24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1174
EFFECT OF NI CONTENT ON THE HARDENABILITY OF A BANITIC STEEL FOR PROCESSING OF PLASTICS

José Britti Bacalhau
Villares Metals S.A. – Sumaré – SP – Brasil
Programa de Pós Graduação em Ciência e Engenharia de Materiais (PPG-CEM), Universidade Federal de São Carlos (UFSCar), São Carlos – SP, Brasil
e-mail: jose.bacalhau@villaresmetals.com

Túlio Mumic Cunha
Conrado Ramos Moreira Afonso
Programa de Pós Graduação em Ciência e Engenharia de Materiais (PPG-CEM), Universidade Federal de São Carlos (UFSCar), São Carlos – SP, Brasil
e-mails: tuliomumic@gmail.com conrado@ufscar.br

Abstract. *This work deals with an innovative and technological manner in order to develop a new tool steel specifically designed to the manufacture of screws and barrels for plastics processing. The new grade presents greater microstructural homogeneity than the traditional steel DIN 1.8550 widely used in this application. Searching for a grade with superior dimensional stability when compared to DIN 1.8550 steel is also part of this work aiming to reduce distortion on plasticizing components while being manufactured with machining operations.*

Keywords: *Bainitic tool steel, alloying elements, hardenability, microstructure, mechanical properties.*

1. INTRODUCTION

The traditional plastic/polymer processing machines such as extrusion and injection molding equipment use a key component responsible for plasticizing/melting the polymer previously to the forming steps in a mold or die. A steel screw and cylinder also known as barrel are the main pieces of this component which shears the plastic molecules generating heat, mixing the masterbaches with other additives, degassing the raw material and transporting the softened polymer to be processed, see a schematic example of a plastic extruder with a good overview of the plasticizing component in Fig. 1. The main properties of steels used on screws and barrels are wear resistance and tensile strength being the grade DIN 1.8550 hardened to around 28 HRC the most used steel for the manufacturing of this component.

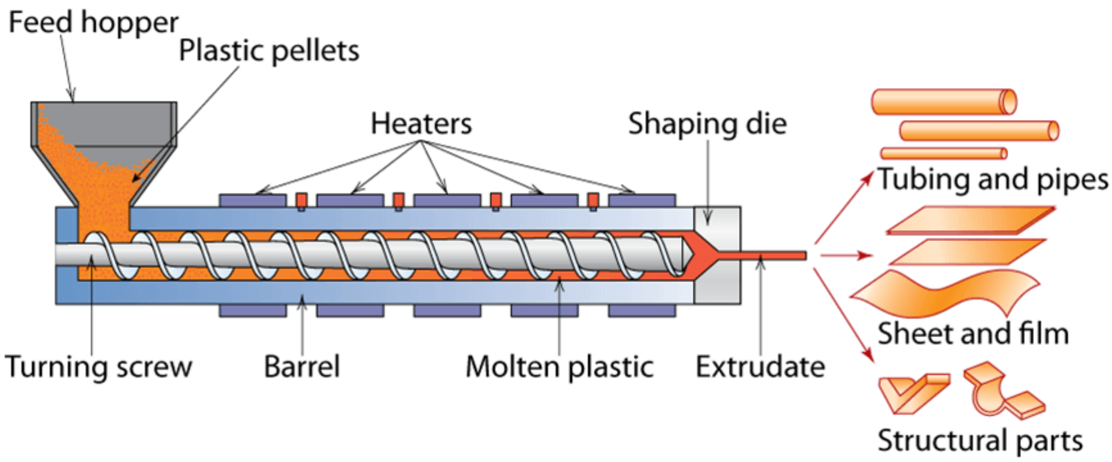

Figure 1. Overview of a plastic extrusion machine with the plasticizing component in evidence. The two main industrial tools in the machine are the screw and the barrel, figure adapted from Roscacil (2017).

The paper presents the effect of Ni content in the chemistry of a new tool steel specifically developed for the manufacturing of screw and barrels, comparing its properties with the traditional DIN 1.8550. Four steel ingots of 55 kg were melted in a pilot scale VIM furnace, three of them with a new proposed chemical composition being the Ni content the only difference between them, also the steel 1.8550 was melted like a reference grade for properties comparison. All ingots were hot forged to bars and cooled at room temperature in fresh air. CCT (Continuous Cooling Transformation) curves of the proposed steels compositions were determined by dilatometry and therefore their hardenability compared between themselves and with 1.8550. Mechanical and microstructural characterization via hardness measurements, impact tests and optical microscopy were also performed. The new steels proposed in this work presented higher hardenability and more homogeneous microstructures than DIN 1.8550. The steel with 1.4% Ni is a good candidate to promote reduction in the manufacturing costs of screws and barrels when compared to the standardized costs of using 1.8550. The main reason is because the new steel should present better machining response thanks to its homogeneous bainitic microstructure, and its bars more dimensional stable related with a superior hardenability. Very low distortions levels and residual stresses are expected in the bars of the new grade, since its high hardenability allows the material to be hardened via air cooling instead of oil or water quenching like 1.8550. Other examples for bainitic steels with similar behavior of high hardenability can be found in published papers from Bacalhau and Otubo (2012, 2015).

