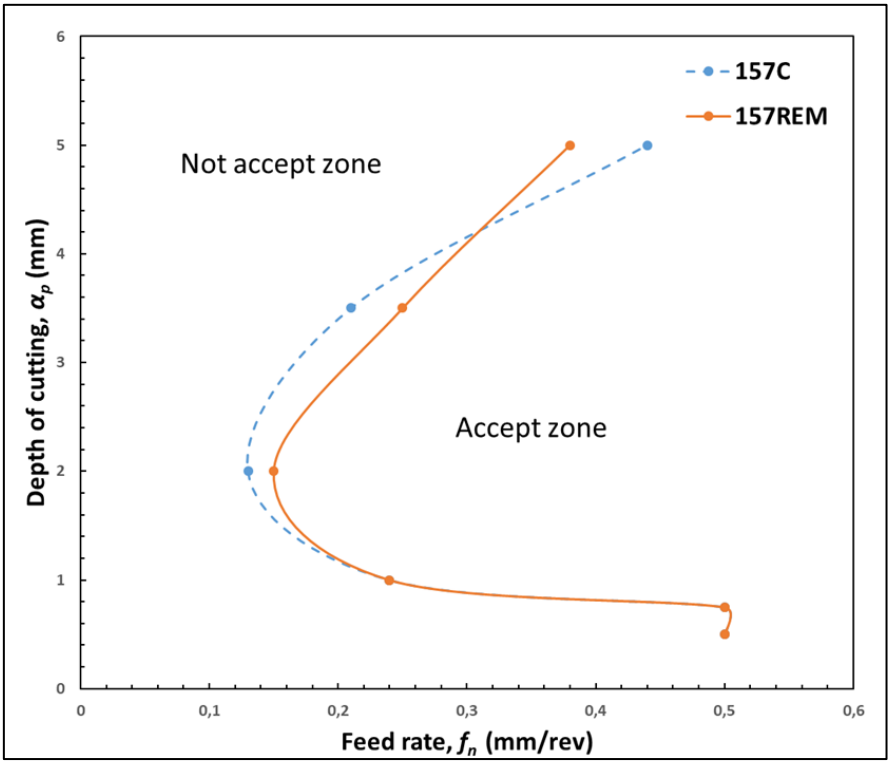


Figure 2. *An illustration of a Chip breaking curve, when using a cutting speed V_c of 200 m/min. [21]*

Chip chart method

Figure 3 illustrates another conventional method for evaluating the chip breakability, namely the chip chart method. Data are shown when applying different cutting parameters (α_p and f_n) and using a cutting speed of 200 m/min. As shown, chips from the area marked with light red lines

are acceptable to be used for evaluations. In **Figure 3**, more detailed differences can be seen compared to the information shown in the chip breaking curves in **Figure 2**. However, in the red accepted zone in **Figure 3**, the chips look similar based on the visual evaluations. Especially for selected parameters for chips analysis, the two steels show almost the same chip breakability values. Thus, these results determined with the chip charts method cannot be used to quantitatively determine whether the Ce modification of 157C steel has improved the chip breakability or not.

