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# STEEL FOR MECHANICAL APPLICATIONS: MACHINABILITY EVALUATION OF THREE SIMILAR MEDIUM-CARBON ALLOYS

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**Abstract.** *This study evaluated the machinability in turning of three different medium-carbon steel alloys similar to AISI 1045. Two of these alloys were candidates for replacing a former third material. For the two new candidate materials, initial tests had indicated that one of them could provide better chip control, despite their similar processing route and mechanical properties. This study aimed to evaluate machinability differences for the three materials in terms of chip control, chip root analysis and machining forces. A merit index was proposed for quantifying chip control which allowed for summarizing the behavior of all materials in a single indicator. Chip roots obtained with an in-house built quick-stop device allowed for identification of adhesion formation in the new candidate materials which aided on discussing the origin of previously observed differences. Cutting force tests allowed conclusions to be made in relation to the effect of feed rate and cutting speed. By combining all results it was concluded that despite a better chip control observed for one of the new candidate materials at lower speeds, a large gap in terms of machinability still needs to be overcome to meet the same performance as the previously used material.*

**Keywords:** turning, AISI 1045, chip formation, cutting force, quick-stop device

## 1. INTRODUCTION

Machining is a manufacturing process in which material is removed from a workpiece in the form of chips. Conventional machining processes can be classified into two main groups: 1 – cutting with a defined tool geometry and 2 – abrasive processes (Kalpakjian and Schmid, 2010). An industrially relevant machining process that falls under the first group is external turning, in which material removal is achieved by means of rotating the workpiece as the cutting tool edge travels along its surface.

Several factors affect the performance of machining processes. Factors related to the workpiece's geometry and material, fixture system, process parameters, machine tool in general, and cutting tool geometry are only a few that should be taken into account when designing a machining process. The current study focuses on one of these factors, related to the workpiece material, more specifically its machinability.

According to Astakhov (2010) the properties of the workpiece material influence the unit cost of machined parts directly since they affect tool wear and quality of the machined surface. Additionally, for the author, this fact does not gather sufficient attention of researchers since a large number of studies focus on the properties of tool materials and

coatings, while the properties of the workpiece materials are often overlooked. This can be explained by the vast amount of variations of workpiece materials available, tailored according to each specific industrial application. This is even more critical when developing new alloys with minor composition modifications, which is the case of modern low alloy steels. These small changes may cause machinability to differ, resulting in financial impact for large scale productions.

The term machinability may have different meanings according to the specific scenario in which it is used. Generally, it can be defined as the ease with which a material can be machined acquiring an acceptable surface finish (Black & Kohser, 2013). To evaluate the machinability of a material, criteria must be chosen according to the specific application scenario of interest. Common criteria are cutting forces, tool life, surface quality, and chip formation characteristics (Klocke, 2011; Trent and Wright, 2000; Stemmer, 1993). A common shop floor criterion related to chip formation is the occurrence of long washer-type helical chips, which are highly undesirable due to operational hazards and need for process interruption (Maity and Das, 1998). Desirably, automated machining processes should provide adequate chip control in order to maximize productivity (Tirkey, 2009).

This study concerns the machinability of three variations of an alloy similar in composition to AISI 1045. The main objective of this study is, therefore to identify eventual machinability differences and their cause for the three different batches of steels. One of these three materials demonstrates consistent and adequate chip breaking, and consequently good machinability (material C). However, this steel is being replaced by a new kind, with similar properties. Therefore, for this new steel, two batches (A and B) have been selected for investigation. For the three steels, machinability was investigated according to the following criteria:

- Chip form characterization, according to the standard ISO 3685 (1993) and a proposed merit index;
- Metallographic characterization of chip roots obtained with a quick-stop device (QSD);
- Machining forces as measured by a piezoelectric dynamometer.

## 2. EXPERIMENTAL PROCEDURE

Experimental procedure for evaluating the three machinability criteria consisted of designing experiments that, by eliminating external influences, could indicate differences among the materials in terms of: chip form, chip flow at the shear zone, and cutting forces. Tests were performed on a CNC turning center (ROMI® E 280) under dry cutting conditions as to reduce the number of factors to be analyzed. Additionally, disturbances such as chatter and workpiece runout were mitigated by means of adequate fixture and sample preparation. Tool wear was kept below 0.02 mm (maximum flank wear) in order to eliminate any influence. The following sections describe the design of each experiment used to evaluate the three aforementioned criteria.

### 2.1 Chip form characterization

In order to evaluate chip formation, an experiment was designed to replicate typical conditions found in the industrial machining scenario of these materials (Fig. 1). Sample bar dimensions were defined according to the usual diameter of the application of interest (compression rods) while the total length was defined in order to provide rigidity and a test section long enough for stable chip formation (30 mm). A soft jaw fixture was adopted to accommodate the workpiece with minimum radial runout, which was kept below 0.04 mm. A mechanical stop was adopted to avoid slipping of parts along the axial direction and the lathe's tailstock was used to increase rigidity and avoid chatter under all conditions.