2. EXPERIMENTAL PROCEDURE

The chemical composition of the four steel ingots weighing 55 kg each is shown in Tab. 1. A pilot scale vacuum induction melting (VIM) furnace was used to cast the steels; three of them were named like “Experimental Alloy” and the only difference between them is the Ni content. The fourth grade was melted according to the standardized chemistry of DIN 1.8550.

Table 1. Chemical composition of the steels produced in pilot scale. All values are presented in mass percentage and iron balance.

Steel	C	Si	Mn	Cr	Mo	Ni	V	Al
DIN 1.8550	0,35	0,30	0,60	1,70	0,20	1,00	<0,01	0,90
Experimental alloy without Ni	0,20	0,25	1,45	1,55	0,65	**<0,01**	0,07	0,90
Experimental alloy with 0.7% Ni	0,20	0,25	1,45	1,55	0,65	**0,70**	0,07	0,90
Experimental alloy with 1.4% Ni	0,20	0,25	1,45	1,55	0,65	**1,40**	0,07	0,90

After casted these ingots were hot forged at 1260°C with an open die forging press to square bars with 80 mm on side, and cooled down in fresh air to room temperature.

A dilatometer was used to build CCT curves of all proposed steels and therefore their hardenability were quantified and compared to DIN 1.8550. In order to perform the dilatometer tests, cylindrical samples with 3.0 mm of base and 9.0 mm of height from proposed grades were machined. Figure 2 shows in the upper picture an overview of the dilatometer used to determine CCT curves, and in the bottom picture a more detailed perception from the induction system responsible to control the heating and cooling of samples.

The tests were performed under vacuum control. Samples were first heated at a rate of 3.0ºC/s to 900ºC, soaking time of 10 minutes at temperature, and then cooled to room temperature at the following rates: 0.01ºC/s; 0.02ºC/s; 0.05ºC/s; 0.5ºC/s; 1.0°C/s and 50ºC/s.

The samples tested in dilatometer were metallographic prepared to optical microscopy observation and hardness measurements with micro indentation Vickers-HV1kgf.

From the forged bars, samples were also cut and machined to perform Charpy V impact tests. A single tempering treatment of 2h at 670°C was done with the impact test samples of all Experimental Alloys to adjust hardness in the range of 26 - 30 HRC.

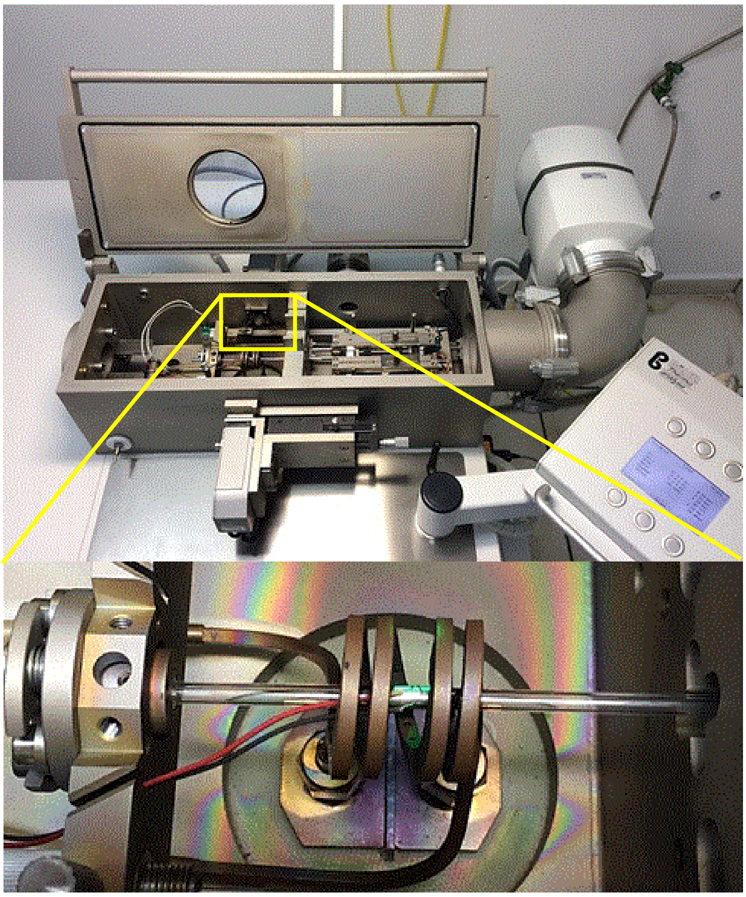

Figure 2. Overview of dilatometer Bähr Thermo Analyses - DIL805 on top and detailed image on bottom from the heating chamber with a sample assembled in the equipment and ready for running the tests. Photo is courtesy by Villares Metals S.A.