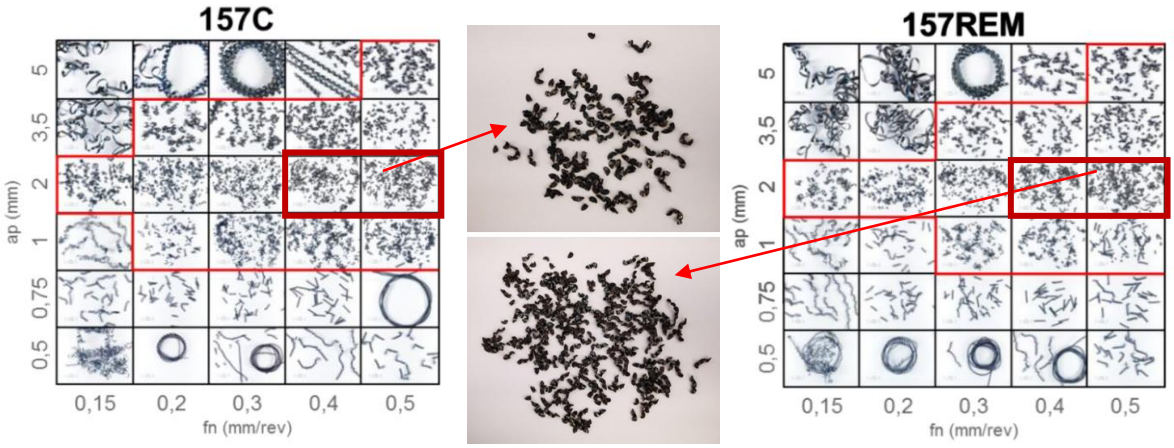


Figure 3. *Chip charts for bearing steels at V_c = 200 m/min. [21]*

In this case, experiments using a cutting depth $\alpha_p = 2.0\ mm$ and a feed rate $f_n = 0.4$ *and* $0.5\ mm/rev$ (dark red zone) were selected for studies using a newly developed quantitative evaluation method for these two steels.

3.2. Classification of Chips using the Chip Weight Distribution Method

The chips obtained from the accepted zone from **Figure 3** were in **Table 3** classified into the following three types based on weight: i) type I chips have a weight of less than 0.08 g and are small pieces having a shape containing one curve, ii) type II chips have weights between 0.08 g and 0.15 g and shapes containing two curves, and iii) type III chips have shapes containing multi-curves and weights larger than 0.15 g. Also, it can clearly be seen from **Table 3** that the chips of type II and type III are discontinuous

chips. It should also be mentioned that this classification is similar to the one used in a previous study [10].

It is our assumption that type I chips that have the lowest weights and are the shortest, have the best breakability. This, in turn, corresponds to a better machinability. This assumption is based on practical experience from industry, where it is known that especially longer chips may cause many different production problems.

Table 3. *Classification of different chips.*

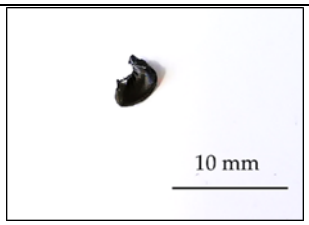
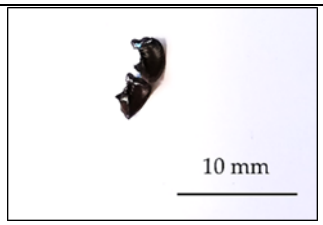
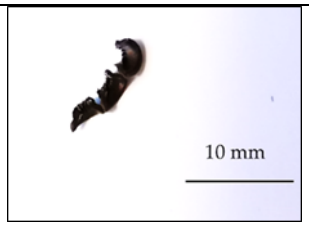
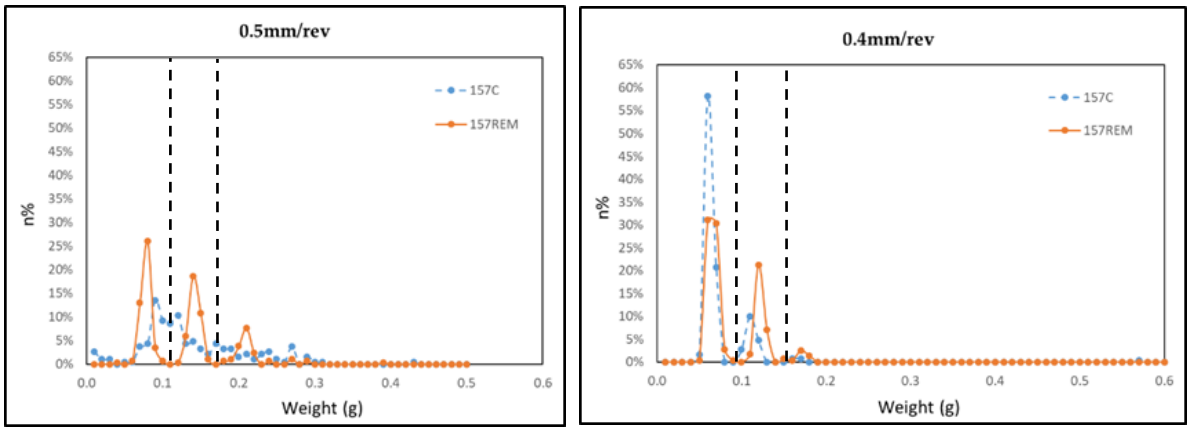
Type of Chips	I	II	III
Weight (g)	<0.08	0.08–0.15	>0.15
Photograph			

Figure 4 shows the difference in chip distributions for the 157C and 157REM steels when using different cutting parameters. The figures show that the Ce modification and the use of the current cutting parameter (feed speed f_n) can affect the distribution of chips. As seen in **Figure 4 a** for the reference steel 157C, approximately 35 % of the chips are distributed around a weight of approximately 0.1 g (0.09 g to 0.11 g) when using a feed speed of 0.5 *mm/rev*. However, at a lower feed speed of 0.4 *mm/rev* the following can be seen: 60 % of the chips have a weight of approximately 0.08 g, 10 % of the chips have a weight of 0.10 g and 3 % of the chips have a weight of 0.16 g.