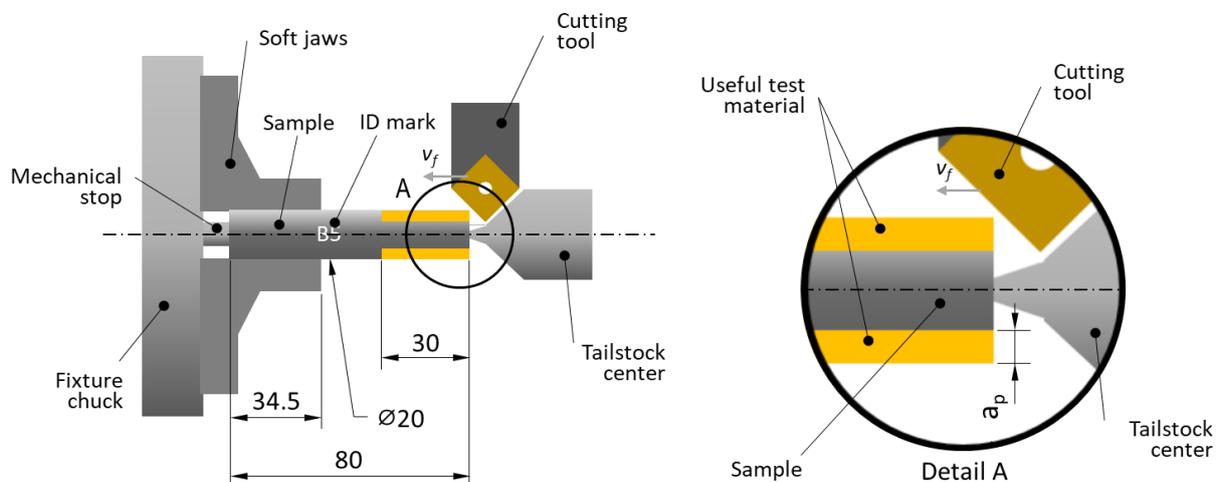


Figure 1. Adopted setup for chip type and form testing. Dimensions in millimeters.

Cutting parameters were selected for a commercial tool, which consisted of an SNMG insert mounted on a PSDNN holder. This geometry was selected because it is more prone to producing chips that are harder to break (Smith, 2008). Inserts had an integrated chip breaker and multi-layer coating commonly used in the application of interest. Selection of parameters occurred based on manufacturer recommendations and process limitations, which are illustrated in Fig. 2. A parameter range that is compatible with the usual industrial process point was covered in order to allow for replicating actual shop floor conditions. Two different cutting speeds were selected,  $v_{c1}$  and  $v_{c2}$ , which replicate a condition in which machine tool spindle speed is limited and a second condition based on the optimal point recommended by the cutting tool manufacturer. An additional reason for selecting this cutting speed range was the fact that both points fall into the constant-power range of the used machine tool (ROMI® E 280). For cutting depth and feed, twelve conditions were selected since these two parameters have a large influence on chip formation (Smith, 2008).

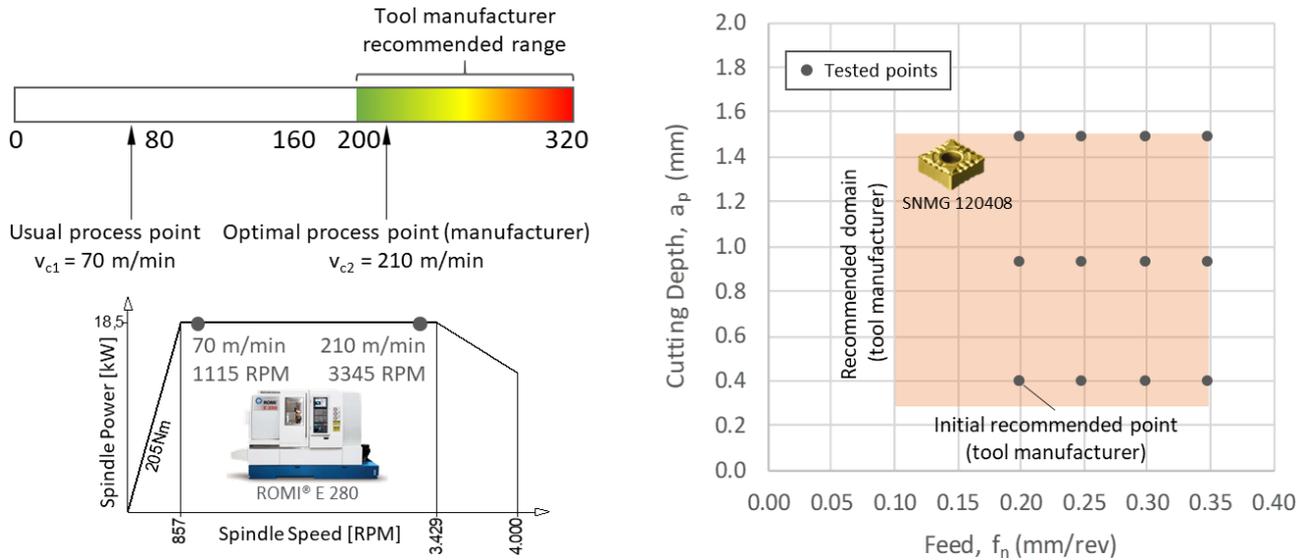


Figure 2. Selected parameters for testing. Cutting speeds (left) and cutting depth and feed (right).

A full factorial design encompassing the three parameters ( $a_p$ ,  $f_n$ , and  $v_c$ ) was adopted for all materials (Fig. 3), which resulted in 72 total runs for evaluating chip formation. All collected chips were photographed under controlled lighting conditions with a camera set to manual-mode (no variation of camera parameters). Photographs were cropped to the same dimensions and chips were classified according to typical forms found in standard ISO 3685 (1993). A merit index was proposed to evaluate chip controllability, which will be described in the results section.

