

COB-2023-0944

MACHINABILITY EVALUATION OF FREE-CUTTING STEELS WITH BISMUTH ADDITIONS BY CONSTANT PRESSURE TEST IN DRILLING PROCESS

João Paulo Luiz Grisotto Alves

Eduardo Sigler Junior

João Batista Ribeiro Martins

Mariane Gonçalves de Miranda Salustre

Marcelo Bertolete Carneiro

Patrícia Alves Barbosa

Federal University of Espírito Santo, Mechanical Engineering Department, 29075-910, Vitória/ES, Brazil

joao.l.alves@edu.ufes.br; eduardo.sigler@ufes.br; jbmartins2008@gmail.com; mariane.miranda@edu.ufes.br;

marcelo.b.carneiro@ufes.br; patricia.a.barbosa@ufes.br

Abstract. Free-cutting steels are defined by the element alloying additions that interrupt the matrix and facilitate machining, with sulphur and lead as the main elements. In the automotive industry, its application is known to increase productivity and reduce costs. However, the addition of lead presents several adversities, and its use has been banned in several countries. Alternatively, “friendly” free-cutting steel developments are replacing lead with bismuth. In this sense, this work aims to evaluate the machinability of different free-cutting steels, coded as: Steel A (without Pb/Bi), Steel B (with Pb/Bi), and Steel C (with Bi). Short-duration ranking machinability test in drilling process was performed, following 2³ statistical design of experiments. Test conditions were varying in two levels for spindle speed, applied load, and material. Drilled hole length (L_f), and chip characteristics were the machinability criteria evaluated. L_f results indicate that Steel C had better machinability at a higher applied load for both spindle speeds. Steel B had better machinability at a lower load for both speeds. Pb/Bi additions to free-cutting steel contributed to chip embrittlement, however, only the Bi addition showed tendency to longer and snarled chip formation.

Keywords: machinability, drilling process, free-cutting steel, bismuth, lead

1. INTRODUCTION

Machinability is defined as a technological index that characterizes the material behavior during cutting process. It is commonly understood as the diagnosis of the difficulty or ease degree of machining the material under evaluation. However, machinability is not treated as a physical constant or an intrinsic property of the material, in fact, its evaluation implies an examination of all aspects of the machining system (Pollet-Villard, 2006; Trent and Wright, 2000; Yashin et al., 2005). One way to access the material machinability response is through the short-term machinability tests. Short-term machinability tests or ranking tests indicate the relative machinability of two or more workpiece-tool pair for a given set of cutting conditions.

The constant pressure test is a short-term machinability rating test that can be carried out by drilling process through an adapted drilling machine. It consists of applying a constant feed force during a fixed cutting time, followed by measuring the drilled hole length (or feed length – L_f) in the workpiece material under investigation. According to Mills and Redforg (1983), the constant pressure test has been particularly useful for evaluating the relative merits of free-cutting steels.

Free-cutting steel is known to increase productivity and reduce costs compared to other steels' grades. It is applied mainly in automotive industry for mass production parts requiring rapid metal removal, such as hydraulic parts of gear box units of automobiles, crankshafts, connecting rods, spark plugs, screws (Zivkovic et al., 2011). This grade of especial steels is defined by the element alloying additions that, alone or forming compounds, interrupt the matrix and facilitate machining, with sulphur and lead as the main elements (Kurka et al., 2022). However, the addition of lead presents several adversities, and its use has been banned in several countries owing to its toxicity to the environment and human beings (Hashimura, 2007; Luiz and Machado, 2008; Watari et al., 2017). Alternatively, “friendly” free-cutting steel developments are replacing lead with non-toxic alloying elements, such as bismuth, without reducing the machinability with acceptable degrees on environmental effect and cost of production (Hashimura, 2007; Zivkovic et al., 2011; Xie et al., 2022).

In this sense, this work aims to evaluate the machinability of three different free-cutting steels, named as Steel A (without Pb and Bi), Steel B (with Pb and Bi) and Steel C (with Bi), by constant pressure test in drilling process.

2. MATERIALS AND METHODS

The materials investigated in this work are three different free-cutting steels, coded as Steel A, without Pb and Bi additions; Steel B, with Pb and Bi additions; and Steel C, with only Bi additions.

Figure 1 presents a flowchart of the main points of the methodology. The materials were evaluated according to their microstructure characterization and Vickers hardness analysis and their machinability using criteria related to drilled hole length, and chip characteristics.