It is of interest to compare the results for the reference steel with the results of the 157REM steel. At a feed speed of 0.5 *mm/rev*, the chips from the Ce modified steel 157REM are clearly divided into the three types, as shown in **Table 3**. Specifically, 25 % of the chips have a weight of 0.08 g, 20 % of

the chips have a weight of 0.14 g and 8 % of the chips have a weight of 0.22 g. In addition, there is a small indication that 3 % of the chips have a weight of 0.28 g. At a lower feed speed of 0.4 mm/rev, 30 % of the chips have a weight of 0.08 g, 20 % of the chips have a weight of 0.12 g and 2 % of the chips have a weight of 0.18 g.

As shown in a previous study [12], the chip formation process is a deformation process where enormous strains are created near the primary shear zone, which results from the internal cracking or void formation as well as due to a possible crack formation around the edge of the cutting tool. Even though the chip formation process is associated with a crack formation around the cutting edge, the process of chip formation does not lead to a crack breeding phenomenon, which would result in a fracture of the chip. As a result, the compressive stress field at the tip of the cutting edge suppresses the shear-type of crack propagation. [12]



(a) (b)

Figure 4. *Distribution of chip weights with a step of 0.01 g at the parameters (a) v = 200 m/min, α_p = 2 mm, f_n = 0.5 mm/rev; (b) v = 200 m/min, α_p = 2 mm, f_n = 0.4 mm/rev.*

Table 4 shows the detailed results of the determinations of the weight of the chips distribution, which was done by selecting the chips from the dark red rectangle zone in **Figure 3**. The chip weights were used to determine these three groups, shown in **Table 3**. As mentioned before, it was not possible to see a difference between a reference steel and a cerium-

treated steel with respect to machinability. However, as the results in **Table 4** shows the method based on the weight of the chips distribution makes it possible to determine the influence of a cerium treatment on the machinability.

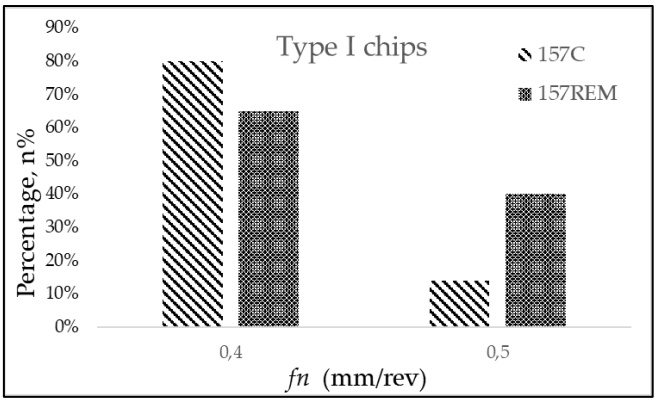
For set 1 at $f_n = 0.4$ *mm/rev*, 80 % of the chips belong to type I for the 157C steel compared to 65 % for the Type I chips from steel 157REM, which represents a decrease by 15 percentage points. However, after performing a Ce modification, the fractions of type II and type III chips for the 157REM steel increase by 13 to 2 percentage points after the completed machining test, respectively. However, for set 2 the use of a feed rate of *0.5 mm/rev* results in that the fraction of type I chips from the 157REM steel is increased by 26 percentage points. On the other hand, the fraction of chips belonging to type II and type III for the 157REM steel decreased by 14 and 13 percentage points, respectively, compared to the chips from the 157C steel. It is obvious that for set 2 ($v = 200$ *m/min*, $\alpha_p = 2$ *mm*, $f_n = 0.5$ *mm/rev*), which is performed at a higher feed rate, the Ce modification has improved the chip breakability compared to the reference steel.