3. RESULTS AND DISCUSSION

The hardenability of all four grades studied in this work is presented in the CCT (Continuous Cooling Transformation) curves below, Figs. 3 to 6. Figure 3 shows the transformation temperatures and the microstructures formed for certain cooling rates applied to DIN 1.8550 which is the grade of reference traditionally applied in the manufacture of screws and barrels for plastic processing. Figs. 4 to 6 also present the transformation temperatures and microstructures formed when the new grades proposed in this work were submitted to the exactly the same cooling rates, but with different levels of Ni content in their chemical composition, Experimental alloy without Ni, Experimental alloy with 0.7% Ni and Experimental alloy with 1.4% Ni, respectively. The traditional 1.8550 has limited hardenability once there was the formation of pro-eutectoids (F+P: ferrite + perlite) microstructures starting from intermediate cooling rates such as 0.5°C/s and slower. The result was the formation of a non-homogeneous microstructures composed of bainite, ferrite and perlite at this particular cooling rate of 0.5°C/s.

The three other alloys were proposed intending to obtain steels with high hardenability even when low carbon content is added, since substitutional elements such as Cr, Mn, Mo and Ni are also present in their chemical composition, and contribute significantly to increase steels' hardenability, Thelning (1984). Due to economic reasons the adequate amount of Ni was also an object of interest to develop a material with competitive production cost, since no more than the necessary percentage must be added to obtain a fully bainitic steel when quenched in fresh air just after the forging operations of a bar.

The Experimental Alloy without Ni despites having higher hardenability than 1.8550 steel, the absence of Ni did not allow the obtaining of a fully banitic steel formation, since it was found pro-eutectoid ferrite upon cooling rates of 0.05°C/s and lower, see Fig. 4. However when Ni was added like in Experimental Alloy with 0.7% Ni and 1.4% Ni, the formation of ferrite is delayed in the transformation sequence, fact that can be seen in CCT diagrams (Figs. 5 and 6), the ferrite formation fields were dislocated to the right of the curves, and then reached the purpose of producing steels with outstanding hardenability and fully bainitic microstructure.

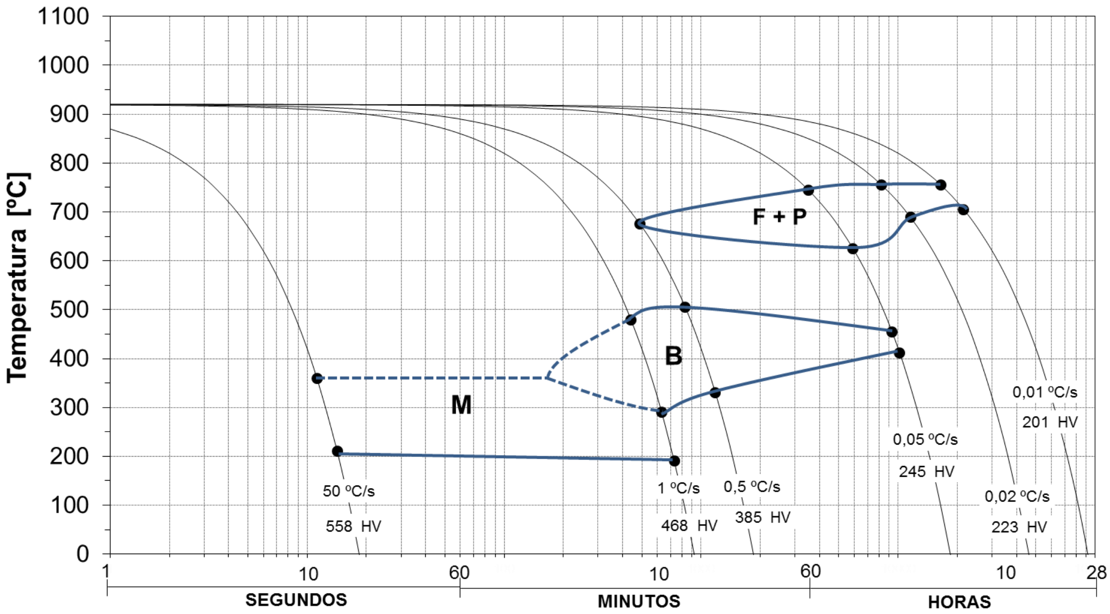

Figure 3. CCT curve of DIN 1.8550. M: martensite; B: bainite; P: perlite; F: ferrite.

