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ROUGHNESS OF AUSTENITIC STAINLESS STEEL DEPENDING ON MICROALLOYING ELEMENTS AND NONMETALLIC INCLUSIONS

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ABSTRACT

The demand for stainless steels has been steadily increasing across industries such as automotive, aerospace, aviation, medical technology, and household appliances, primarily due to their excellent corrosion resistance, low thermal conductivity, and favorable strength-to-weight ratio. Many of these applications involve components with complex geometries and strict dimensional tolerances, making machinability a crucial factor.

Technical surfaces are not ideally smooth geometric surfaces separating two media, but are, from a microscopic point of view, rough surfaces characterized by a series of irregularities of different sizes, shapes, and arrangements. The roughness represents the microgeometric irregularities of the surface, i.e., unevenness at the small reference length (l) of a given direction of the surface.

According to the available literature, the effect of alloying elements on roughness during conventional turning has not been sufficiently investigated. Therefore, the objective of this study is to investigate and quantify the effect of alloying elements and nonmetallic inclusions on roughness magnitudes in the longitudinal turning process of X8CrNiS18-9 stainless steel.

Keywords: boron, zirconium, tellurium, nonmetallic inclusions, roughness

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1. INTRODUCTION

The demand for stainless steels has been steadily increasing across industries such as automotive, aerospace, aviation, medical technology, and household appliances, primarily due to their excellent corrosion resistance, low thermal conductivity, and favorable strength-to-weight ratio [1]. Many of these applications involve components with complex geometries and strict dimensional tolerances, making machinability a crucial factor. Austenitic stainless steels are more difficult to machine than carbon or low-alloy steels because of their high deformability, low thermal conductivity, and strong tendency to work hardening, which often leads to elevated cutting forces, tool vibrations, and accelerated tool wear. During machining, chips frequently adhere to the tool or workpiece, which can cause material removal from the cutting edge and further degrade surface quality. To enhance machinability, free-cutting elements such as sulfur, selenium, tellurium, lead, bismuth, copper, aluminium, and phosphorus are commonly added, as they reduce friction, facilitate chip breakage, and help control cutting forces [2, 3]. Among these, stainless steel EN 1.4305, commonly known as X8CrNiS18-9 (AISI 303), is the most readily machinable austenitic stainless steel due to the addition of sulfur, and is therefore classified as a “free-machining” grade [4]. A comprehensive review on the machinability of austenitic stainless steels is presented in [5], which describes various technologies and methods applied in the machining of this steel group, with particular emphasis on challenges encountered during experimental research. Copper- and sulfur-enhanced free-machining steels have received particular attention because they improve machinability without significantly compromising corrosion resistance, whereas elements such as lead, selenium, and tellurium are limited due to health and environmental concerns.

Technical surfaces are those surfaces of machine parts that have been obtained by processing with chip removal or with one of the processes without removing material. During the processing and exploitation of machine parts, they are exposed to the effects of various types of loads, such as, e.g., mechanical, thermal, electrical, chemical or biological (combinations are possible). However, mechanical and chemical loads are the most significant, and their frequent consequence is abrasion (wear) of parts and corrosion. Technical surfaces are not ideally smooth geometric surfaces separating two media, but are, from a microscopic point of view, rough surfaces characterized by a series of irregularities of different sizes, shapes, and arrangements. The consequences are methods of machining or processing with chip removal, or methods of machining or processing without removing material [6].

Surface roughness is the small irregularities on the surface of a material caused during manufacturing or machining (Figure 1). These micro-irregularities, which can usually be seen under magnification, are a result of cutting, grinding, or other material removal procedures.