Table 4. *Summary of results of fractions of different types of chips, based on weighting measurements.*

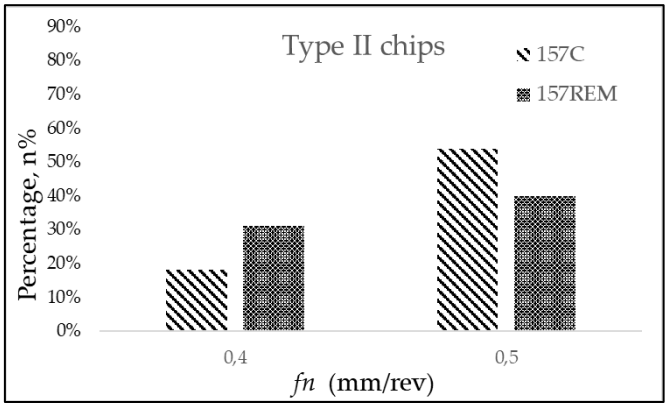
Sample	**157C**		**157REM**		**Δ[Type^i(rem)-Type^i(ref)]** (percentage points)	
Set	1	2	1	2	1	2
Speed (m/min)	200	200	200	200		
α_p *(mm)*	2.0	2.0	2.0	2.0		
f_n *(mm/rev)*	0.4	0.5	0.4	0.5		
Number (Num.)	251	184	283	284		
Type I (%)	80	14	65	40	-15	+26
Type II (%)	18	54	31	40	+13	-14

Type III (%)	2	32	4	19	+2	-13

Figure 5 shows the frequencies of different types of chips from the reference bearing steel 157C and the Cerium modified 157REM steel at different feed rates (f_n), but using a constant a cutting speed of 200 m/min. It can be seen that for the 157REM steel, the fraction of type I chips was decreased by 25 % (from 65 % to 40 %), after increasing the feed rate from 0.4 to 0.5 mm/rev. The same tendency also applies to the reference steel 157C, where the type I chips significantly decreased by 66 % (from 80 % to 14 %). By contrast, after increasing the feed rate to 0.5 mm/rev, the fractions of both type II and type III chips increase. For the 157C steel, the fraction of type II chips increased by 36 % (from 18 % to 54 %), and for type III it increased by 30 % (from 2 % to 32 %) after an increase of the feed rate from 0.4 to 0.5 mm/rev. The fractions of type II and type III chips increased by 9 % (from 31 % to 40 %) and 15 % (from 4 % to 19 %) for the 157REM steel, respectively, as shown in **Table 4**. This phenomenon could be associated with the distribution of heat during machining along the cutting zone, when increasing the feed rate. The temperature ahead of the cutting edge and contact surface could be up to more than 800 ˚C at $f_n = 0.3$ *mm/rev*. [22] Compared to MnS inclusions, as will remain only 20% of the hardness at room temperature, Ce inclusions have thermal expansion coefficients only slightly higher (10.7×10^{-6} - 13.4×10^{-6} 1/˚C) but close to those of the steel matrix (10.1×10^{-6} - 11.8×10^{-6} 1/˚C). [1] Thus, after a Ce modification, the deformation property of the steel could be improved. When the cutting tool contacts the steel surface at an external force the stress concentration could decrease, which will result in that the crack initiation will be delayed. [23]



(a)



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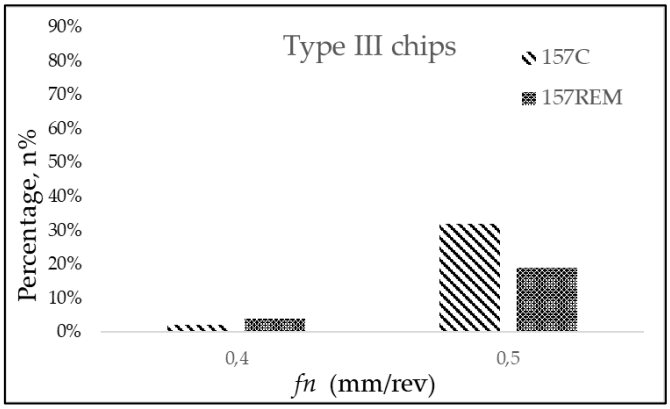


(C)

Figure 5. *Chip weight distribution for type I (a), type II (b), type III (c) chips obtained at α_p = 2 mm, υ = 200 m/min.*

Overall, the use of a lower feed rate (f_n = *0.4 mm/rev*) of cutting, leads to a decreased formation of small Type I chips, whereas the number of both type II and type III chips are increased after a Ce modification. However,