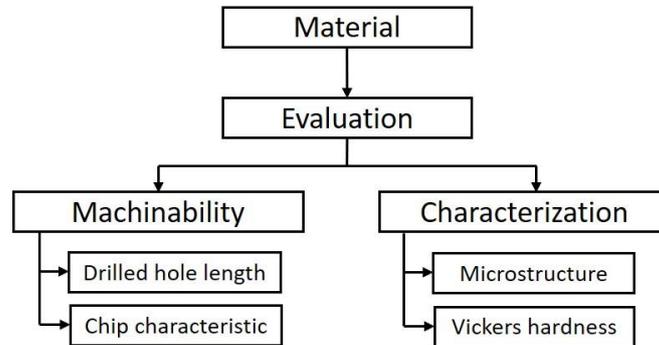


Figure 1. Flowchart of the methodology.

Samples of transverse and longitudinal sections of each material were metallographically prepared and etched by Nital 2%. Microstructural characterization was evaluated by optical microscopy. Vickers Hardness tests were performed according to ASTM E92 (2017) applying a load of 30 kgf for 10 s.

Short-term machinability response by constant pressure testing in drilling process was carried out on an adapted Kone KM32 column drilling machine following a 2³ full statistical design of experiments. Spindle speed, applied load and material were varied at two levels as shown in Table 1. Cutting time was kept constant in 15 s. A 10 mm diameter Dormer A-002 HSS – DIN 388 drill, with 118° point angle and 20-35° helix angle (λ), was the cutting tool used. Figure 2 shows the drill features.

Table 1. Experimental design of two-level input factors.

Factor	Level (+)	Level (-)
Spindle speed, RPM	1150	840
Applied load, kgf	10	5
Material	Steel (A-B)	Steel (B-C)

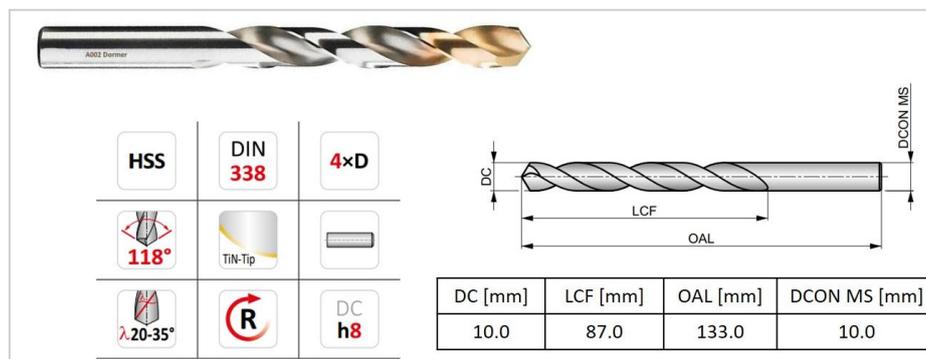


Figure 2. Dormer A-002 drill features (Dormer Pramet, 2023).

Drilled hole length (L_f), and chip characteristics were the machinability criteria evaluated. L_f was measured with a Mitutoyo digital caliper with measuring range of 150 mm and resolution of 0.01 mm. Chip samples were collected during tests and visually classified by type and shape according to ISO 3685 (1993).

3. RESULTS AND DISCUSSION

3.1 Microstructure

Figure 3 (a) shows the transverse section of Steel A (without Pb/Bi), where a pearlitic matrix and circular inclusions of manganese sulfides (MnS) can be observed. Figure 4 (b) and (c) shows the microstructure of transverse sections of Steels B (with Pb/Bi) and C (with Bi), respectively. It is observed that both have ferritic matrix, in the former, the dark grey circular inclusions are formed by MnS+Pb/Bi, and in the later, the inclusions are MnS+Bi. Figure 3 presents the longitudinal section of the samples, in which the inclusions are stretched in the lamination direction.

