http://dx.doi.org/10.4322/2176-1523.1170

AN EXPERIMENTAL METHOD TO SIMULATE THE HOT STAMPING PROCESS

André Olah Neto [1]
Guilherme Ourique Verran [1]
Rodinei Rocha Dutra [1]

Abstract

In this study a new experimental method using low closing pressure and a flat aluminum die was developed in order to investigate the hot stamping process of a 22MnB5 steel grade. Initially, an experimental set up was developed and validated. Next, experiments were carried out to evaluate the behavior of this steel when subjected to quenching, using this experimental set up and different cooling conditions such as water, oil and air. Results were assessed by cooling curves, as well as by mechanical tests and metallographic analyzes. Cooling rates close to 110°C/s, hardness up to 480HV and ultimate tensile strength up to 1600 MPa were achieved, which are considered acceptable values for this steel in normal conditions of hot stamping.
Keywords: Hot stamping; 22MnB5 steel; Quenching; Cooling rate.

UM MÉTODO EXPERIMENTAL PARA SIMULAR O PROCESSO DE ESTAMPAGEM A QUENTE

Resumo

Nesta pesquisa foi desenvolvido um novo método experimental, utilizando baixa pressão de fechamento e uma matriz plana de alumínio, com o objetivo de investigar o processo de estampagem a quente do aço 22MnB5. Inicialmente um aparato experimental foi desenvolvido e validado. A seguir foram realizados experimentos com o objetivo de avaliar o comportamento deste aço quando submetido a diferentes meios de têmpera, usando este método e diferentes condições de resfriamento, tais como água, óleo e ar. Os resultados foram avaliados usando curvas de resfriamento, bem como ensaios mecânicos e análises metalográficas. Foram obtidas taxas de resfriamento próximas de 100^{0}C/s, durezas acima de 480HV e limite de resistência acima de 1600 MPa, valores que são considerados aceitáveis para este aço em condições normais de estampagem a quente.
Palavras-chave: Estampagem a quente; Aço 22MnB5; Têmpera; Taxa de resfriamento.

1 INTRODUCTION

In recent years the hot stamping process has been widely studied, generating significant technological advancement and allowing its use in the production of several components with excellent performance due to the combination of high mechanical properties with high dimensional accuracies.

An important aspect in the hot stamping process is that sheet conformation occurs at elevated temperatures, where the mechanical strength of the material is significantly reduced. Thus, the load required to deform the sheet is very low, opening up the possibility of the use of less robust and cheaper equipment, which results in lower operating costs and investment. The stamping tools would also be less stiff and cheaper. The use of low stress for deformation also requires the evaluation of the thermal behavior because the material is hot formed and simultaneously quenched to room temperature, in order to obtain a component with good dimensional accuracy and high mechanical resistance [1]. The conditions involving contact between the tool and the blank and the closing pressure have a significant influence on the heat extraction coefficient, on the cooling rate and consequently, on the final properties of the component. In hot stamping the cooling rate must be high enough to avoid the formation of ferrite, pearlite or bainite, ensuring the formation of a fully lath-martensitic microstructure. The critical cooling rate, which is intrinsic to material, is determined primarily by the alloying elements in steel,

[1]*Mechanical Engineering Department, Universidade do Estado de Santa Catarina – UDESC, Joinville, SC, Brasil. E-mail: guilherme.verran@udesc.br*

in the 22MnB5 steel the element that ensures this effect is the boron [2].