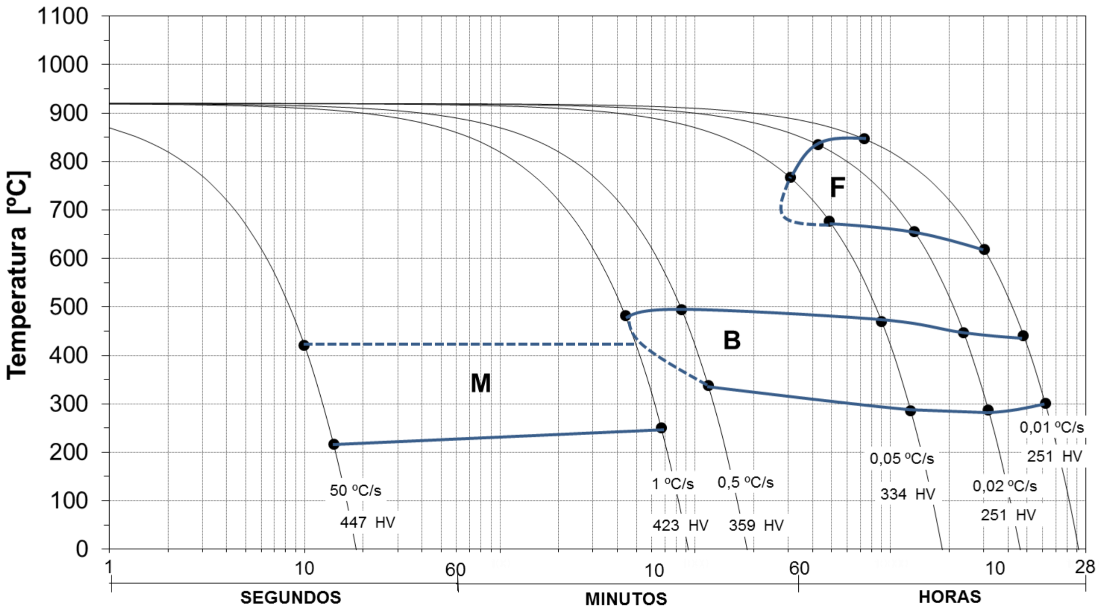

Figure 4. CCT curve of Experimental alloy without Ni. M: martensite; B: bainite; F: ferrite.

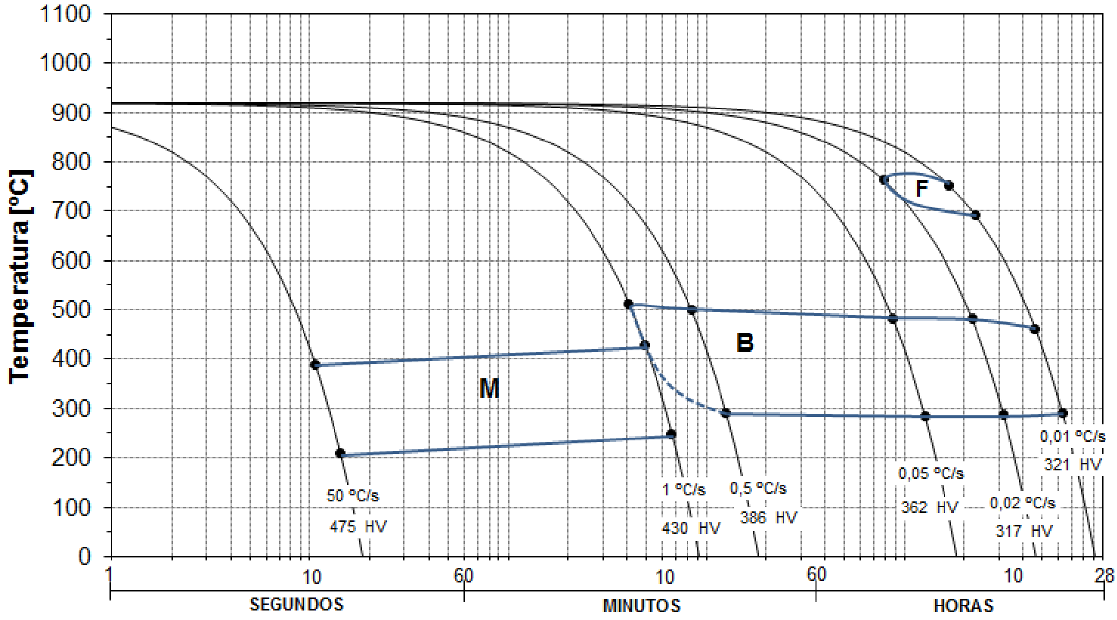

Figure 5. CCT curve of Experimental alloy with 0.7% Ni. M: martensite; B: bainite; F: ferrite.