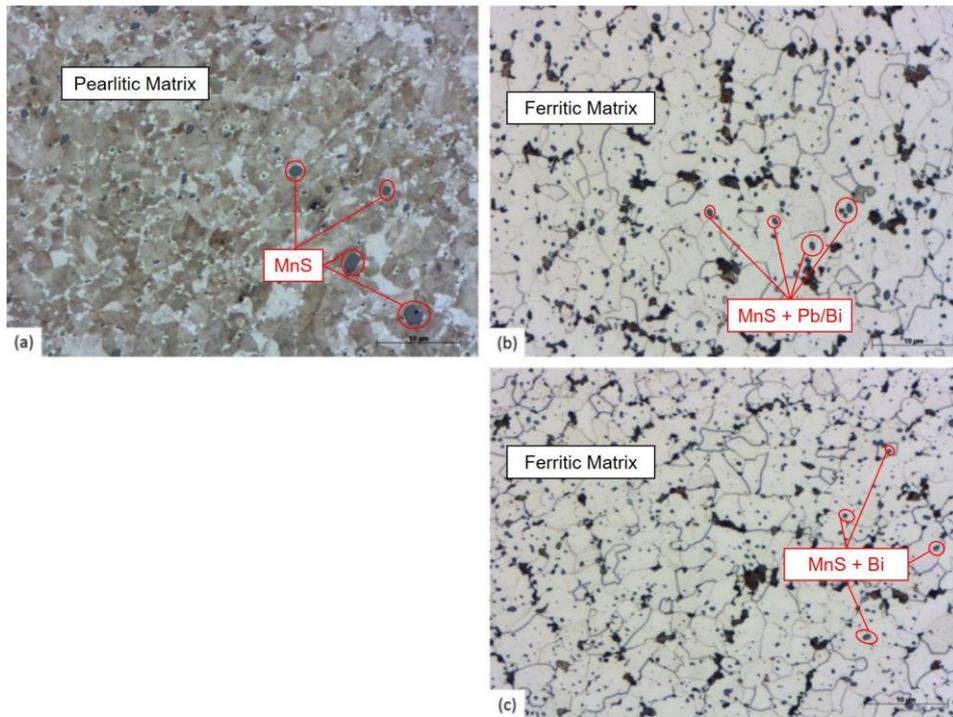


Figure 3. Microstructure of transverse section etched by Nital 2%. (a) Steel A. (b) Steel B. (c) Steel C.

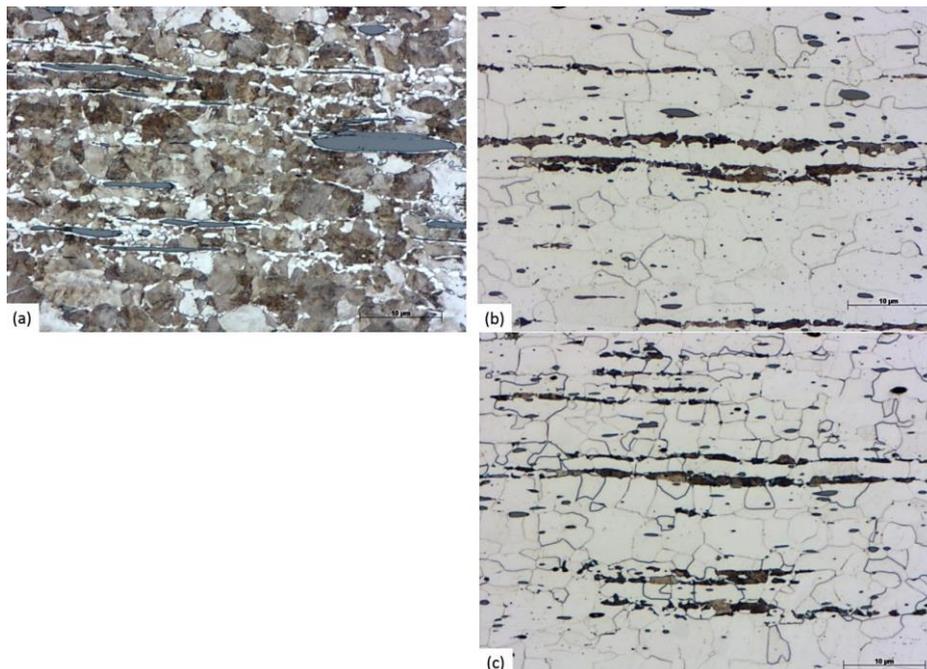


Figure 4. Microstructure of longitudinal section etched by Nital 2%. (a) Steel A. (b) Steel B. (c) Steel C.

3.2 Vickers Hardness

Table 2 shows the results for Vickers hardness number (average HV30) for transverse and longitudinal sections of the evaluated materials.

Table 2. Vickers hardness number (HV30).

Material	Transverse	Longitudinal
Steel A	328.7±6.1	317.0±4.5
Steel B	188.3±5.3	185.0±4.9
Steel C	180.5±6.4	180.6±4.1

Table 3 presents analysis of variance (ANOVA) at a significance level of 5% for the Vickers hardness number, considering the different materials and sample sections. The main variables, Material and Section, besides their interaction were statistically significant ($p < 0.05$ or 5%).

Table 3. Analysis of variance (ANOVA) for the Vickers Hardness number.