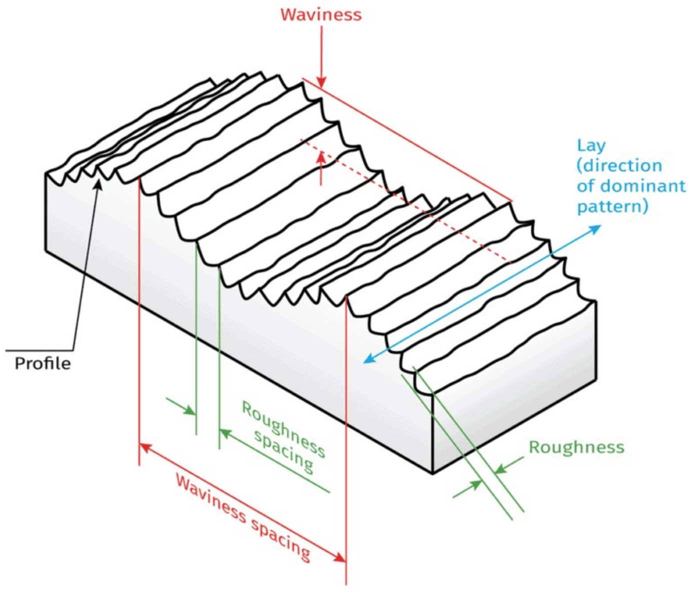


Figure 1. Surface roughness [7]

Surface roughness affects [8, 9]:

- wear resistance of parts. The rougher the surface, the smaller the effective contact area between the mating surfaces, and the higher the pressure, the faster the wear.
- fatigue strength of parts. There are large wave depressions on the surface of the rough parts, which are susceptible to stress concentration as notches and sharp-angled cracks, which affect the strength of the fatigue parts.
- corrosion resistance of parts. A rough surface can easily cause corrosive gas or liquid to penetrate the inner layer of the

metal through micro-grooves on the surface, resulting in surface corrosion.
- on the impermeability of parts. Rough surfaces cannot be closely fitted, and gas or liquid can leak through the gap between the contact surfaces.
- contact stiffness of parts. Contact stiffness is the ability of the part's connecting surface to resist contact deformation under the action of an external force. The stiffness of the machine largely depends on the contact stiffness between the parts.
- parts measurement accuracy. The surface roughness of the measured surface of the parts and the measuring surface of the measuring tools will directly affect the measurement accuracy, especially in precision measurement.

In addition, surface roughness has various effects on the coating, thermal conductivity, and contact resistance, reflection and radiation performance, resistance to liquid and gas flow, and current flow on the conductor surface [8].

For the roughness to be examined with a view to identifying the conditions under which she would be moving in the permitted limits, the roughness itself must be defined. The roughness parameters are defined in the center line system (M-medium system), where the center line represents the baseline of the nominal profile. The center line is determined so that within the limits of the reference length l, the square deviation of the profile (y_1, y_2, ..., y_n) is minimal.

The following parameters (Figure 1) can be defined for the machined surface profile [10]:
- the maximum height of the irregularities (R_{max}) as the distance between two parallel planes which, within the limits of the reference length, touch the highest and lowest point of the profile and are parallel to the center line;
- mean arithmetic deviation of profile height (R_a) as the mean arithmetic magnitude of distance of the absolute values of all points of the effective profile within the limits of reference length:

$$R_a = \frac{1}{l}\int_0^l y \, dx \qquad (1)$$

- mean height of the irregularities (R_z), as the difference between the arithmetic mean of the five highest and five lowest points of the profile within the limits of the reference length, measured from an arbitrary straight line parallel to the center line:

$$R_z = \frac{(R_1+R_3+\cdots+R_9)-(R_2+R_4+\cdots+R_8)}{5} \qquad (2)$$

The basic roughness criterion is R_a, while R_{max} and R_z are additional criteria.

2. NONMETALLIC INCLUSIONS

In order to produce steels with the best machinability, such as X8CrNiS18-9, a number of inclusions with a carefully designed composition are required [11].