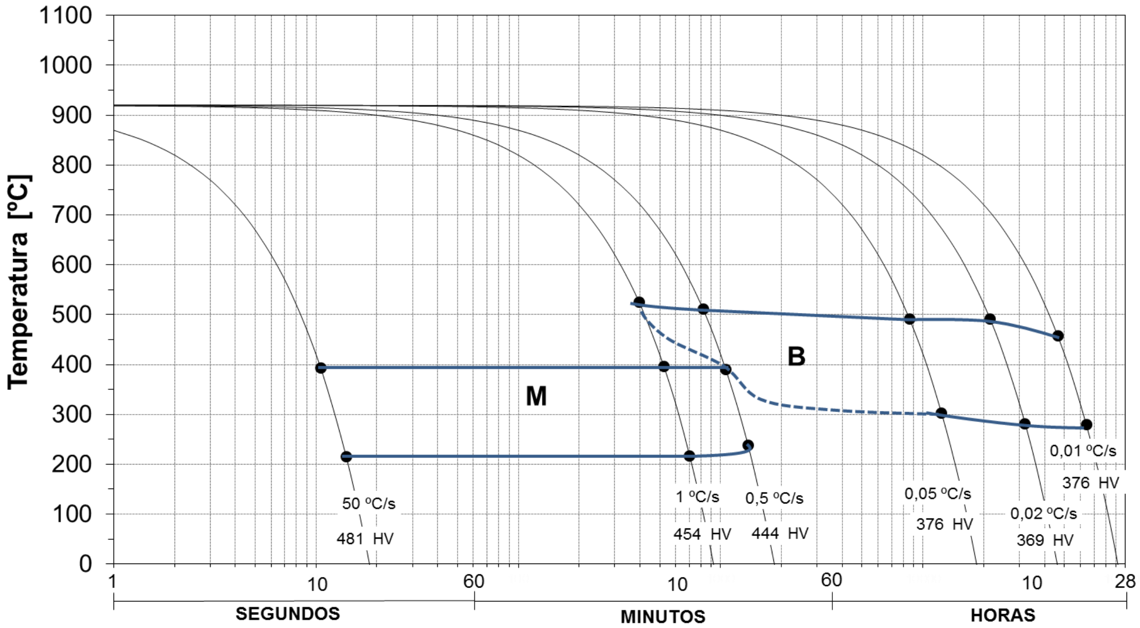

Figure 6. CCT curve of Experimental alloy with 1.4% Ni. M: martensite; B: bainite.

The microstructure of all four grades after quenched at the selected cooling rate of 0.01°C/s is showed in Fig. 7. The steel 1.8550 with its poor hardenability only formed soft microstructures such as ferrite and perlite, and the Experimental Alloy without Ni presented a mixture of banite and ferrite. When increased Ni content in the other two Experimental Alloys, the volumetric fraction of ferrite decreased reaching a point of no formation of pro-eutectoid phases in the Experimental Alloy with 1.4%Ni.

In the application of screws and barrels for plastic plasticizing components is necessary to use steels with good mechanical properties to resist the loads and strengths during the processing of plastics and its additives. For this reason the present work aimed during the alloy design studies, the target of obtaining fully bainitic steels after quenched at slow cooling rates, which will be the real conditions of a bar cooling in fresh air just after hot forged at steel mill plants.

Another very important point is that the manufacturing processes of screws and barrels are via machining operations, approximately 60-70% of the overall cost of these components comes from machining operations and mechanical adjusts necessary to get the components straight according to desired tolerances. Ways of reducing steel bars distortions during machining operations and also make these processes easier are offering to tooling shops: steel bars with very homogeneous microstructure (fully bainitic for example) instead of a mixture of others; and/or steel bars with reduced inner residual stresses. The level of residual stresses created in a steel bar after heat treatment can be related with its geometry, the quenching media severities used to hardening steels such as water, oil or air, and the intrinsic steels' hardenability related to its chemical composition. Residual stresses are also generated during the straightening operations of steel bars to eliminate distortions on the material surface which are often present in quenched and tempered products.

According to Hippenstil (2004), the cooling rate necessary for quenching the core of a steel bar with diameter 500 mm is 0.05°C/s, when a nonaggressive quenching media such as air is applied to cool the steel from its austenitizing field to room temperature. A bar with diameter of 500 mm covers all possible known geometries of screws and barrels for plastic processing, Wortex Máquinas (2017), furthermore the cooling rate of 0.05°C/s was targeted to select which Experimental Alloy proposed would be suitable to substitute DIN 1.8550, when the new steels were quenched in fresh air cooling. The non-severe cooling rates generate less bars distortions, but it is also imperative to achieve minimum hardness of 28 HRC in the bar core that is only possible with no formation of pro-eutectoid microstructures, i.e., a fully bainitic steel must be obtained to guarantee enough mechanical properties for the final application.