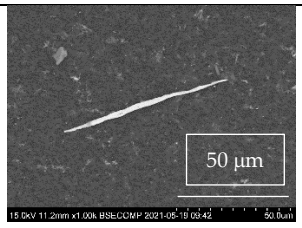
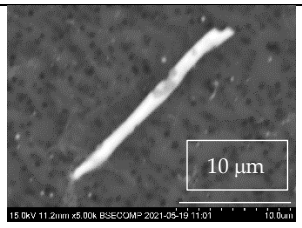
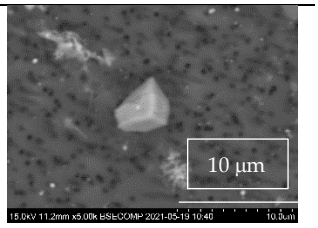
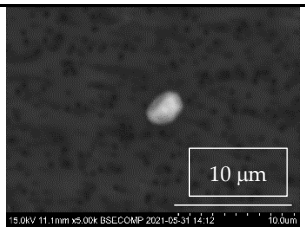
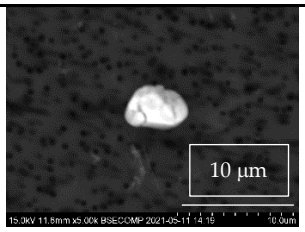
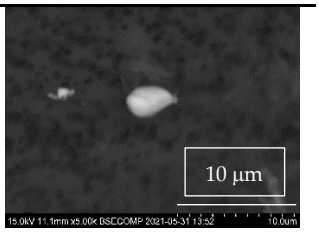
at a higher feed rate ($f_n = 0.5$ *mm/rev*), there is an opposite tendency for all types of chips compared to the results obtained when using the lower feed rate, after a Ce modification of the steel has been performed. Moreover, for both the 157C and 157REM steels and when using a higher feed rate, the fraction for type I chips are all lower than the values found at the lower feed rate. However, for type II and type III chips, there is an opposite tendency. The fraction of chips at the higher feed rate is higher compared to the one at a lower feed rate.

3.3. The non-metallic inclusions in two different steels

For the machinability (chip breakability) of the steel, the non-metallic inclusions (NMIs) are essential. One of the purposes of this study is to use rare earth elements (Cerium) to increase the chip breakability of bearing steel 157C by modifying the inclusions present in the reference bearing steel. The difference in chip breakability of the two steels 157C and 157REM is mainly caused by the difference in the NMIs, which are formed after a Cerium modification. For both the 157C and 157REM steels, three main groups of NMIs were found when operating the SEM observations (**Table 5**). These types can be divided into Group I (pure Sulfides), Group II (Oxy-sulfides) and Group III (Oxides) inclusions. As shown in **Table 5**, elongated MnS, elongated oxy-sulfide ((Al, Mg, Si)O + MnS), and undeformed oxides ((Al, Mg, Si)O) were found in the reference steel 157C before a Cerium modification in the ingot mould. However, after a Cerium modification, the 157REM steel contained sulphides (Group I Ce_xS_y), Oxy-sulfides (Group II Ce (O,S), mostly Ce_2O_3 + Ce_xS_y) and Oxides (Group III Ce_2O_3). It was found that approximately 50 % and 40 % of the observed inclusions corresponded to the Ce_xS_y sulphide inclusions and Ce(O,S) inclusions respectively. Approximately less than 10 % of the inclusions are Ce_xO_y. The Ce/(O,S) ratios mainly varied from 3 to 7.65 in the Group II inclusions. It should be noted that the SEM was operated according to the procedure of method when determining the composition and phases of inclusions as well as when taking photos of typical inclusions.

Furthermore, the SEM was operated according to Method 1 to determine the frequency of the different inclusion types for 157C as well as the L_{max} and AR values, since the focus was to especially find both small and large inclusions. For 157REM Ce treated sample, only Method 2 was enough for determining the characteristics (sizes, composition and frequency of different types inclusion) as well as the particle size distribution (**Table 6** and **Figure 6**).