Manganese sulphide inclusions tend to elongate in the rolling direction, and elongated manganese sulphide inclusions are less desirable from a machinability standpoint than globular manganese sulphide inclusions. Also, from a machinability standpoint, smaller manganese sulphide inclusions are considered less desirable than larger inclusions [12].

Non-metallic inclusions adversely affect many properties sensitive to the continuity of the steel structure, while they have little or no effect on other properties [13].

The presence of inclusions also affects the machinability of the steel; the hard oxides exacerbate, and the soft manganosulphides improve the machinability [14].

3. EXPERIMENTAL RESEARCH AND TEST RESULTS

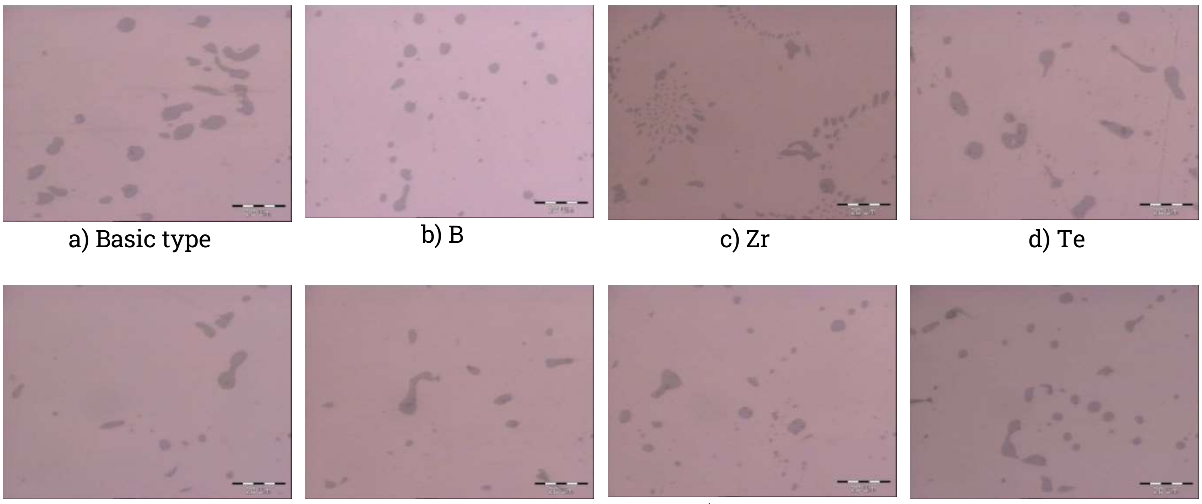
The melting and casting of austenitic stainless steel X8CrNiS18-9 was carried out in a vacuum induction furnace with a capacity of 20 kg, with a maximum power of 40 kW, and is located at the Institute "Kemal Kapetanović". Eight meltings were done. The first melt was a basic type of austenitic stainless steel X8CrNiS18-9, without any modifiers. Subsequently, in the next seven melts, the composition with the corresponding contents of boron, zirconium, and tellurium was modified. Each of the above elements was added independently, then in combination with two, and finally with all three alloying elements. Chemical analysis of the eight melt variants is given in Table 1.

Table 1. Chemical analysis of melt variants [15]

Type of X8CrNiS18-9	Chemical composition (%)									
	C	Si	Mn	P	S	Cr	Ni	B	Zr	Te
Basic type	0.03	0.42	0.61	0.021	0.18	18.3	9.4	–	–	–
B	0.05	0.47	0.66	0.021	0.19	18.5	9.5	0.004	–	–
Zr	0.04	0.35	0.75	0.021	0.17	18.8	9.4	–	0.016	–
Te	0.05	0.40	0.80	0.010	0.16	18.9	9.3	–	–	0.033
B and Zr	0.04	0.49	0.69	0.012	0.17	18.5	9.1	0.004	0.009	–
B and Te	0.04	0.35	0.78	0.011	0.18	18.8	9.3	0.004	–	0.039
Zr and Te	0.03	0.47	0.72	0.012	0.18	18.5	8.9	–	0.007	0.040
B, Zr, and Te	0.04	0.44	0.78	0.012	0.19	17.1	9.3	0.006	0.012	0.042