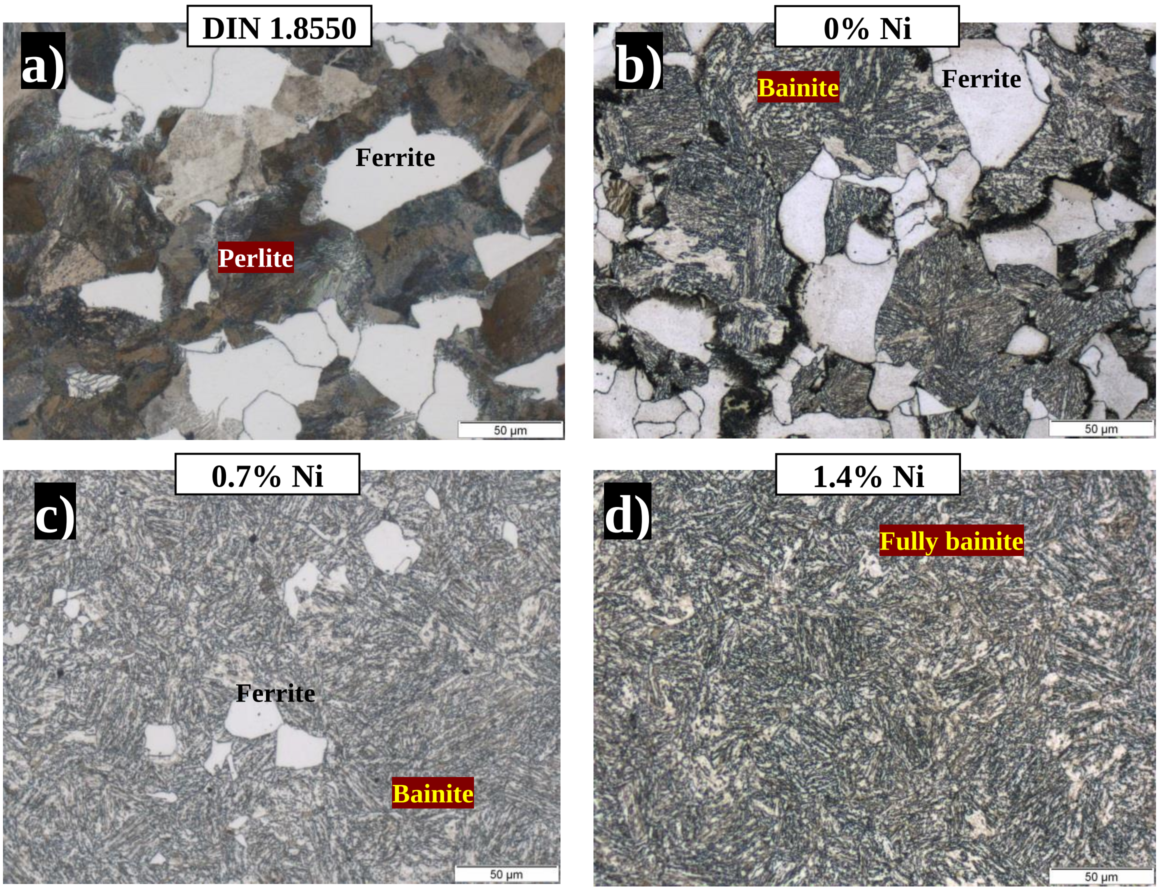

Figure 7. Microstructures from the dilatometer tests after steels submitted at 0.01°C/s cooling rate. a) DIN 1.8550; b) Experimental alloy without Ni; c) Experimental alloy with 0.7% Ni and d) Experimental alloy with 1.4% Ni.

Figure 8 shows the microstructures of all grades after cooled at 0.05°C/s. As expected DIN 1.8550 showed a non-homogeneous microstructure with a mixture of bainite, perlite and ferrite. The Experimental Alloy without Ni presented intensive formation of ferrite islands in a matrix of bainite. But when Ni was added in the other two Experimental Alloys, the hardenability increased and there was no formation of ferrite obtaining a fully bainitic microstructure as desired in this work.

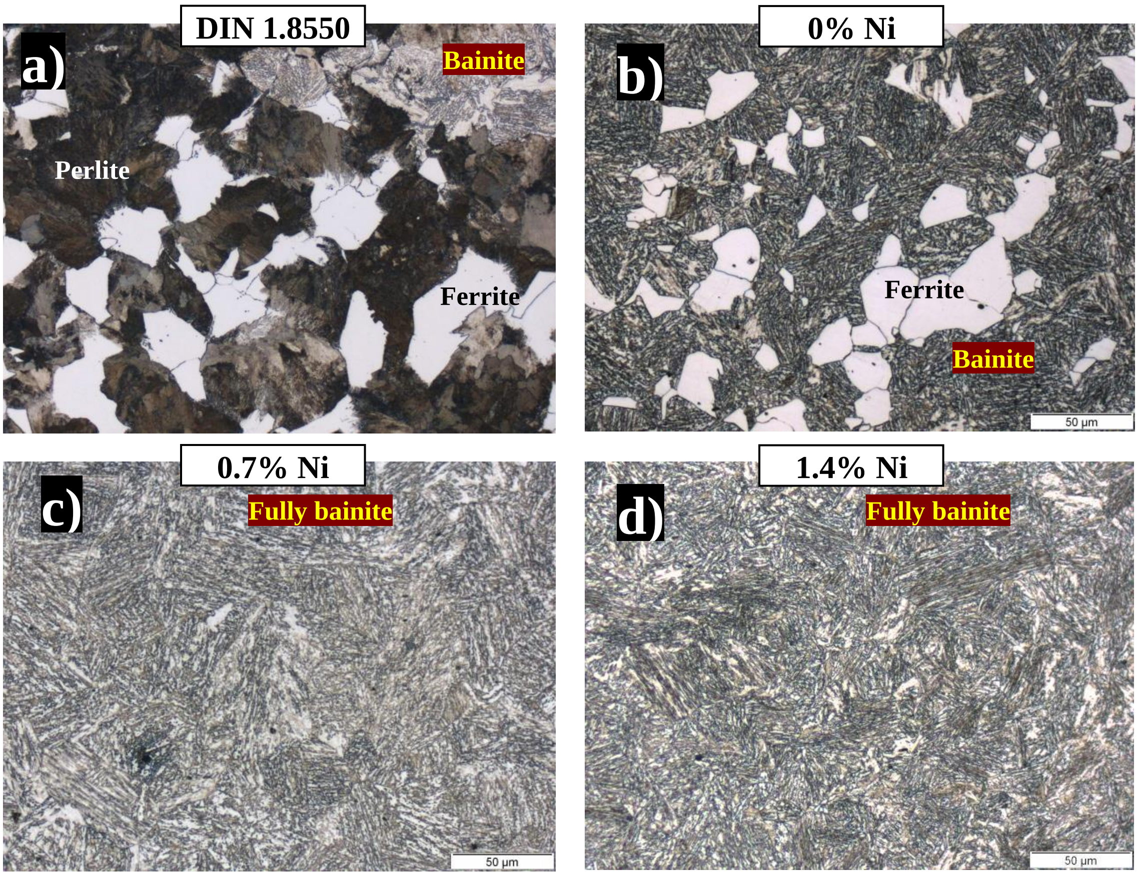

Figure 8. Steels microstructures in dilatometer tests at 0.05°C/s cooling rate. a) The non-homogeneous microstructure of DIN 1.8550 composed of bainite + ferrite + perlite. b) Experimental Alloy without Ni with ferrite grains in a matrix of bainite. c) and d) fully bainitic microstructures respectively from Experimental Alloys with 0.7% Ni and 1.4%Ni.