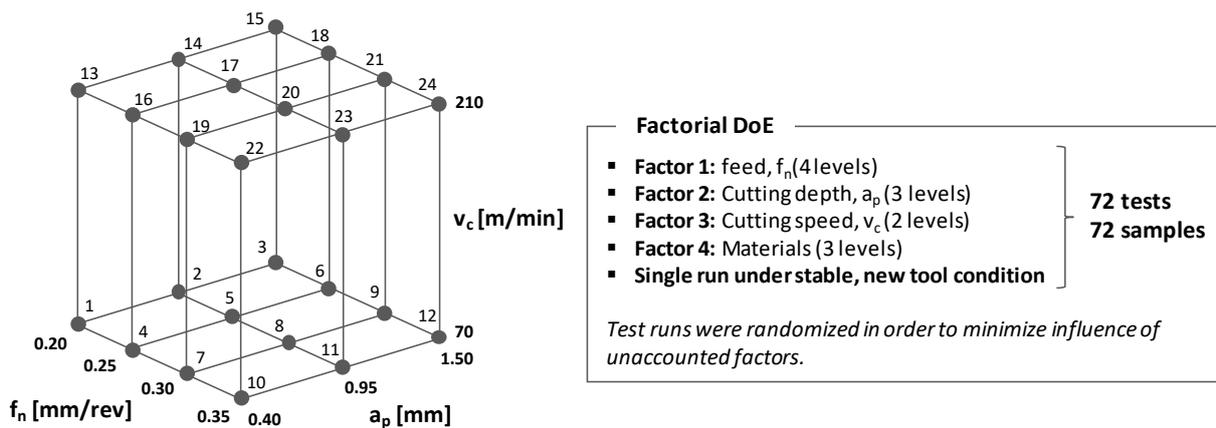


Figure 3. Array of selected parameters for chip characterization and description of factorial design.

## 2.2 Chip root analysis

Figure 4 shows the quick-stop device (QSD) that allows for chip roots of the cutting process to be obtained. According to Lucas (2003), this is a well established procedure to obtain chip roots for analysis. The concept of the adopted device consisted of a pneumatic actuator responsible for activating of a trigger locking mechanism that has the function of

removing the cutting tool from the workpiece in a quick motion (Fig. 4). This motion must be faster than the speed of chip formation, which is directly related to the cutting speed ( $v_c$ ). In view of this fact, cutting speeds lower than the speed of the mechanism should be chosen to allow for the tests to be successful. Ideally, an orthogonal cutting condition is used to produce chips with homogeneous characteristics along the depth direction (Klocke, 2011). For the current test a tool originally intended for radial grooving was used to simulate an orthogonal cutting condition. The tool had a neutral rake angle and no chip breaker geometry was used.

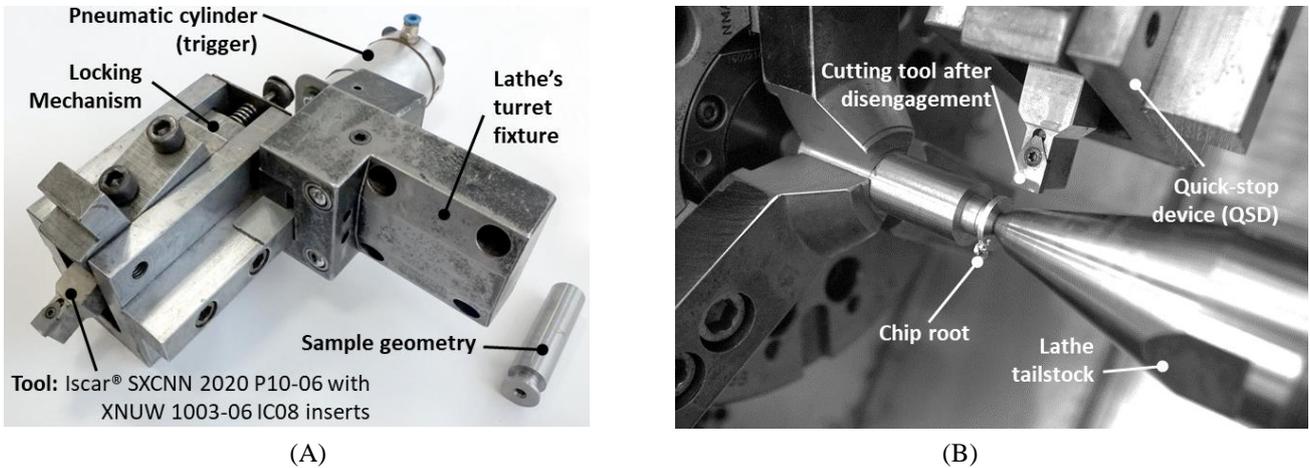


Figure 4. In-house developed pneumatic quick-stop device used in the tests (A) and example of a chip root obtained after disengagement of cutting tool (B).

A similar setup to the one used in chip formation tests was adopted in terms of the used fixture system (Fig. 5A). Sample geometry consisted of a 2 mm wide ring previously prepared on one end of each test specimen (Fig. 5B). Due to the radial feed motion of the cutting process, the width of the test ring is equivalent to the cutting depth ( $a_p$ ). Several tests under varying parameters were run in order to reach a condition that would provide chip roots in a consistent manner. The best encountered parameters, which were adopted for actual testing, are found in Fig. 5B. This low cutting speed was considered adequate since tests aim at producing comparative results for the three evaluated materials.