Table 5. *Typical non-metallic inclusions in bulk samples for 157C (Method 1) and 157REM (Method 2).*

Type of inclusions	Group I Sulphide	Group II Oxy-Sulphide	Group III Oxide
Sample 157C Photograph			
L_{max} (µm)	2.2 - 92.0	2.7 – 24.9	1.1- 8.4
AR (Average)	1.5 – 28.8 (9.3)	1.4 – 15.9 (4.6)	1.1 – 2.6 (1.4)
Composition (Frequency %)	MnS (46)	(Al,Mg,Si)O + MnS (28)	(Al,Mg,Si)O (27)
Sample 157REM Photograph			
L_{max} (µm)	0.6 – 5.8	0.7 – 7.2	0.7 – 4.6
AR (Average)	1.0 – 1.6 (1.2)	1.0 – 1.4 (1.2)	1.0 – 1.3 (1.1)
Composition (Frequency %)	Ce_xS_y (50)	Ce (O,S) (40)	Ce_xO_y (10)

The main characteristics of NMIs in the two 157C and 157REM samples are shown in **Table 6**. After a Cerium modification, the number of

inclusions per volume (N_v) increases by almost four times (46560 mm^{-3}) compared to the reference steel 157C (12883 mm^{-3}). However, the sizes of the inclusions for steel 157REM were smaller (1.8 µm) than the inclusion sizes found in the reference steel 157C (2.8 µm).

Table 6. *Main parameters of electrolytic extraction and SEM observations of non-metallic inclusions in different steel samples when using Method 2.*

Sample	Electric Charge (C)	Ce/(O+S)	W_{dis} (g)	D_{dis} (µm)	A_{fil} (mm^2)	A_{obs} (mm^2)	Num. (NMIs)	N_v (mm^{-3})	Size (range) (L*, µm)
157C	1000	0.22	0.2365	166.8	1200	0.7373	240	12883	2.8 (1.0 – 75.7)
157REM	1000	7.65	0.2541	165.2	1200	0.1788	226	46560	1.8 (0.6 – 7.2)

* Length in median value.

Figure 6 shows the particle size distribution of NMIs for the 157C and 157REM steels. It can be seen in the figure that the distribution of NMIs for the 157REM steel at a size of approximately 2 µm is much larger compared to in the reference steel 157C. It is also seen that the majority of the inclusions in both steel grades are smaller than approximately 5 µm.

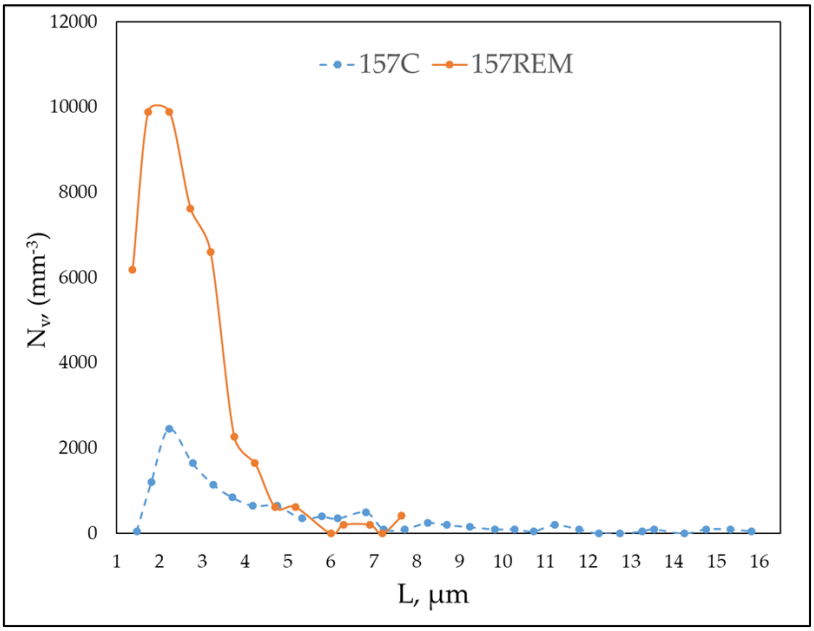


Figure 6. *Particle size distributions of non-metallic inclusions on film filters after electrolytic extractions of 157C and 157REM steel samples from the middle zone of rolled bars.*

It is a common knowledge that NMIs can improve the machinability of working materials due to that they act as a source of stress concentrations when a force is applied. This prenominate could lead to the formation of voids and microcracks between the interface of NMIs and steel matrix. Finally, the stress concentrations, as well as the microcracks and voids, could be a benefit from the chip breakability and the cutting force will be decreased during machining. [1,7,11,24-26] One study [27] also showed that the stress concentration was higher when having a higher aspect ratio (*AR=L/W*, where *L* and *W* are the length and width of an inclusion) of the NMIs in a low cutting speed range (≤35 m/min). However, when the cutting speed increases, the temperature was increased. As a result, the difference in the plastics between the chips and the steel matrix was reduced. Furthermore, the stress concentration could be decreased and the chip breakability was lower than that obtained when using low cutting speed. [27] It should be noted that these results are valid for a resulfurized free-cutting steel with a 0.1 wt % S content. This sulphur content is much higher than the sulphur contents in the steel grades relevant for this study. However, the reference is included for sake of discussion since no other data for lower sulphur contents were found.

