Determination of causes related to the low hardness of cavities and cores of an injection mold constructed with steel AISI 420 treated thermally

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The technical content of this paper is connected with the identification of the conditions directly related to a heat treatment process of quenching and tempering that conducted to a low hardness HRC of cores and cavities of an injection mold produced with martensitic stainless steel AISI 420. For this purpose, three different analyses of these parts of the mold have been performed by qualitative and quantitative techniques of material investigation: determination of chemical composition using mass spectrometry, hardness measurement and metallography. The result of these investigations clearly indicates that a low hardness found in the material of the cores and cavities (AISI 420 type DIN X39 Cr13) was the immediate result of heat treatment parameters defined wrongly in the tempering process. The direct consequences of this hardness for the functional characteristics of the injection mold in dependence on the injection molding technology normally encountered in the practice are also mentioned in this paper.

Keywords:
AISI 420, hardness, injection mold, core, cavity, heat treatment

INTRODUCTION

Special types of steels, as for example, AISI P4, P20, P21, H13 and 4340 (Boyer and Gall, 1995), are being commonly used to construct specific parts of injection molds to support the extreme conditions of the injection molding process. The martensitic stainless steel AISI 420 is also other important type of metallic material used to produce mold components, mainly cores and cavities. The heat treatment technology of this steel (quenching and tempering) consequently determines the final intensity of surface hardness of such cores and cavities, which must be situated between 48 – 52 HRC (according to specifications of the constructive project of the mold) to enable the injection of polypropylene parts (PP) at temperatures around 180 °C. With this high level of hardness, these mold parts are able to produce a great quantity of polymeric components with correct fabrication tolerances without being subjected to an intensive surface wear, what makes it possible the full amortization of costs related to the manufacturing processes of the injection mold. Furthermore, in some special situations, the production capacity of the mold can be improved by increasing tribological properties of surface hardness of cores and cavities constructed with AISI 420 using very specific processes of heat treatment, as for example, plasma nitriding. Independently of the heat treatment process to be applied, these cores and cavities of an injection mold normally present a condition of surface hardness of approximately 20 HRC (delivery condition of raw material). This hardness value ensures the correct realization of all machining processes of the cores and cavities with geometric dimensions near to final desired shape before executing their heat treatments with highly controlled parameters. Apart from the hardness, the heat treatment technology should also ensure that the surface of these mold parts be able to support high impact pressures (avoiding material embrittlement) and an eventual presence of corrosive media during the injection molding process.

This paper shows technical investigations realized about the material of four cores and cavities of an injection mold constructed with AISI 420. During the utilization of this mold there were suspicions that some geometric variations encountered in injected plastic parts have been generated by a low hardness at the surface of the cores and cavities. It was also previously suspected that this low hardness could be a consequence of the utilization of a steel type to fabricate such cores and cavities with a different chemical composition of the steel AISI 420 previously defined in the injection mold project. Other possible explication for the cause of the low hardness would be that the heat treatment process of cores and cavities of material AISI 420 was performed wrongly. Thus, to verify the fabrication condition of these parts of the injection mold, three analyses of their material were conducted in laboratory: identification of chemical composition by mass spectrometry, hardness measurement and metallography. The results of these investigations are directly compared with various theoretical and practical informations found in the literature about the state of the art relative to the heat treatment process of the steel AISI 420.

LABORATORY ANALYSES OF CORES AND CAVITIES OF THE INJECTION MOLD

To conduct laboratory investigations of four cores and cavities of the injection mold, a sample of their material was firstly obtained in a special location (Fig. 1). These analyses were conducted with equipments of the material laboratory of the Sociedade Edu-

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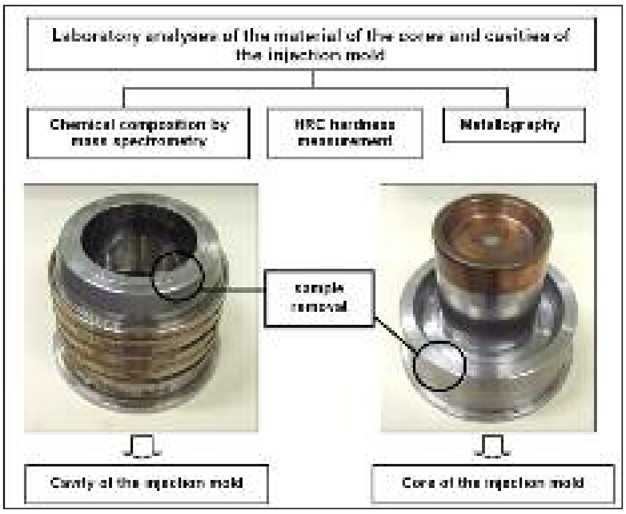