Factor	Variance	F	p
Mean	3174046	102428.2	0.000000
Material	129413	4176.2	0.000000
Section	372	12	0.001055
Material x Section	187	6	0.004299

Figure 5 (a) shows that there is a significant difference in the hardness values among materials, including between Steels B and C. On average, the Vickers hardness number for Steel A is 78% and 84% higher than Steel B and Steel C, respectively, and Steel B is 3% higher than C. Figure 5 (b) shows there is a significant difference in the hardness values between the transverse and longitudinal section for Steel A. An anisotropic behavior, such inference cannot be made for Steels B and C. The Vickers hardness values can be explained by the microstructure phase detection, Steel A has a pearlitic matrix which is harder than a ferritic matrix from Steels B and C.

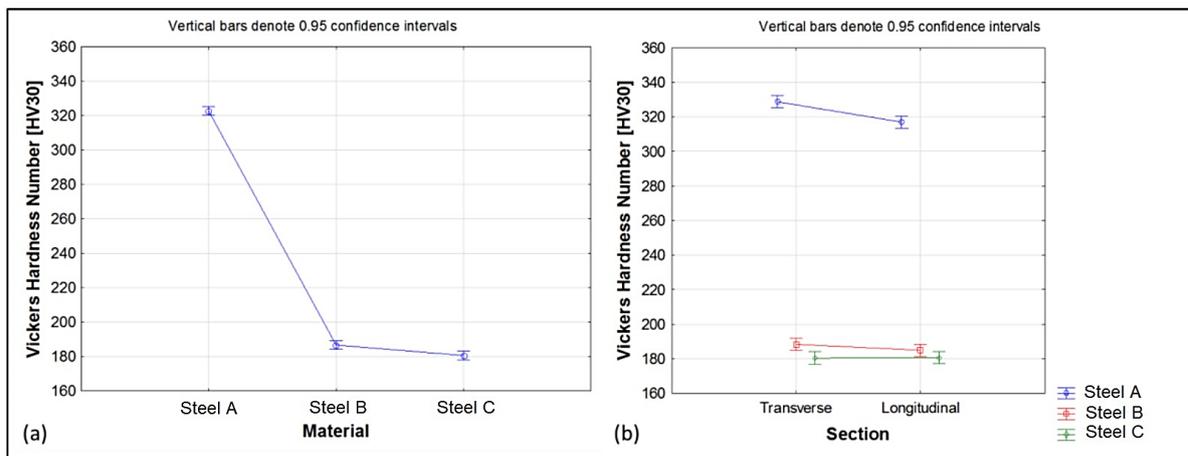


Figure 5. Effects on Vickers hardness number. (a) Material. (b) Material x Section interaction.

3.3 Constant Pressure Test

Figure 6 shows drilled hole length (Lf) average results performed by cutting tool during constant pressure tests in drilling process for materials under evaluation, considering variation of applied load and spindle speed for a constant cutting time of 15s. It can be seen that the three materials behave similarly, increasing drilled hole length with load applied and spindle speed. This result was more pronounced for the highest applied load. This variable is related to feed rate, which is directly proportional to the material removal rate. Therefore, increasing the applied load leads to an increase in Lf. There is difference in machinability among free-cutting steels investigated. Steel A was the material that presented the greatest difficulty in machining, that is, the shorter drilled hole length. Steels B and C were the materials with the best machinability response. For the highest applied load, better machinability of the Steel C was observed, and for the lowest applied load evaluated, Steel B showed the deepest hole machined among the three investigated materials.

These results agree with the literature since the materials machinability is influenced by their chemical composition, microstructure and hardness (Klocke, 2001; Shaw, 2005). Steel A has a pearlitic matrix presenting greater hardness and consequently high strength during machining, while the other two free-cutting steels have a ferritic matrix with lower hardness and therefore easier to machine. Furthermore, lead and/or bismuth additions may have contributed to the improvement in machining performance compared to Steel A.