Considering the chemical compositions of Experimental Alloys were for the first time proposed in this work, and the steel bars were quenched just after hot forging by cooling down in fresh air to room temperature, the full tempering curve of these grades had to be done in order to determine what is the right temperature to achieve the hardness range of 26-30 HRC. The hardness of approximately 28 HRC is obtained after 2 hours in temperature at 670°C. Figure 9 shows the complete tempering curve of the three Experimental Alloys.

It is observed in the tempering curve the presence of a secondary pick of hardness in temperatures around 550°C, this intensive precipitation of very small phases responsible to increase the steel hardness are possibly due to occurrence of Mo and V secondary carbides.

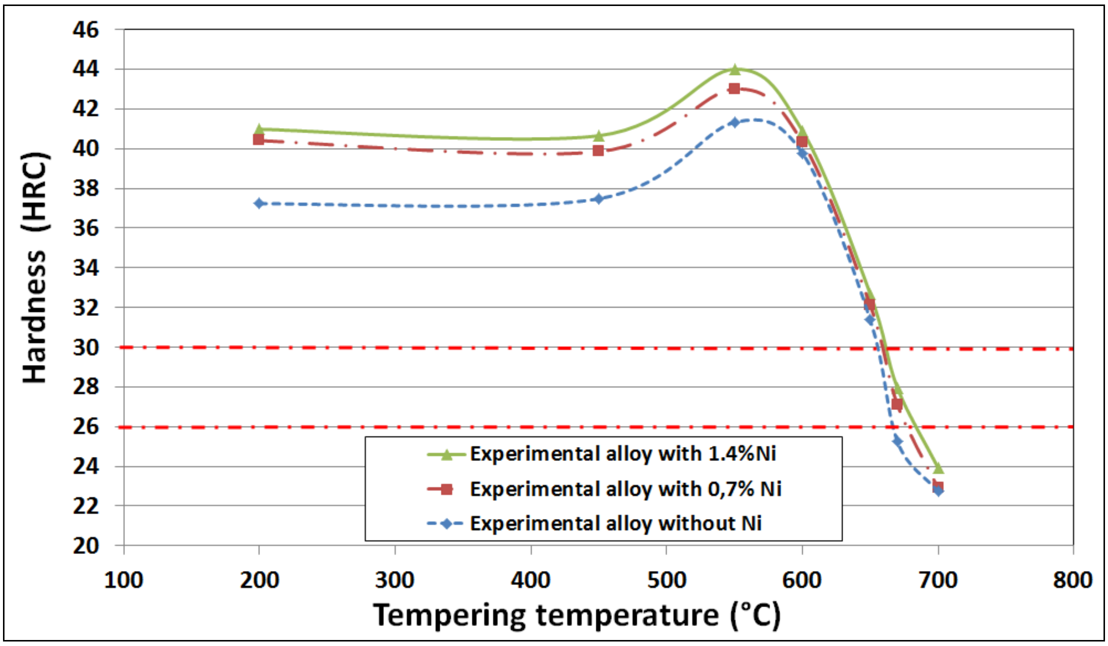

Figure 9. Tempering curve of Experimental Alloys.

The ability of Experimental Alloys to be tempered at higher temperatures than 600°C allows the possibility of screws and barrels being surface hardened. Thermochemical heat treatments such as gas nitriding are widely used on plastic plasticizing components to increase their wear resistance, and it is important that there is no change of the substrate hardness during the usual very long nitrinding cycles for this application, typical nitriding times of screws and barrels are 12 to 96 hours in temperature, Metaltecnica Sul (2017).

The results obtained in the *Charpy* V impact tests can be seeing in Fig. 10. The increasing of Ni content in the chemical composition of Experimental Alloys not only had a role to adjust the steel’s hardenability but was also precise to leverage the mechanical properties over 30J, which is the minimum absorbed energy expected from DIN 1.8550.