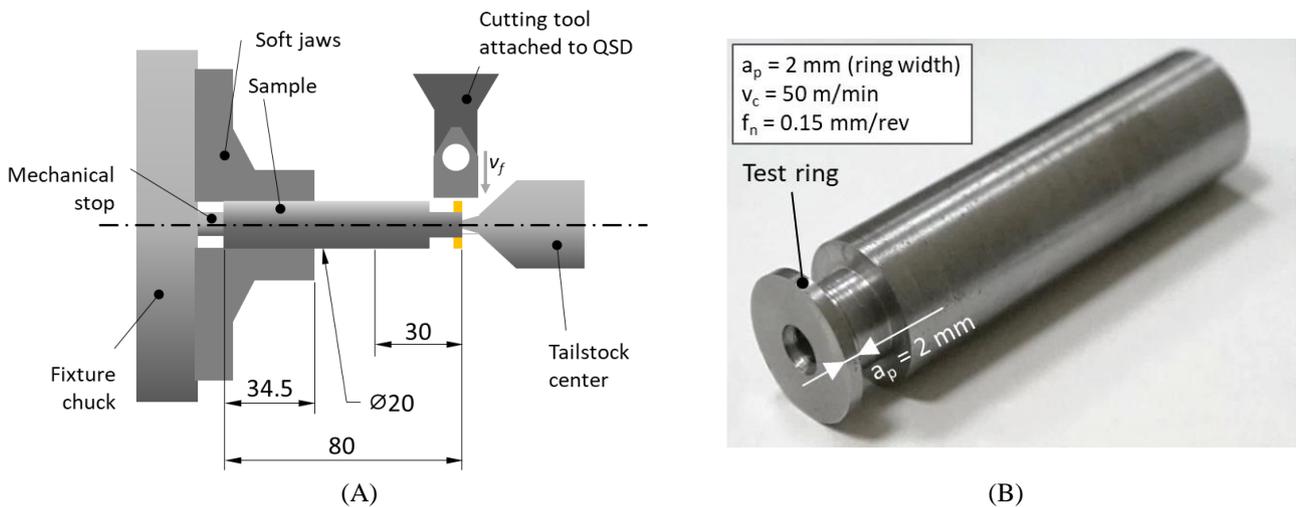


Figure 5. Adopted setup for quick-stop testing (A), specimen geometry and parameters used (B). Dimensions in mm.

### 2.3 Cutting force measurement

For characterization of cutting forces the adopted setup was comprised of a Kistler® Type 9265B / 9441B dynamometer connected to a charge amplifier (Kistler® Type 5070A, maximum sampling rate of 8 kHz) and acquisition software Dynoware® 2825A. The piezoelectric dynamometer was mounted on the lathe's turret by means of an in-house designed fixture plate (Fig. 6).

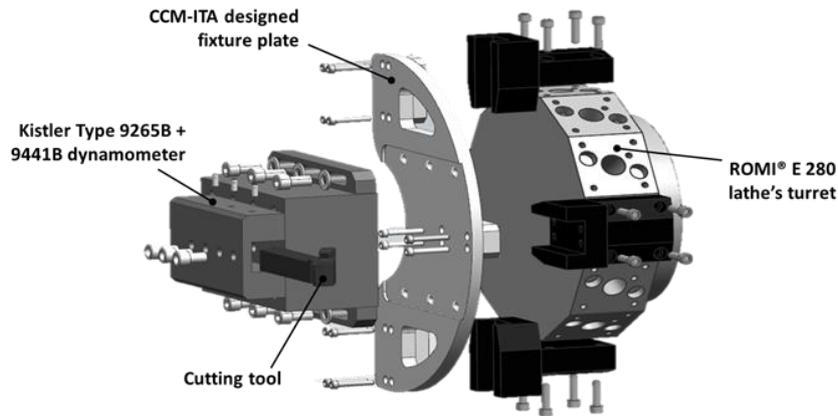


Figure 6. Dynamometer mounted on lathe's turret by means of a fixture plate (Moda, *et al.*, 2017).

For this set of trials, a tailstock was not used due to lack of space when entering the cut with the dynamometer setup. A depiction of the actual test setup is shown in Fig. 7, in which the measured force components are indicated by  $F_p$  (passive),  $F_f$  (feed), and  $F_c$  (cutting). The same cutting tool used for chip formation tests was used for these tests.

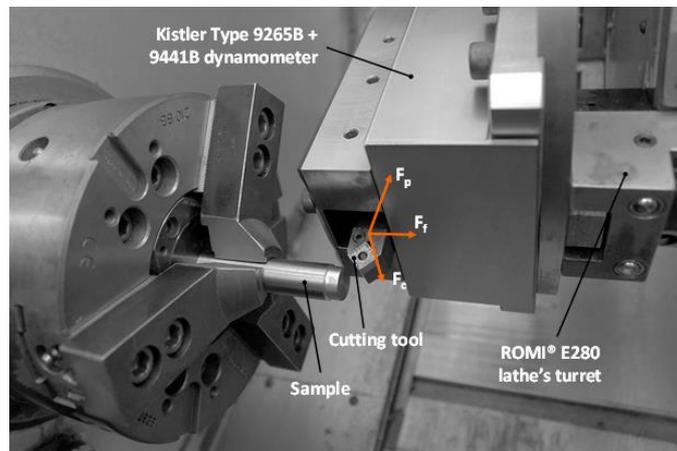


Figure 7. Fixture view of the cutting force measurement test.

This experiment had two main purposes: 1 – evaluating the effect of cutting speed and 2 – evaluating the effect of increasing the cutting section. Therefore, in order to optimize testing time and achieve the desirable results, a customized factorial design was used in which feed was varied for all materials at  $v_{c1} = 70$  m/min (bottom plane in Fig. 8) and a single feed rate was used to evaluate all three materials at  $v_{c2} = 210$  m/min (vertical plane in Fig. 8). In order to reduce the number of runs, cutting depth was fixed at  $a_p = 0.95$  mm for all tests and a total of 3 runs was conducted for each condition, totaling 36 runs. Additionally, in order to minimize the influence of unaccounted factors, tests were run in a randomized fashion. The absence of external bias was confirmed by means of a statistical analysis of residuals.