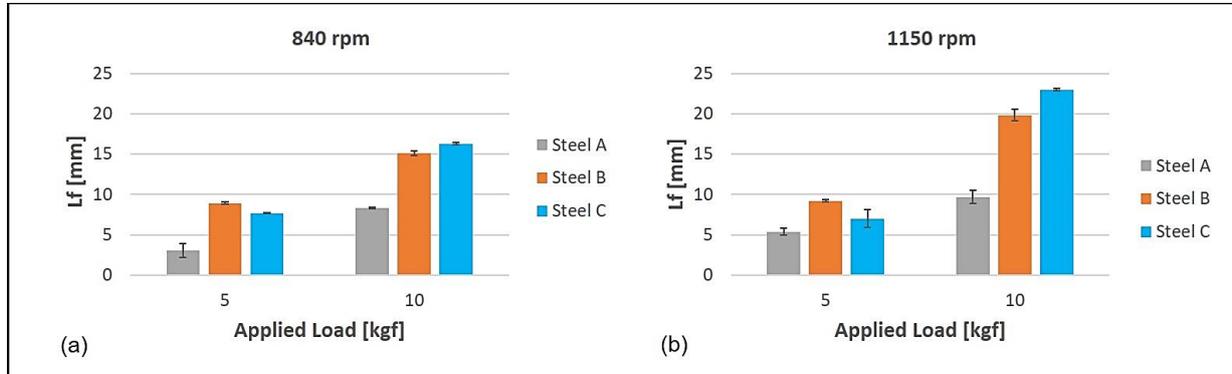


Figure 6. Drilled hole length (Lf) average results as function of applied loads. Spindle speed: (a) 840 rpm and (b) 1150 rpm.

Significance analyses for 2³ full factorial design of experiments were performed comparing the materials two by two (Steel A x Steel B; Steel A x Steel C; and Steel B x Steel C) to statistically confirm the behavior of the materials and evaluated test conditions. These analyses are presented in the following items.

3.3.1 Drilled hole length (Lf) - Steel A (without Pb/Bi) x Steel B (with Pb/Bi)

Table 4 presents the analysis of effects on the drilled hole length for a significance level of 5%. The main variables, Material, Spindle speed and Applied load, as well as Material x Applied load interaction had statistical significance ($p < 0.05$), increasing the hole depth.

Table 4. Analysis of variance (ANOVA) for the Drilled hole length - Steels A and B.

Factor	Effect	Std. Dev.	p
Mean	9.935417	0.205533	0.000000
Material	6.657500	0.411066	0.000000
Spindle speed [RPM]	2.180833	0.411066	0.000058
Applied load [kgf]	6.590833	0.411066	0.000000
Material x Spindle speed	0.354167	0.411066	0.400908
Material x Applied load	1.807500	0.411066	0.000394
Spindle speed x Applied load	0.860833	0.411066	0.051540

Figure 7 (a) presents the influence of Material on Lf. It can be seen that Steel B had higher machinability (twice the drilled hole length) than Steel A, considering the evaluated experimental range. Figure 7 (b) shows the influence of the interaction Material x Applied load, in both cases, when the applied load is increased, the Steel B performs better. At the lowest load, drilled hole length of steel B was 115% higher than Lf machined in steel A, and for the highest load, steel B was 94% superior in drilled hole length compared to steel A.

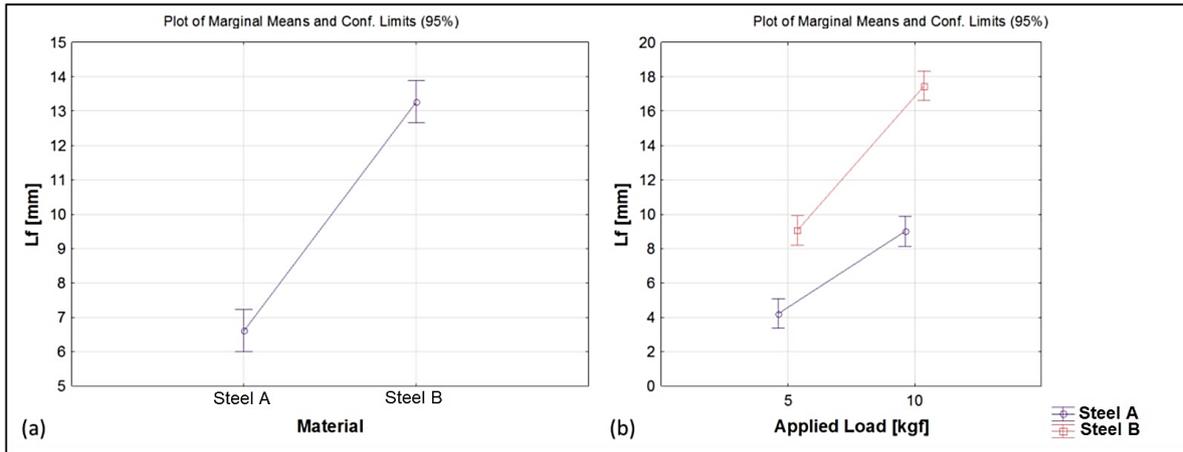


Figure 7. Effects on Lf. (a) Material (Steels A and B). (b) Material x Applied load interaction.