3.1 Metallographic testing of cast samples

All ingots are subjected to heat treatment: solution annealing – heating to 1050 °C, followed by rapid cooling in water. After the heat treatment, samples were taken next to the ingot head for metallographic testing of the cast state. The imaging of samples under a specific magnification (x50) was performed on an Olympus PMG3 type optical microscope, and one image was given for each sample (Figure 2). The figures show inclusions of average size, while Table 2 also lists individual inclusions that are significantly larger than average.



a) Basic type b) B c) Zr d) Te

e) B i Zr f) B i Te g) Zr i Te h) B, Zr i Te

Figure 2. Microstructure of all melt variants for the casted state [15]

Subsequently, an analysis of the content, size, and distribution of the nonmetallic inclusions in the unetched state was performed, and the results of the tests are given in Table 2.

Table 2. Results of metallographic testing of casted samples [15]

Melt variants	Size of sulphide inclusions (μm)		The total number of inclusions by zones *			Note
			I	II	III	
Basic type	200.1 150.0 90.0 85.0	60.1 55.5 40.8	7	8	4	Lots of small sulphide inclusions; Size porosities 264 i 140μm
B	221.2 125.7	92.8 37.1	7	5	6	Lots of small sulphide inclusions
Zr	115.3 193.1	69.2	3	3	6	Lots of small sulphide inclusions
Te	162.1 110.8	63.1	1	5	7	Lots of small sulphide inclusions
B i Zr	64.0 100.8	150.0 104.0	8	2	8	Lots of small sulphide inclusions
B i Te	31.0 25.0	120.0 28.0	3	1	2	Lots of small sulphide inclusions
Zr i Te	54.0 75.0 102.0	168.0 184.0	4	8	8	Lots of small sulphide inclusions
B, Zr i Te	110.0 90.0	80.0 35.0	4	Small inclusions	Small inclusions	Lots of small sulphide inclusions; Porosity observed

* Zones I, II, and III represent sample areas, so that zones I and III represent the edges of the sample, while zone II represents the central part of the sample.

3.2 Estimation of parameters of roughness

In the Laboratory for Metal Cutting and Machine Tools of the Faculty of Mechanical Engineering in Zenica, the machinability test of the samples was done, based on the estimation of the parameters of roughness. Processing was performed on a universal lathe, PA-501 M Potisje (Figure 3). Maximum speed is 2000 rpm.

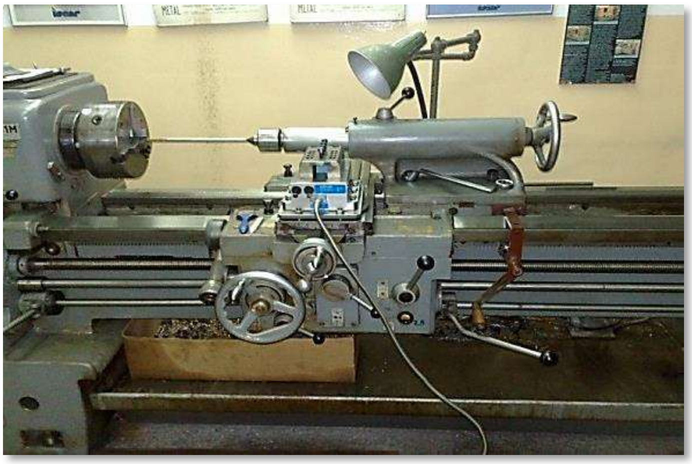


Figure 3. Universal lathe

The turning process itself is defined by three basic elements of the machining regime. These elements have an impact on many factors of this process, such as tool life, chip characteristics, machining time, cutting forces, and the integrity of the machined surface. The basic elements of the machining regime in turning are: cutting speed (n), feed (s), depth of cut (d) [16].