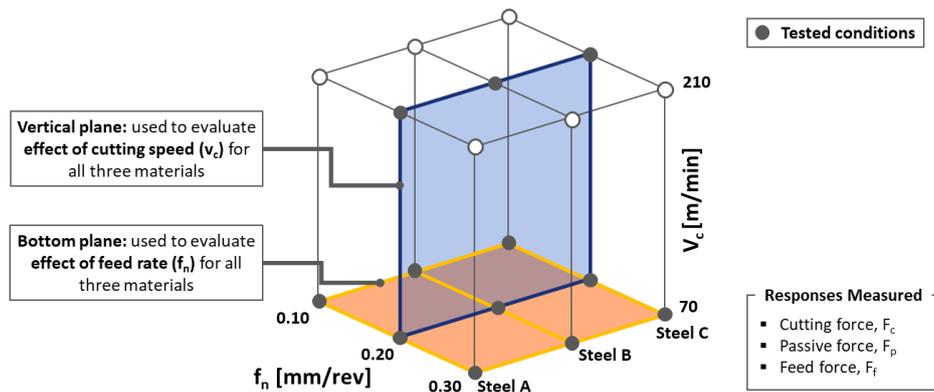


Figure 8. Array of tested conditions depicting purpose of selected parameters and measured responses.

### 3. RESULTS AND DISCUSSION

#### 3.1 Chip form characterization

Chip formation allowed for visual characterization of the chip breaking performance of the three investigated materials. Results were arranged in diagrams such as the one depicted in Fig. 9, which allowed for chips to be classified according to the typically observed forms described in standard ISO 3685 (1993). Once all chips were classified according to their form, these were used to calculate a merit index for each material. Merit indexes (*MI*'s) are widely used in materials science for ranking materials according to a ratio of desirable and undesirable characteristics (Ashby, 1999). For this study, a similar approach that weighs each produced chip form in terms of occurrence (*o*) and form quality (rank - *r*) ranging from 1 (least desirable) to 5 (most desirable) was adopted (Fig. 9 - right). From the equation in Fig. 9B, by considering that 12 conditions were tested for each material, a range from 12 (worst performance) to 60 (best performance) can be expected.

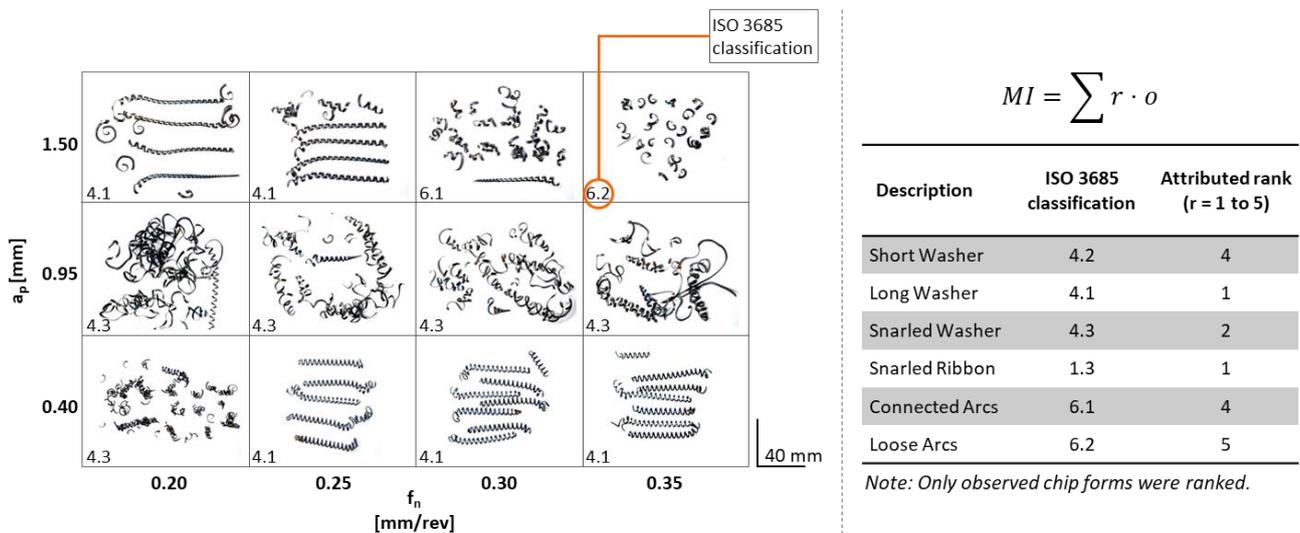


Figure 9. Example of a chip form diagram (left) and merit index (MI) adopted for ranking chip forms (right).

Results of *MI* for all three steels at two different cutting speeds are indicated in Fig. 10. From these results it is possible to notice a significant difference of steel C to the two new batches of material (A and B). A small difference between steels A and B was observed. However, this difference is not enough to judge one material as better than the other in any situation. This statement is based on the fact that chip breakage can occur due to collision between the formed chips and the workpiece or tool, which can be facilitated by selecting a more adequate cutting tool geometry, for instance.

A point to be noted, however, is the smaller difference between materials A and B at higher speeds, which could be attributed to metallurgical characteristics causing different chip formation behavior for each material. On the other side, the larger difference observed between material C and the two candidate materials (A and B) is explained by the shorter chips produced under almost all conditions, which are considered better for the industrial application in question. These shorter chips indicate that chip breakage for material C may occur despite collision with either the cutting tool or workpiece. This characteristic of material C may be a key factor for designing a robust process that is immune to changes in tool geometry or cutting parameters.