In this study, the aspect ratio of sulfide inclusions in sample 157C without Ce modification is much larger than the inclusions in Ce treated sample 157REM as shown in **Table 5**. Although the cutting speed was fixed at 200 m/min, a higher feed rate (f_n = *0.5 mm/rev*) could also lead to a higher temperature. This, in turn, decrease the plastics between the chips and steel matrix as well as the stress concentration between the interface of the NMIs and steel matrix. Therefore, it can be easily understood that the 157C steel has a better chip breakability than the 157REM steel when using a lower feed rate (f_n = *0.4 mm/rev*). However, at the higher feed rate (f_n = *0.5 mm/rev*), the chip breakability of 157REM steel was higher than the 157C steel.

3.4.Summarized Discussion

According to results obtained in the previous publication [10] and in the current study, the conventional qualitative methods for evaluation of chip breaking, such as the Chip Breaking Curves and Chip Chart methods, cannot often detect any differences in chip breakability when using similar steel grades and approximately similar machining conditions. However, the Weight Distribution of chips (WDC) method can be used for quantitative determinations of those differences, which can help to optimize the applied machining parameters. Furthermore, to determine the effect of different inclusions on the chip breakabilities of similar steel grades. In using this method it is assumed that a larger number of small chips corresponds to a better chip breakability. For instance, it was found in the current study that the frequency of small chips (type I) during longitudinal turnings decreases drastically by 66 % and 25 % with an increased feed rate (f_n) from *0.4* up to *0.5 mm/rev* in the 157C and 157REM steel samples, respectively. Moreover, it was found that the frequency of small chips in the 157C steel is 15 % larger when using a feed rate of 0.4 mm/rev and 26 % smaller when using a feed rate of *0.5 mm/rev*, compared to the results for the 157REM steel. It means, that the REM modification of sulfides in the given steel grade can significantly improve the chip breakability at a larger feed rate (≥ 0.*5 mm/rev* at the given other machining conditions), but not at a lower feed rate (*0.4 mm/rev* at the given other machining conditions).

The results of machining tests and evaluation of inclusion parameters are summarized in **Table 7**. It can be seen that the Ce-addition in the steel melt promoted the formation of a larger number Ce containing inclusions (Ce_xS_y, Ce(O,S) and Ce_xO_y), which is expected. These inclusions have smaller sizes (about 2 μm), higher hardness values and very low deformability values compared to the MnS and oxysulfide inclusions, which are present in the 157C steel. Based on the results obtained in this study, it can be assumed that, at a lower feed rate (*0.4 mm/rev*), the MnS

inclusions having a larger amount of large-sized inclusions and higher thermal expansion promoted to better chip breakability of the 157C steel compared to the Ce-modified inclusions in the 157REM steel. However, at the higher feed rate (*0.5 mm/rev*), when the temperature of the steel in the local cutting zone is increased, the MnS inclusions will become more elastic and more easily deform. This, in turn, can significantly decrease the steel stress in the cutting zone and chip breaking efficiency. In this case, the undeformed hard Ce-containing inclusions will have a larger effect on the chip breakability compared to deformed soft MnS inclusions at the changed conditions of machining. This reasoning supports the results obtained by using the WDC method in this study.