FIG. 1 ***Laboratory analyses of cores and cavities of the injection mold.***

Analisi di laboratorio di cavità e core dello stampo per iniezione.

cacional de Santa Catarina (Sociesc, Joinville, Brazil), based on standardized procedures of the ABNT (Brazilian Association for Technical Standards). Firstly, a chemical material analysis of the cores and cavities was made by a spectrometer using the calibration standard BCS/SS CRM 465/1 of the Sociesc's laboratory. This investigation allowed the identification and quantification in percentage of chemical elements contained in the material samples, such as, carbon, manganese, silicon, chromium, phosphorous and sulfur. Moreover, in the sequence of the laboratory analyses, measurements of the HRC hardness of the cores and cavities were performed with a durometer (model "fix test") applying an indentation load of 150 kgf with diamond point on the surface of the samples. Each individual material sample of a total of eight was precisely measured four times, in different points, within the same surface. All measurement procedures of hardness were made according to the technical recommendations of the Brazilian standard NBR NM ISO 6508-1:08. Finally, the last of three laboratory analyses investigates the metallographic structure of the injection mold parts through metallography. After metallography procedures (polishing and electrolytic attack of the material with oxalic acid in chemical concentration of 10 %, based on the standard NBR:13284:95) high quality photos of samples' surface were obtained in different magnifications (200 and 1000x) through use of an optical microscope with a precise image analyzer (model, Olympus BX 51). The results of the material analyses previously mentioned are explained in details within the chapter "results and discussions" of this paper.

RESULTS AND DISCUSSIONS

The tables 1 and 2 show the results of chemical composition of the cavities and cores by mass spectrometry, respectively. The spectrometry results clearly indicate that the four cores and cavities were constructed with a special type of martensitic stainless steel with the technical denomination of AISI 420 (also defined in the Germany standard as DIN X39 Cr13) (Wegst, 2004), correctly according to the technical conditions previously defined in the project of the respective injection mold. The realization of a heat treatment process of quenching and tempering (Van Vlack, 1984) of this steel is necessary to establish the exact surface hardness of cores and cavities within the desired range (48 - 52 HRC) (Soares, 2003) for resisting to tribological solicitations of the injection molding.

The table 3 presents the HRC hardness measurements encountered in the surface of the cores and cavities. For each core and cavity a confidence interval (CI) was also calculated with a confidence level of 95 % (Montgomery, 2005) applying the statistical software "Minitab" (Petruccelli and et al., 1999). The corre-

Chemical elements	Cavity 1 (% weight)	Cavity 2 (% weight)	Cavity 3 (% weight)	Cavity 4 (% weight)	DIN X39 Cr13 1.4031	AISI 420
carbon	0,405	0,407	0,410	0,351	0,36 – 0,42 %	0,15 min %
manganese	0,435	0,458	0,434	0,372	≤ 1,00 %	1,00 %
silicon	0,56	0,56	0,54	0,420	≤ 1,00 %	1,00 %
chromium	12,31	13,03	12,20	11,40	12,5 – 14,5 %	12,0 – 14,0 %
phosphorus	0,033	0,039	0,033	0,040	≤ 0,040 %	0,04 %
sulfur	0,0068	0,015	0,013	0,028	≤ 0,015 %	0,03 %

TAB. 1 ***Percent of chemical elements in the material of the cavities.***

Percentuale degli elementi chimici nel materiale delle cavità.

Chemical elements	Cavity 1 (% weight)	Cavity 2 (% weight)	Cavity 3 (% weight)	Cavity 4 (% weight)	DIN X39 Cr13 1.4031	AISI 420
carbon	0,414	0,402	0,414	0,413	0,36 – 0,42 %	0,15 min %
manganese	0,432	0,425	0,428	0,431	≤ 1,00 %	1,00 %
silicon	0,55	0,55	0,54	0,55	≤ 1,00 %	1,00 %
chromium	12,13	11,97	11,96	12,16	12,5 – 14,5 %	12,0 – 14,0 %
phosphorus	0,031	0,031	0,031	0,031	≤ 0,040 %	0,04 %
sulfur	0,0062	0,0070	0,0089	0,0067	≤ 0,015 %	0,03 %

TAB. 2 ***Percent of chemical elements in the material of the cores.***

Percentuale degli elementi chimici nel materiale dei core.