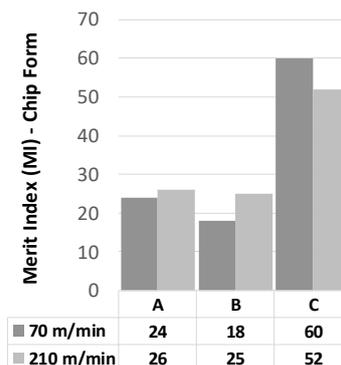


Figure 10. Merit index for chip forms obtained for steels A, B, and C under two different cutting speeds.

### 3.2 Chip root analysis

Chip roots were obtained for all three materials under the same conditions and the obtained micrographs are shown in Fig. 11. Measurements of the primary shear zone angle for the A and B steels produced very similar values ( $17^\circ$  and  $18^\circ$ ) which in turn were slightly larger than material C's shear angle ( $15^\circ$ ). The most relevant results from the analysis of chip roots was the identification of built-up-edge (BUE) formation for materials A and B. BUE formation is corroborated by the higher hardness values found in the adhesion regions indicated in Fig. 11 (over 400 HV). In addition, formation of BUE at these speeds is in agreement with data exposed by Trent and Wright (2000) for a similar condition in which BUE occurs at around  $v_c = 50$  m/min. Trent & Wright (2000) also expose that adhesion formation is influenced by metallurgical characteristics of the workpiece material. These differences in terms of metallurgical phases at a microstructural level can result in smaller or larger propensity to BUE formation.

Cracks were observed for all three materials. However, the only material that formed a complete crack close to the substrate was material C, which also proved to be more prone to chip breaking in chip formation tests. This observation corroborates to explain the smaller chips when turning this material. The cross section of chip roots of materials A and B show cracks farther away from the primary shear zone, which can explain the formation of longer chips but could also be related to the sample preparation procedure used.

Larger hardness values were observed within the chip region of material C, despite the smaller number of measured points, as compared to materials A and B. This indicates larger work-hardening which in turn can be linked to decreased toughness and larger propensity to crack propagation.

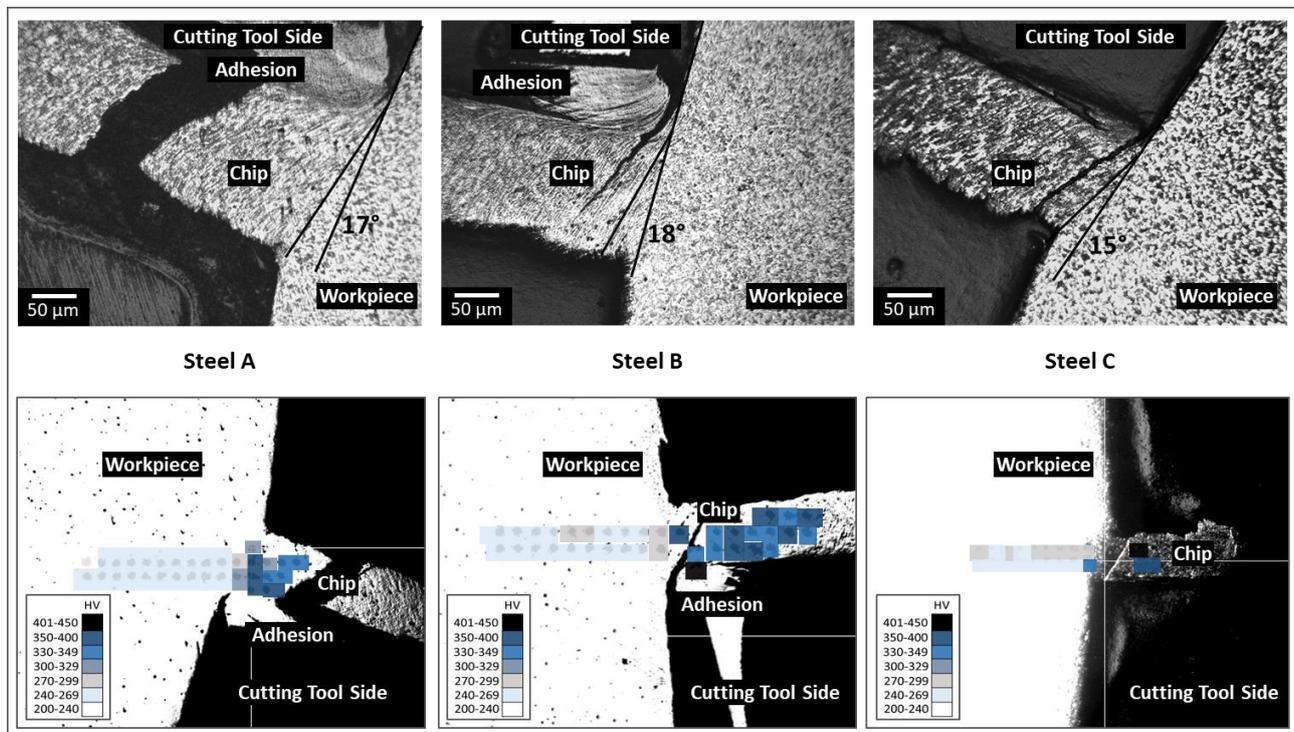


Figure 11. Chip root characterization for all three materials under same condition ( $v_c = 50$  m/min,  $a_p = 2$  mm,  $f_n = 0.15$  mm/rev), showing primary shear plane angle (above) and Vickers micro-hardness of different regions (below).