Table 7. *Summary of main characteristics of 157C and 157REM steel samples when using Method 2.*

Steel		***157C*** (40 ppm S)	***157REM*** (30 ppm S)	**Ref.**
Test of chip breaking: - Chip breaking curves; - Chip chart method; - Chip weight distribution		Similar Similar Better at f_n = 0.4 mm/rev	Similar Similar Better at f_n = 0.5 mm/rev	[21] [21] CS*
Main characteristics of NMI:	Typical NMIs	MnS (Al,Mg,Si)O+MnS (Al,Mg,Si)O	Ce_xS_y Ce(O,S) Ce_xO_y	CS*
	Median length, L (average) (μm)	2.8 (1.0 – 75.7)	1.8 (0.6 – 7.2)	CS*
	Total N_v (incl./mm^3)	12883	46560	CS*
	N_v of large NMIs (> 5 μm)	3274 (61)	824 (4)	CS*
	Hardness of NMIs	MnS – low; Oxides - high	High	[1]
	Deformability of NMIs	MnS - very high at T<1000 °C Oxides – not at T<1300 °C	Very low	[1]

	Thermal expansion, α (x10^{-6}, 1/°C)	MnS - high (~18.1), Oxides - low (~8.0-8.6)	Middle (~11.2-13.4), similar with steel matrix	[1]
	Effect of NMIs on the machinability of steel	MnS: - Cutting force and power consumption are low or middle. - Chip formation is good. - Tool wear rate is low due to the presence of soft and ductile NMIs and lubrication effect.	Ce_xS_y, Ce(O,S), Ce_xO_y: - Cutting force and power consumption are high or middle. - Chip formation is poor or normal. - Tool wear rate is low or normal due to some lubrication effect of NMIs.	[1]

*CS - current study

4. Conclusions

This study was focused on the possibilities to improve the machinability (chip breakability) of bearing steel by modifying the non-metallic inclusions (NMIs) system by adding a rare earth element (Cerium) during steelmaking. The chip breakability was determined by measuring the chip weight with a newly developed evaluation method based on weight distribution (WDC). These new results were compared to determinations using the more common methods named the chip breaking curve and chip chart methods. When using the WDC method the chips were classified into three types, namely i) type I chips having the shape of one arc and a weight of less than 0.08 g, ii) type II chips having the shape of two arcs and weighing between 0.08 g and 0.15 g, and iii) type III chips having a shape consisting of more than three arcs and weights larger than 0.15 g. Here, it is known that it is preferable to have as many type I chips as possible, to obtain the best breakability during machining. The study was made on two steel grades, a 157C steel and a Cerium modified 157REM were studied. The non-metallic inclusions from the two steel samples were extracted using the electrolytic extraction method and thereafter the characteristics were determined using scanning electron microscopy in combination with energy dispersive spectroscopy. The following conclusions can be made based on the results from this study:

1. For evaluating the chip breakability of steel, chip breaking curve and chip chart methods are the most commonly used conventional methods. However, the results are not accurate enough to make it possible to find a difference between the two studied steel grades. Thus, the weight distribution of chips (WDC) method was applied. By using this new method it is possible to observe the difference of chips obtained from two steels, namely a 157C steel and a Cerium modified 157REM steel.
2. At a lower feed rate ($f_n = 0.4$ *mm/rev*), the majority of the chips belong to type I small chips, which are beneficial for obtaining a good chip

breakability. Specifically, the percentages of type I chips are 80 % and 65 % for the reference 157C steel and the Cerium modified 157REM steel, respectively. The better chip breakability for the reference steel is due to the presence of a large amount of MnS inclusions with a high thermal expansion, which promotes a good chip breakability.

3. At a higher feed rate ($f_n = 0.5$ *mm/rev*), the percentages of type I chips are 14 % and 40 % for the reference 157C steel and the Cerium modified 157REM steel, respectively. The better chip breakability for the REM-treated steel is due to that at this higher feed rate the temperature in the local cutting zone is increased. This, in turn, will cause the MnS inclusions in the reference steel to more easily be deformed as they become elastic, which in turn will decrease the steel stress in the cutting zone as well as the chip breakability. However, the undeformed hard Ce-containing inclusions in the Ce-treated steel will be less influenced by the increased temperature at this higher feed rate. Overall, the percentages of type I chips are a lot lower at this higher feed rate at 0.5 *mm/rev* compared to the results for the feed rate of 0.4 *mm/rev*.
4. Before a Cerium (Ce) modification, the NMIs in the steel 157C are elongated MnS, elongated Oxy-sulphides ((Al, Mg)O + MnS) and undeformed oxides ((Al, Mg, Si, Ca)O) inclusions. After a Ce modification, most inclusions are Ce_xS_y as well as Ce(O,S) and Ce_xO_y inclusions.

Acknowlegments:

I would like to thank for the financial support from China Scholarship Council (CSC) and Jernkontoret, Stiftelsen Axel Ax: son Johnsons Forskningsfond during my entire research and all other colleagues who participated in this study.

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