TAB. 3
Values of HRC hardness of cores and cavities.

Valori di durezza HRC di core e cavità.

Identification	HRC Hardness	Confidence interval (95 %)
Core 1	36 – 37 – 37- 36	35,58<HRC<37,4
Core 2	38,5 – 38 – 38 – 37,5	37,5<HRC<38,6
Core 3	37 – 36 – 37 – 36,5	35,9<HRC<37,4
Core 4	39 – 39,5 – 39 -39	38,2<HRC<39,5
Cavity 1	41 – 40 – 40 - 41	39,5<HRC<41,4
Cavity 2	40,5 – 40 – 39,5 – 39,5	39,1<HRC<40,6
Cavity 3	39 – 38,5 – 38 – 38,5	37,8<HRC<39,1
Cavity 4	44 – 44 – 43,5 – 44,5	43,3<HRC<44,6

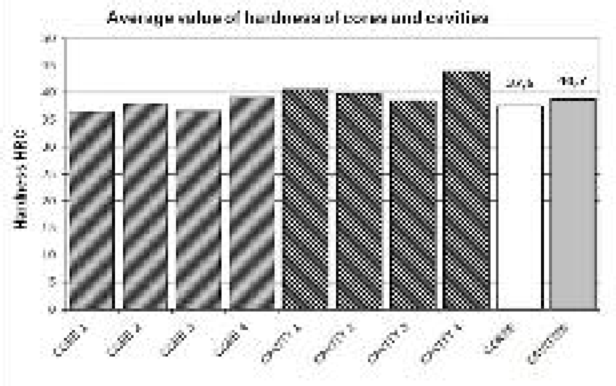


FIG. 2 ***HRC average values of cores and cavities of the injection mold.***

Valori medi HRC di core e cavità dello stampo per iniezione.

sponding average values of these confidence intervals as well as the average value of hardness of all cores and cavities can be visualized in the graphic of Fig. 2. Moreover, the informations of the table 3 made it possible to realize statistical comparisons of surface hardness between cores and cavities by “One-way ANOVA” based on an analysis of variance (“F-test”) with a significance level of 5 % (Koder, 2010). The result of this ANOVA indicates by a “p-value” calculation using the software Minitab (table 4) that there is a statistically significant difference between the average values of HRC hardness of the cores and cavities. As an important complement of this analysis a Tukey’s test (Casarin and et al., 2009) was carried out with Minitab to clearly identify which of these hardness average values are really different from each other. This test indicates that the hardness average value of: core 1 ≠ core 2 and core 4; core 2 ≠ core 3 and core 4; core 3 ≠ core 4, and the hardness average value of: cavity 1 ≠ cavity 3 and cavity 4; cavity 2 ≠ cavity 3 and cavity 4. For example, supposed that all cores were thermally treated with the same process conditions, these differences of HRC values can be explained by the small variations of chemical composition of each individual core of the injection mold. Finally, from the Fig. 2, it can be observed that the total average value of HRC hardness relative to all cores and cavities are 37,6 and 40,7, respectively. The difference between these two hardness values is probably a consequence that the heat treatment process conditions of the cores have been realized differently from those related to the cavities. These high values of hardness certainly confirm that the steel X39 Cr13 of the mold parts were thermally treated. The raw material of X39 Cr13 is normally delivered with 20 HRC, as mentioned previously in the chapter 1.

Fig. 3 shows in different magnifications the result related to the microstructure of the cores and cavities constructed with steel X39 Cr13. In this case it can be verified that this structure is basically constituted of ferrite (-phase) (Meyrick, 2001) and precipitated carbides, typically obtained through a combined heat treatment process of quenching and tempering (Moreno, 1992). The temperature levels of quenching and tempering defines the HRC hardness of the steel as function of the distribution and morphology of carbides in the ferrite, where with this the corrosion resistance of material and its mechanical capacity to receive strong impacts during the injection mold process are determined.

TAB. 4
One-way ANOVA of cores and cavities with Minitab.