The test was carried out on all samples under the same treatment regime with the following parameters: n = 600 rpm; s = 0.1 mm/r; d = 1.0 mm.

Figure 4. Application of the Perthometer M1 in measuring pieces

The manual perthometer M1 (Figure 4), which was used to measure surface roughness, belongs to the group of devices with a feeler and works on the contact principle. The action between the needle and the measuring disc plays a key role and affects the quality of surface measurement tasks. The results of the surface roughness test, the roughness parameters R_a, as its reference parameter, for various steel types of X8CrNiS18-9, are given in a diagram in Figure 5.

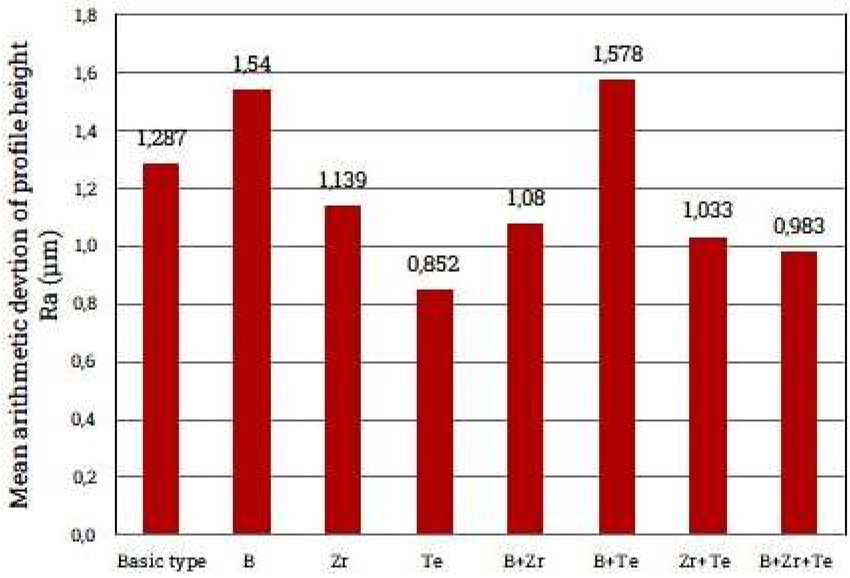


Figure 5. Diagram of the roughness parameter R_a [14]

When it comes to the influence of microalloying elements on surface roughness, ie. the mean arithmetic deviation of profile height R_a, as its reference parameter, we can conclude that in the melts microalloyed with only one element, the most favorable effect was observed in the melt microalloyed with tellurium, which overall represents the best variant in terms of reduction of surface roughness (parameter R_a). In melts microalloyed with combinations of two and with all three alloying elements, the most favorable effect was observed in the case of the melt microalloyed with all three alloying elements.

Melt microalloyed with boron, and boron and tellurium has a marked increase in surface roughness (parameter Ra), so it can be concluded that the most negative effect was observed in the melt microalloyed with boron and tellurium. All other variants reduce the value of the parameter Ra (surface roughness), which has a positive effect on machinability compared to the melt without the addition of alloying elements.

4. CONCLUSIONS

This work aims to determine the influence of microalloying elements boron, zirconium, and tellurium, and nonmetallic inclusions on the roughness of austenitic stainless steel X8CrNiS18-9.

After the tests, it is possible to draw the following conclusions:

- The main types of inclusions in this steel are manganese sulphides.
- The influence on the shape and size of non-metallic inclusions is particularly shown by zirconium and tellurium.
- The addition of tellurium to zirconium and boron improves the globularization of austenitic stainless steel X8CrNiS18-9; in this respect, tellurium is particularly dominant.
- Overall, the best variant in terms of reduction of surface roughness (parameter R_a) is melt microalloyed with tellurium.

Conflicts of Interest

The authors declare no conflict of interest.

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