### 3.3 Cutting force measurement

Cutting force measurements aimed at evaluating differences in tested materials by means of highly accurate measurements conducted with a piezoelectric dynamometer. These were performed under stable conditions for different cutting conditions in a randomized order. In order to verify the validity of measurements an analysis of residuals for the acquired data was conducted. Figure 12 shows the results of this analysis for one of the force components ( $F_c$ ). The analysis demonstrated that: 1 – the obtained distributions are normal, 2 – the order of execution did not influence the results, 3 – no significant outliers were observed and 4 – tests that rely on analysis of variance (ANOVA) can be used since homogeneous variance is observed (versus fits).

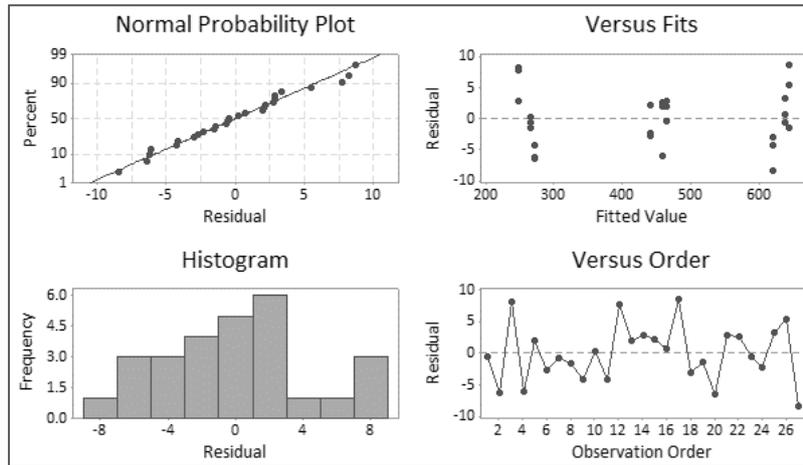


Figure 12. Analysis of residuals for cutting component ( $F_c$ ) of machining force.

Results obtained demonstrated a difference between material C and the other two (A and B) in terms of force at low speeds (Fig. 13). Material C demanded smaller machining forces in all cases. For the lower cutting speed ( $v_c = 70$  m/min) a difference between materials A and B was also observed, which ceased to exist at the higher cutting speed ( $v_c = 210$  m/min), as demonstrated in Fig. 14. The same figure also indicates reduction of cutting forces over the investigated range (70 to 210 m/min), which is in compliance to experimental data found in engineering handbooks (Fischer, 1978).

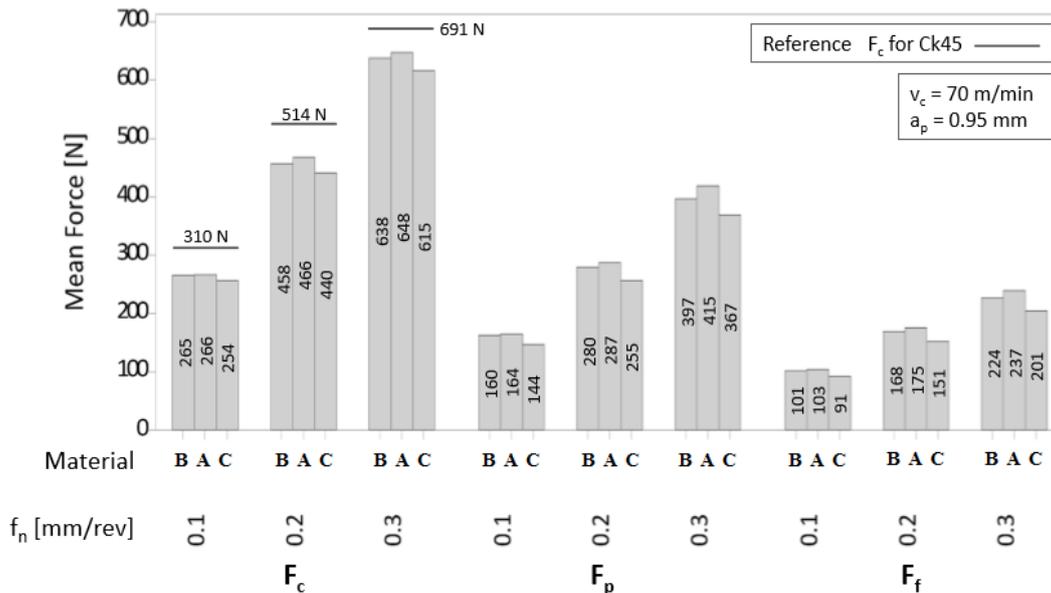


Figure 13. Analysis of the cutting forces measured at  $v_c = 70$  m/min. Reference values for  $F_c$  calculated by Kienzle-Victor model (Fischer, 1978).

In order to evaluate the statistical validity of the differences in cutting forces observed at lower and higher speeds a pairs comparison test (Tukey's) was used under a confidence interval of 95% (Montgomery, 2006). The test indicated that materials A and B are in fact different in terms of machining force at the low cutting speed but not at the higher speed (Fig. 15). As for material C, it can be stated that it is statistically different from the other two materials (A and B) in terms of machining forces under all tested conditions.

As exposed by Klocke (2011), occurrence of adhesion at the tool-workpiece interface has a tendency to occur at lower cutting speeds, which explains the higher forces observed for all materials at these speeds. The adhesion phenomenon becomes insignificant at higher speeds, which would explain the converging force values at higher speeds for materials A and B. Formation of BUE was observed in chip roots of the A and B materials at 50 m/min, as previously exposed, which serves as additional evidence for explaining this behavior.