“One-way ANOVA” di “core” e cavità con Minitab.

p-value for hardness of the cores with F-test (variance analysis)

Source	DF	SS	MS	F	p
Core	3	18,563	6,188	31,26	0,000
Error	12	2,375	0,198		
Total	15	20,938			

P= p-value, p<0,05

S = 0,4449; R-Sq = 88,66%; R-Sq(adj) = 85,82%

p-value for hardness of the cavities with F-test (variance analysis)

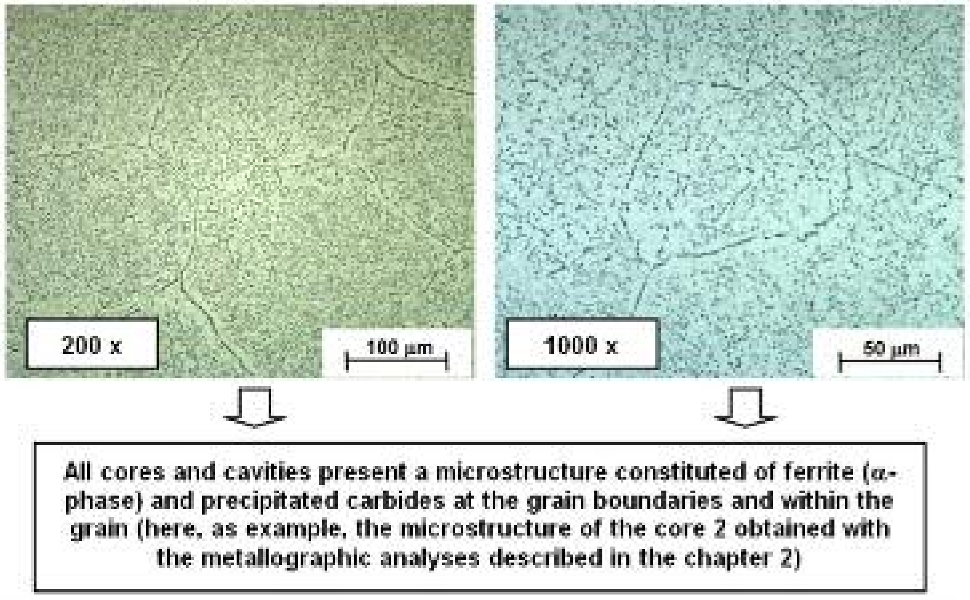
Source	DF	SS	MS	F	p
Cavity	3	65,797	21,932	97,93	0,000
Error	12	2,688	0,224		
Total	15	68,484			

P= p-value, p<0,05

S = 0,4732; R-Sq = 96,08%; R-Sq(adj) = 95,09%

Observations:

DF degrees of freedom of the F-Test; SS → sum of squares; MS → variance between treatments; F → value of the F-test.



All cores and cavities present a microstructure constituted of ferrite (α-phase) and precipitated carbides at the grain boundaries and within the grain (here, as example, the microstructure of the core 2 obtained with the metallographic analyses described in the chapter 2)

FIG. 3
Microstructure of the cores and cavities in different magnifications.

Microstrutura di "core" e cavità a diversi ingrandimenti.

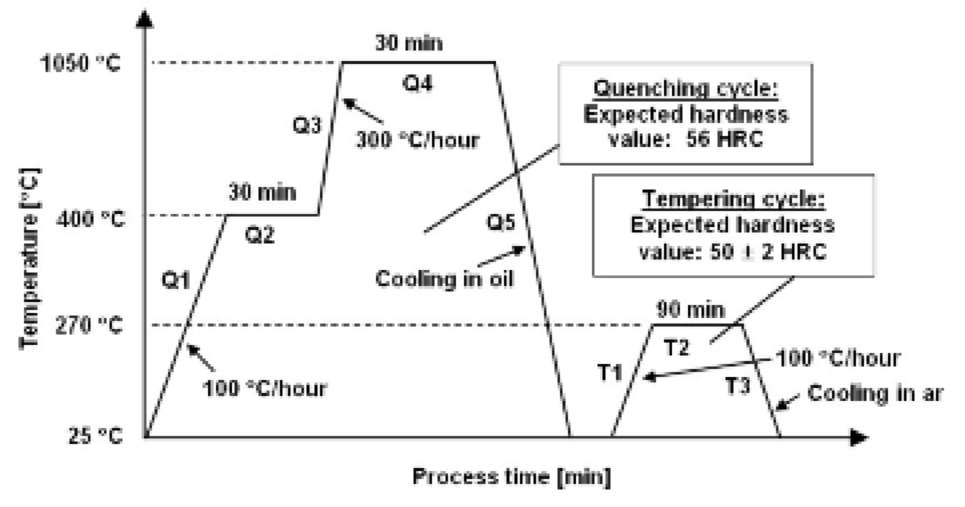


FIG. 4
Quenching and tempering cycle recommended in the literature for the steel X39 Cr13.