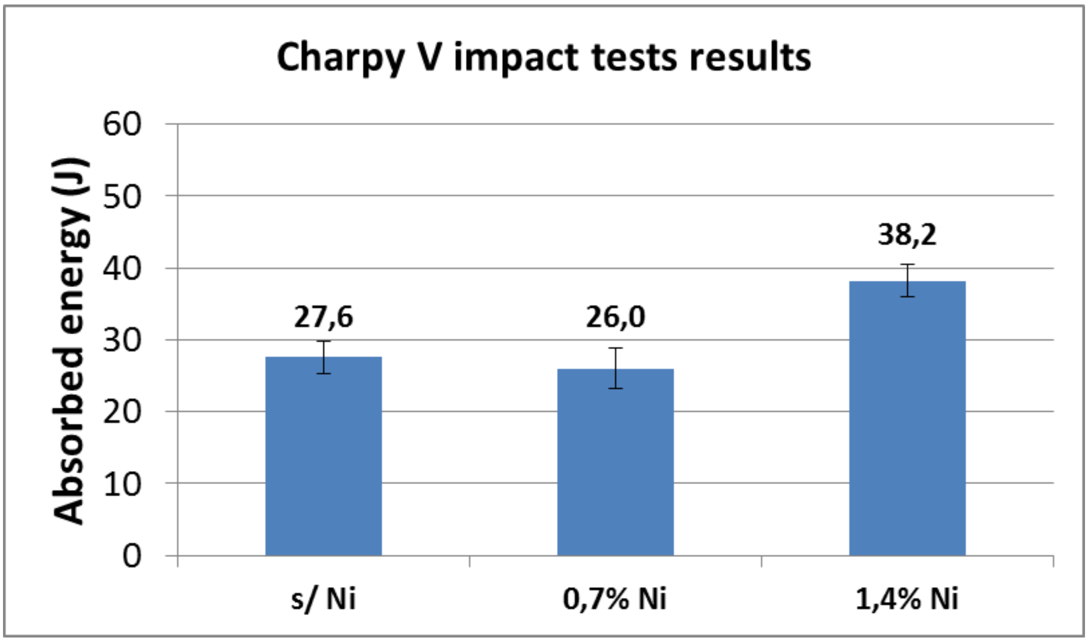

Figure 10. Impact tests results of Experimental Alloys according to Ni content in their chemical composition.

4. CONCLUSIONS

All proposed new Experimental Alloys steels showed higher hardenability than conventional DIN 1.8550 steel irrespective of the Ni content in their chemical composition. The main reason for that is the higher amount of Mn+Cr+Mo alloying elements which are substitutional elements and compensate the lower carbon content.

The element Ni plays and important role in the Experimental Alloys to adjust the desired hardenability to obtain a full bainitic steel even when quenched at low cooling rates like 0.05°C/s and lower.

Homogeneous hardness and microstructure was achieved in the Experimental Alloys with 0.7 and 1.4% Ni even after submitted to low cooling rates for hardening. This behavior allows the new steels the possibility to be air-quenched just after the production of hot forged bars in steel mills.

The Experimental Alloy with 1.4% Ni is a promising steel candidate in order to substitute the traditional DIN 1.8550 in applications of screws and barrels for plastic processing, because the new proposed steel chemistry combined with a production process of air-quenched bars were able to reach good combination mechanical properties, homogeneous microstructure and low level of residual stresses.

It is expected that Experimental Alloy with 1.4%Ni will show a much better machining response than DIN 1.8550, since the new steel will be hardened via air cooling generating much less distortions and residual stresses than 1.8550 quenched in severe medias such as water or oil. Steels with more homogeneous microstructure and dimensional stability tend to be machined easier and are less susceptible to distortions and deviations.

5. ACKNOWLEDGEMEN

The authors would like to thanks “Programa de Pós Graduação em Ciência e Engenharia de Materiais” (PPG-CEM)/UFSCar and Villares Metals S.A. to support the authors to developing this work.

6. REFERENCES

BACALHAU, J.B.; BARBOSA, C.A.; OTUBO, J. Avaliação da temperabiliade de aços com baixos teores de carbono por dilatometria. 67º Congresso Anual da ABM, 31 de julho a 03 de Agosto de 2012, Rio de Janeiro, RJ, Brasil.

BACALHAU, J.B.; OTUBO, J. Aço para moldes plásticos de alto desempenho: inovando para o aumento da competitividade da cadeia produtiva. 70º Congresso Anual da ABM, 17 a 21 Agosto de 2015, Rio de Janeiro, RJ, Brasil.

Gehricke, B.; Schruff, I. Trends in plastic mould steel applications. In: INTERNATIONAL CONFERENCE ON TOOLING, 5., 1999, Leoben. Proceedings…Leoben: Univ. of Leoben, 1999. p.83-92.

Hippenstiel, F. et al. Handbook of plastic mold steel. Wetzlar: Edelstahlwerke Buderus, 2004.

KONSTRUKTIONSBÜRO JAKOB. Institutional website. 2011. Disponível em: <www.gojakob.de>. Access on 03/01st/2012

Metaltécnica Sul. http://www.metaltecnicasul.com.br/; Hardness tables of gas nitriding cycles, 2017.

Nitrodur Brochure – Nitriding Steels – EDELSTAHL WITTEN-KREFELD GMBH - 2001.

ROSCACIL, Ind. e comércio de roscas e cilindros Ltda. http://www.roscacil.com.br/new/construcao.html, access on 04/18th/2017.

Thelning, K. E.; Steel and Its Heat Treatment, 2nd edition, 1984, Butterworths

VILLARES METALS S.A. V8550 steel data sheet, 2005.

Wortex Máquinas institutional data sheet: Recycling Technologies for a sustainable future, 2017.

7. RESPONSIBILITY NOTICE

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