3.3.2 Drilled hole length (Lf) - Steel A (without Pb/Bi) x Steel C (with Bi)

Table 5 presents the analysis of effects on the drilled hole length for a significance level of 5%. The main variables, Material, Spindle speed and Applied load, as well as Material x Applied load and Spindle speed x Applied load interactions had statistical significance ($p < 0.05$), increasing the hole depth.

Table 5. Analysis of variance (ANOVA) for the Drilled hole length - Steels A and C.

Factor	Effect	Std. Dev.	p
Mean	10.04417	0.289385	0.000000
Material	6.87500	0.578771	0.000000
Spindle speed [RPM]	2.42000	0.578771	0.000626
Applied load [kgf]	8.55000	0.578771	0.000000
Material x Spindle speed	0.59333	0.578771	0.319654
Material x Applied load	3.76667	0.578771	0.000005
Spindle speed x Applied load	1.59167	0.578771	0.013666

In Figure 8 (a), Steel C has higher machinability (104% higher) than Steel A. This result may be indicating that the only Bi addition slightly improved the machinability compared to Pb/Bi addition (Steel B), since Steel C showed a better machinability response than Steel B (100%) when compared to Steel A. For the interaction Material x Applied load, Figure 8 (b), in both cases, when the load is increased, Steel C performs better. At the lowest load, it was 74% superior, and at the highest load, it was 118% superior.

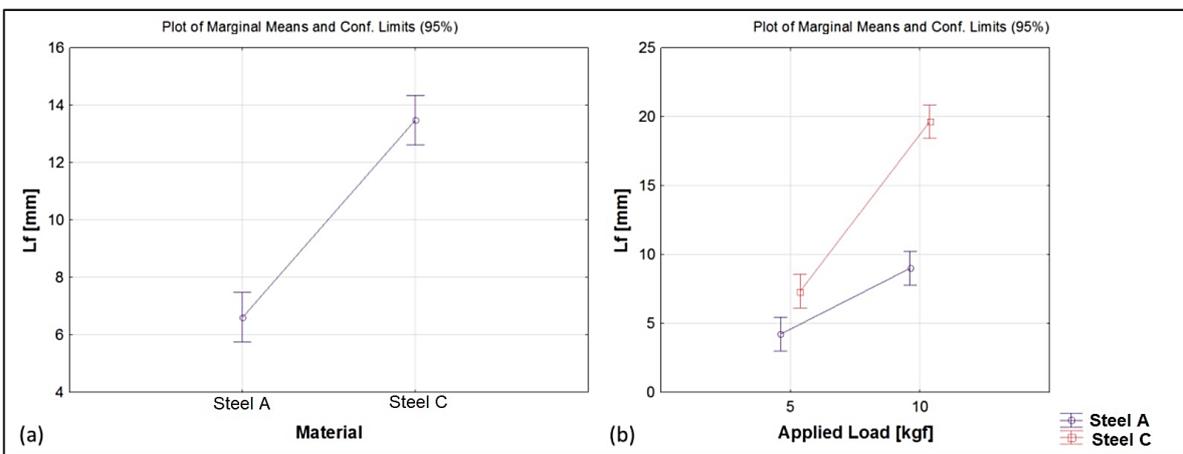


Figure 8. Effects on Lf. (a) Material (Steels A and C). (b) Material x Applied load interaction.

3.3.3 Drilled hole length (Lf) - Steel B (with Pb/Bi) x Steel C (with Bi)

Table 6 presents the analysis of effects on the drilled hole length for a significance level of 5%. Accordingly, the main variables, Spindle speed and Applied load, as well as Material x Applied load and Spindle speed x Applied load interactions had statistical significance ($p < 0.05$), increasing the hole depth. The main variable Material did not influence the response ($p > 0.05$), then, statistically the materials have the same behavior in the experimental range performed.

Table 6. Analysis of variance (ANOVA) for the Drilled hole length - Steels B and C.

Factor	Effect	Std. Dev.	p
Mean	13.37292	0.140173	0.000000
Material	0.21750	0.280346	0.448510
Spindle speed [RPM]	2.77417	0.280346	0.000000
Applied load [kgf]	10.35750	0.280346	0.000000
Material x Spindle speed	0.23917	0.280346	0.405457
Material x Applied load	1.95917	0.280346	0.000002
Spindle speed x Applied load	2.96250	0.280346	0.000000

In Figure 9 (a), no statistical difference can be observed between the materials. Machining performance between Steels B and C were similar, this is, lead and/or bismuth additions might not influence on the machinability when compared with the drilled hole length response. From the Figure 9 (b), at an applied load of 5 kgf, Steel B was 24% superior to the Steel C, however, at an applied load of 10 kgf, Steel C was 12% superior to the Steel B.