Ciclo di tempra e rinvenimento raccomandati in letteratura per l'acciaio X39 Cr13.

The correct definition of the thermal conditions of the tempering process is very important to completely avoid embrittlement of the steel X39 Cr13 as material of cores and cavities.

Based on the three laboratory analyses previously indicated, the main causes of low hardness of the cores and cavities are now explained with the knowledge of the state of art relative to the cycle of heat treatment process of the steel X39 Cr13 (Fig. 4). The quenching and tempering technology of this material consist of different process steps with highly controlled conditions. The technical details of these steps with their relevant characteristics are presented as following:

- **Process steps Q1, Q2 and Q3:** These steps represent a heating process of the steel X39 Cr13. Initially, in the condition of 20 HRC as raw material referring to a temperature of 25 °C, the material X39 Cr13 presents a microstructure basically constituted of -phase (body-centered cubic structure or "bcc") and precipitated carbides with chemical composition $(Fe,Cr)_{23}C_6$ (Cunat, 2000; Murry, 2002). This heating is gradually made in oven with controlled atmosphere to avoid problems of oxidation or descarbonation of the steel, where here the material absorbs a constant flux of thermal energy by conduction (Kreith, 2000) (Eq. 1). During the heating at 100 °C/h to high temperatures, the transformation of ferrite to austenite takes place, which is also accompanied at soaking temperature of 1050 °C by partial dissolution of carbides. During carbides dissolution at 1050 °C, Cr and C diffuse out from (Fe,Cr)23C6 carbides into austenite matrix. The temperature of the start of ferrite to austenite transformation on heating is defined as T_i and can be estimated using Eq. 2. This temperature is a function of the chemical composition of the steel X39 Cr13. In the situation of the cores and cavities of the injection mould, with knowledge of the tables 1 and 2, it is thus possible to obtain their respective values of T_i (table 5) using the weight percentage of each chemical element in the equation 2.

$$q_k = -k.A\frac{\partial T}{\partial n} \qquad (1)$$

here, q_k= flux of thermal energy through the material; k= thermal conductivity of the material; A= area of the material in contact with a temperature T; ∂T/∂n = temperature gradient in a direction "n" of the material thickness.

$$Ti(C°) = 723 - 20.7(\%Mn) - 16.9(\%Ni) - 16.9(\%Cr) \qquad (2)$$

- Process step Q4: The temperature of 1050 °C indicates that the steel X39 Cr13 is in a complete condition of austenitisation, where the material ceases to magnetically behave by the total formation of austenite. For approximately 30 min the steel should remain in this temperature to provoke a greater diffusion of Cr

Identification	Ti (°C)	Ms (°C)	RA (%)
Cavity 1	505,9	199,1	17,3
Cavity 2	493,3	187,2	19,8
Cavity 3	507,8	194,9	18,2
Cavity 4	522,6	270,9	7,8
Core 1	509,1	191,3	18
Core 2	511,9	207,01	15,9
Core 3	512,01	193,66	18,4
Core 4	508,6	192,10	18,7

TAB. 5 ***Parameters of heat treatment process of the steel X39 Cr13.***

Parametri del processo di trattamento termico dell'acciaio X39 Cr13.

and C of the carbides $(Fe,Cr)_{23}C_6$ into the structure fcc. This time depends on the wall thickness of the cores and cavities and also defines the HRC hardness level of the material X39 Cr13 after its rapid cooling process with an appropriate quenching medium (Brockenbrough and Merritt, 2006) (process step Q5).