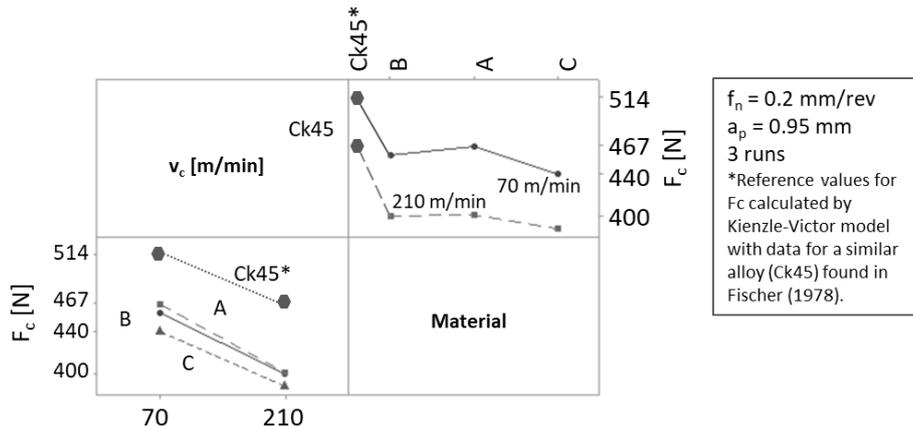


Figure 14. Cutting force as a function of cutting speed for the tested materials and estimated reference value for a material with similar application (Ck45).

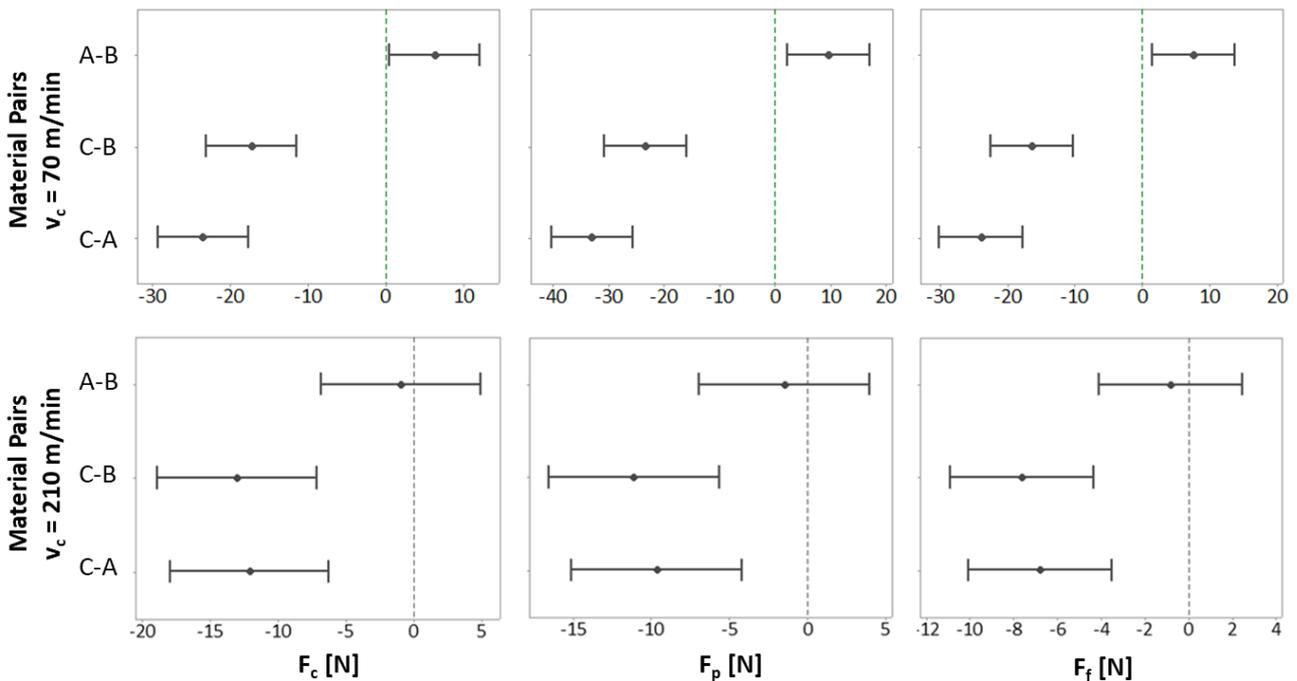


Figure 15. Tukey's test for comparison of pairs applied to machining force results under a low and high cutting speed. If the horizontal lines do not cross 0 N line a considerable difference between materials exists in statistical terms. The adopted confidence interval was 95%.

#### 4. CONCLUSION

By combining results from the three machinability criteria (chip form, chip root and machining force) it was possible to conclude that all materials are different in terms of chip formation at low speeds ( $v_c = 70$  m/min). However, at higher speeds ( $v_c = 210$  m/min), only material C is different from materials A and B since the behavior of the latter two becomes equivalent. Material C demonstrated considerably higher machining performance in terms of chip control under all conditions.

The observed difference between materials A and B at lower speeds can be attributed to adhesion formation, which was observed in chip roots of both materials. In turn, small differences in adhesion behavior for the two materials can be an influencing factor in chip control and machining force, which explains the slight differences observed for materials A and B at  $v_c = 70$  m/min.

The proposed merit index ( $MI$ ) for evaluating chip control can be replicated in future studies, thus allowing for chip breaking performance to be evaluated by means of a more objective performance indicator. However, a standard ranking of chip forms needs to be established for this to become a widely adopted method. In addition, the procedure adopted for

analyzing force data allowed for statistically relevant statements to be made, which can be readily replicated to similar machinability tests.

The considerable difference in performance between the new candidate materials (steels A and B) and the material to be replaced (steel C) needs to be investigated in terms of metallurgical aspects. This further investigation may allow a better performing alloy to be designed thus reducing or eliminating the observed performance gap.

## 5. ACKNOWLEDGEMENTS

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