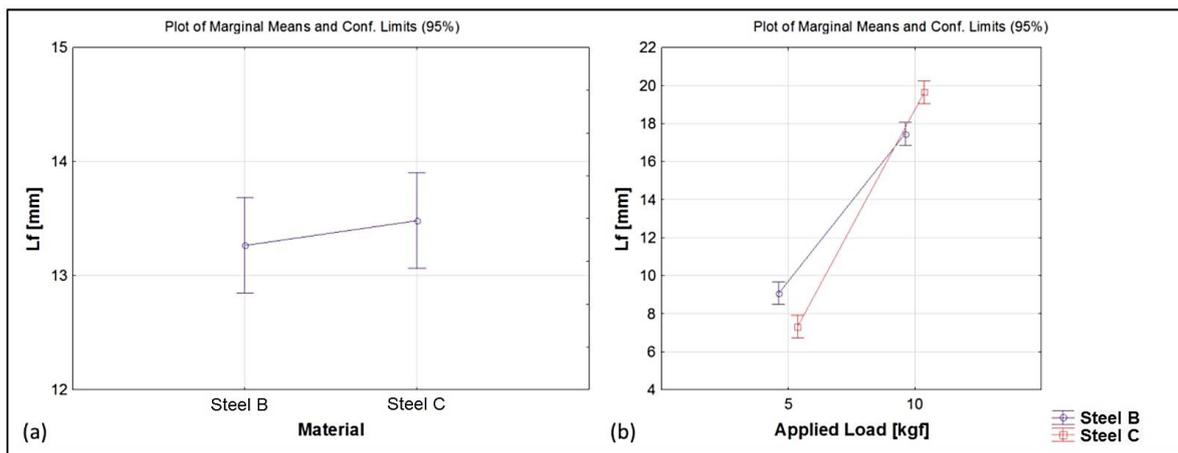


Figure 9. Effects on Lf. (a) Material (Steels B and C). (b) Material x Applied load interaction.

3.4 Chip Characteristic

Figure 10 is a chip diagram-chart with representative steel chip samples collected during constant pressure tests under different test conditions. In general, the materials investigated presented conical helical chips in drilling process. It was observed that higher applied loads tend to make the chips wider. It is also noteworthy that the chips from steels A and C were shorter for the higher applied load. This is related to the higher material removal rate promoted by the increase in applied load, which is associated with feed rate. According to Shaw (2005), feed rate plays an important role in chip control, improving chip breaking with increasing feed rate. Pb/Bi additions (Steel B) can contribute to chip embrittlement, making it shorter, this is more pronounced for the lowest spindle speed and applied load (840 rpm and 5 kgf). On the other hand, the Bi addition (Steel C) showed tendency to longer and snarled chip formation. According to Luiz and Machado (2008) and Kurka et al. (2022), Pb/Bi metallic inclusions promote stress concentration effect into steel matrix. MnS particles, isolated or surrounded by metallic inclusions such as Pb and Bi, promote notch effect, which reduces the apparent shear stress of steel. Additionally, metallic inclusions accommodate strains that reduce the energy required for chip formation.

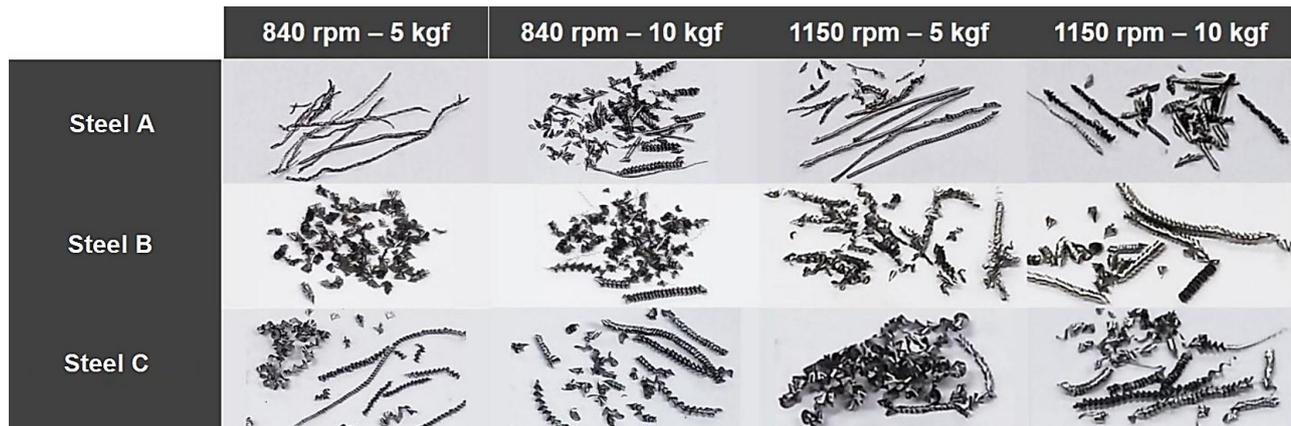


Figure 10. Chip diagram-chart for test conditions.