- Process step Q5: The extremely rapid cooling process of material from 1050 °C ("quenching") until the temperature of the respective quenching medium (mineral oil in 40 °C) is responsible for the hardness of the steel X39 Cr13. It is expected that this hardness reach 56 HRC after this process step. In this case, the steel X39 Cr13 presents a microstructure constituted of martensite and of a very small volumetric quantity of retained austenite (Bala and Pacyna, 2007). This martensite with ferromagnetic properties appears in the steel being cooled just at a temperature M_s (Larok and Rouag, 2008; Ho and et. al., 2003) that can be exactly calculated with Eq. 3, using the informations of chemical composition of the cores and cavities presented in the tables 1 and 2 (calculated values of M_s with Eq. 3 in the table 5). The diffusionless transformation process of the martensite ends up at a temperature denominated of M_f. Generally, the total percentage of retained austenite in presence of martensite is influenced by the chemical elements of the steel X39 Cr13 and also by the temperature of the quenching medium, being determined with very good accuracy through Eq. 4. The expected values of retained austenite in percentage (% RA) for the cores and cavities of the injection mold are visualized in the table 5. To totally transform this retained austenite (Totten, 2007) into martensite it is normally necessary to apply to the steel X39 Cr13 a cryogenic heat treatment process in temperatures of approximately -185 °C. With this technical procedure, the hardness properties of the steel are improved, parallel with a reduction of material residual stresses.

$$Ms = 512 - 453(C\%) + 217(C\%)^2 - 71,5(C\%)(Mn\%) - 67,6(C\%).(Cr\%) \qquad (3)$$

$$RA = e^{-1,1 \cdot 10^{-2}(Ms - T)} \qquad (4)$$

here, M_s= initial temperature of martensite transformation; T= temperature of the cooling medium of the quenching process (40 °C) with a degree of agitation; RA= percentage of retained austenite in the steel after quenching process.

- **Process steps T1, T2 and T3:** These process steps of heat treatment of the steel X39 Cr13 correspond to the tempering conditions. The exact control of the phase T2 is extremely crucial to obtain the correct HRC hardness of this material being thermally treated. During this process step, the martensite obtained in Q5 is transformed into a microstructure composed of ferrite und precipitated carbides with chemical composition $(Fe,Cr)_{23}C_6$. The temperature of T2 and holding time of the steel in this temperature define the quantity of these carbides within the ferrite. The greater the amount of precipitated carbides, the lower the final HRC hardness of the material X39 Cr13 will be. For the steel X39 Cr13 a maximal temperature of 270 °C (during 90 min as holding time in this temperature intensity) (Fig. 4) is recommended in the technical literature to perform the tempering process with an optimum control of the carbides' quantity in precipitated form, thus obtaining a hardness of approximately 50 ± 2 HRC. This total quantity also defines the corrosion properties of the steel. The temperature of 270 °C enables that small quantities of retained austenite eventually existing in the steel be transformed completely into a bainitic microstructure (Hiroshi et al., 2008). The complete elimination of the retained austenite can improve the fracture toughness of the steel (Kokosza and Pacyna, 2008). Moreover, based on Fig. 5,

it can be explained that the low hardness values of the cores and cavities (according to table 1) is a consequence of the application of a very high tempering temperature for the material X39 Cr13 (around 600 °C). Extensive precipitation of $(Fe,Cr)_{23}C_6$ carbides from ferrite matrix results in softening of the injection mold with hardness values decreasing below 42 HRC.

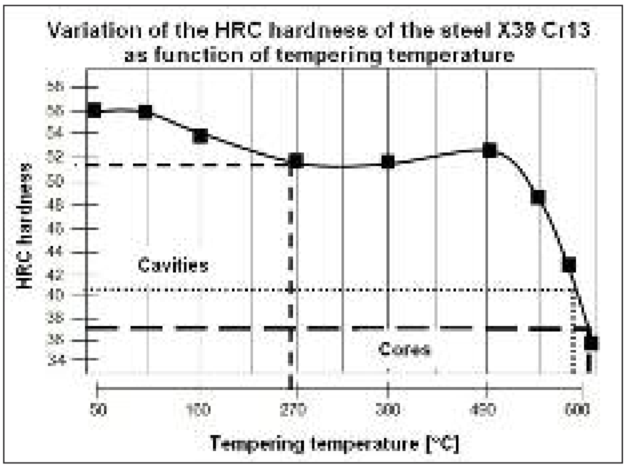


Fig. 5 ***Influence of the tempering temperature on the hardness of the steel X39 Cr13 (Souza, 2011).***

Influenza della temperatura di rinvenimento sulla durezza dell'acciaio X39 Cr13 (Souza, 2011).

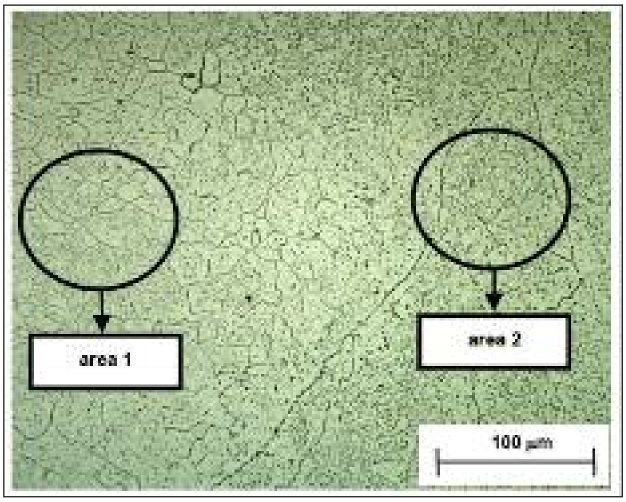


Fig. 6 ***Grain recrystallization in the microstructure of cores and cavities.***

Ricristallizzazione nella microstruttura di "core" e cavità.

Fig. 6 shows the microstructure identified by metallography at the surface of the cavities 1 and 3 as well as of the cores 1 and 4. Two areas with different grain dimensions can be seen in this figure, where between these areas a defined formation of grains can not be identified clearly. This specific situation indicates a recrystallization phenomenon of the microstructure of the cores and cavities as result of the high temperatures (~ 600 °C) used during the tempering process of the steel. The presence of these two grain sizes is responsible for different conditions of mechanical properties in the material of these injection mold parts, what is certainly not desirable for the correct applications of injection molding process.

CONCLUSIONS

Through three laboratory analyses of the material used to construct four cores and cavities of an injection mold, it was identified that incorrect conditions of tempering process has caused the low hardness of steel X39 Cr13. The correct procedure of heat treatment process of this steel referring to quenching and tempering to exactly obtain a final hardness of 48 ± 2 HRC was indicated in the results and discussions of the paper. The detailed knowledge of the most important parameters of these two processes opens a possibility to perform optimizations in the heat treatment technology of the steel X39 Cr13 to be applied as material of cores and cavities for injection mold, for example, using the statistical methodology of “design of experiments” (DOE). Analysis of HRC hardness in combination with observations of microstructure of the steel after quenching and tempering is the main criterion to evaluate the physical steel properties and consequently the effectiveness of the heat treatment process applied. Generally, the informations of this paper provide a laboratory methodology to identify heat treatment problems of parts of injection molds. The technical functionality of these parts produced with special parameters of heat treatment process should be checked further by experimental investigations principally in relation to aspects of corrosion resistance and mechanical load capacity, according to the respective application of injection molding.

ACKNOWLEDGMENTS

I wish to thank the company AS INGPEED (Research and Development in Mechanical Engineering) in Brazil/Blumenau-SC for the financial support to perform this work.

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Abstract

Determinazione delle cause riconducibili alla bassa durezza di cavità e core in uno stampo per iniezione prodotto con acciaio AISI 420 trattato termicamente

Parole chiave: trattamenti termici, acciaio

Il contenuto tecnico del presente lavoro si riferisce all'identificazione delle condizioni direttamente legate ad un trattamento termico di tempra e rinvenimento che ha portato a una bassa durezza HRC di “core” e cavità in uno stampo per iniezione realizzato con acciaio inox AISI 420 martensitico. A questo scopo sono state eseguite tre diverse analisi delle parti dello stampo mediante tecniche di indagine del materiale qualitative e quantitative: determinazione della composizione chimica mediante spettrometria di massa, misurazione della durezza e metallografia. Il risultato di queste indagini indica chiaramente che la bassa durezza riscontrata nelle cavità e nel “core” del materiale (AISI 420 di tipo DIN X39 Cr13) è il risultato immediato dei parametri di trattamento termico definiti in modo errato. In questo documento sono descritte anche le conseguenze dirette di questa durezza nei riguardi delle caratteristiche funzionali di uno stampo per iniezione funzionante secondo la tecnologia di stampaggio ad iniezione normalmente utilizzata nella pratica.