4. CONCLUSIONS

Steel A has a pearlitic matrix and higher hardness than Steels B e C, which are ferritic matrix steels.

Increasing spindle speed or applied load implies an increase in the feed velocity, consequently a higher material removal rate.

Lead and/or bismuth additions contribute to increase drilled hole length (Lf).

Pb/Bi additions (Steel B) contribute to chip embrittlement, making it shorter. Bi addition (Steel C) showed tendency to longer and snarled chip formation.

5. ACKNOWLEDGEMENTS

We thank CAPES, CNPq, FAPES (grant number 144/2020), Embrapii, and UFES for providing financial support offered to the LabTecMec; and ArcelorMittal S.A. for providing workpiece materials.

6. REFERENCES

- ASTM E92, 2017, “Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials”. ASTM International, West Conshohocken, PA, DOI: 10.1520/E0092-17.
- DORMER PRAMET, 2021. *HOLEMAKING – Catalog*. United States of America, https://5wyuco84ao39w9tsgkmmnx.blob.core.windows.net/cms/DORMER_PRAMET_Holemaking_Catalogue_2021_EN.pdf. Accessed 14 March 2023.
- Hashimura, M., Miyanishi, K. and Mizuno, A., 2007. “Development of Low-Carbon Lead-Free Free-Cutting Steel Friendly to Environment”. *Nippon Steel Technical Report*, Vol. 96. pp. 45–49.
- ISO 3685, 1993 (E), “Tool-Life Testing with Single-point Turning Tools”. ISO, Genève, Switzerland. 48p.
- Klocke, F., 2001. *Machining and machinability*. Encyclopedia of Materials: Science and Technology. Elsevier, Amsterdam. pp. 4683–4688.
- Kurka, V., Kuboň, Z., Kander, L., Jonšta, P. and Kotásek, O., 2022. “The Effect of Bismuth on Technological and Material Characteristics of Low-Alloyed Automotive Steels with a Good Machinability”. *Metals*, Vol. 12, p. 301. doi.org/10.3390/met12020301.
- Luiz, N.E. and Machado, Á.R., 2008. “Development Trends and Review of Free-Machining Steels”. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 222(2). pp. 347-360. doi:10.1243/09544054JEM861.
- Mills, B. and Redford, A.H., 1983. *Machinability of Engineering Materials*. Applied Science Publishers LTD, London and New York, 1 st edition. 174p.
- Pollet-Villard, A., 2006. *Substitution of lead in free-cutting steels*. Ph.D. thesis, Graduate Program in Mechanical Engineering, University of Grenoble, Grenoble, France. 198p.
- Shaw, M.C., 2005. *Metal cutting principles*. Oxford University Press, New York, 2 nd edition. 759p.
- Trent, E.M. and Wright, P.K., 2000. *Metal Cutting*. Butterworth-Heinemann, Boston, 4th ed. 464p.
- Watari, K., Iwasaki, T. and Aiso, T., 2017. “Development of Lead-free Free-cutting Steel and Cutting Technology”. *Nippon Steel & Sumitomo Metal Technical Report*, Vol. 116. pp. 32-37.
- Xie, Jb., Liu, Bb., Wu, Xy. and Fu, Jx., 2022. “Correction to: Distribution of Bi–MnS Inclusions Existing in 1215MS Steels: Correlation with Thermal Physical Coefficient”. *Met. Mater. Int.*, Vol. 28, p. 1314. doi.org/10.1007/s12540-021-01150-z.

- Yashin, Y.D., Soldatkin, S.A. and Chesnokov, P.Y., 2005. “High-Machineability Steels”. *Metallurgist*, Vol. 49 (6), pp. 236-241.
- Zivkovic, D., Štrbac, N., Ekinovic, S. and Begović, E., 2011. “Lead-Free Free-Cutting Steels as Modern Environmentally Friendly Materials”. *Ecologica*, Vol. 18. pp. 451-456.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.