Naderi [3],using a thermal dilatation test, designed the CCT diagram for 22MnB5 steel and determined that the eutectoid temperature is 720°C, the start temperature of austenite formation in ferrite primary (Ac3) is 880°C, the start temperature martensite transformation (Ms) is 410°C and that the final temperature (Mf) is approximately 230°C. Furthermore, was observed that the cooling rate to ensure a fully lath-martensitic structure must be higher than 25°C/s, allowing to obtain hardness 510 and 530 HV. Karbasian and Tekkaia [1] and Nishibata and Kojima [4] mentioned very similar values. Turetta [5] determined experimentally through dilatometric analysis that martensitic transformation of 22MnB5 steel starts at 380°C and ends at 290°C. Bandyopadhyay et al. [6] studied the cooling rate in a type steel HSLA and observed that when cooling is slow the hardness is low, associated with the formation of bainite and bainite-ferrite along with martensite. With higher cooling rates the resulting structure becomes fully martensitic, allowing higher hardness values. Steinbeiss et al. [7] showed that the in hot stamping process heat transmission occurs through three factors: heat transfer between the component and the tool, heat conduction through the tool and the transfer of heat between the tool and the cooler. According to Naganathan [8] there are three ways to ensure an efficient heat transfer: use of materials with high thermal conductivity in the dies manufacturing, avoid barriers to the heat driving and improve the cooling system. Cui et al. [9] showed that the higher the water flow on the tool the higher the convection heat transfer coefficient is. Geiger et al. [10] using contact pressures between 0 and 40MPa showed that the heat transfer coefficient increases with increased pressure of the die on the sheet during the hot stamping of a steel 22MnB5. Karbasian and Tekkaia [1] also cites that contact pressure between the die and the blanck exerts an important influence on heat transfer coefficient and establish the thermal behavior between these surfaces. Turetta [5] plotted 22MnB5 steel cooling curves and demonstrated that the higher the contact pressure the higher the cooling rate is. Similar results were reported by several authors [11-15].

It has been observed that most of the experimental apparatus and industrial processes operate with closure pressures higher than 10MPa. In this study, a die quenching experimental method, using low closing pressures and an aluminum flat die, was developed in order to simulate characteristic events of the hot stamping process.

2 EXPERIMENTAL SETUP AND TEST PROCEDURES

The proposed experimental set up was composed of three systems: an electrical resistance heating furnace, a mechanical testing machine type Emic-300kN and a water cooled aluminum flat die, according to what is show in Figures 1 and 2. In order to ensure a closing pressure of 0.33MPa on the test specimen, a force multiplier system was utilized.

The temperature control system (Figure 3) was composed of a type K thermocouple located inside the furnace

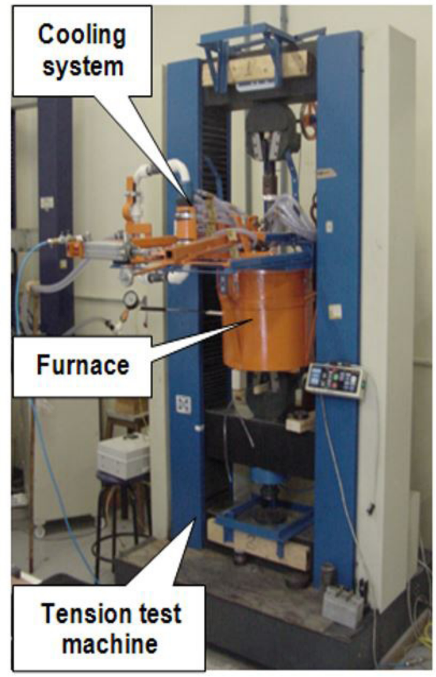

Figure 1. Experimental apparatus formed by heating system (furnace), deformation system (tension test machine) and cooling system (cooler die).

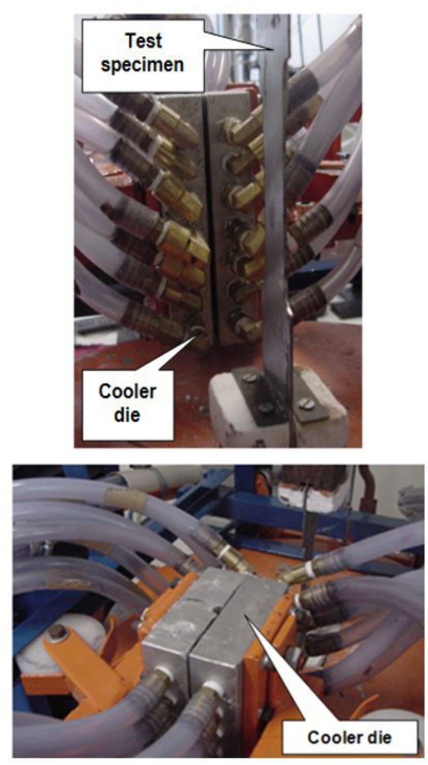

Figure 2. Test specimen and cooling die details.

chamber to control test temperature, a type K thermocouple welded on the test specimen and an electronic system to capture signals and to record temperatures and cooling rates. The signal emitted was captured, processed and recorded in an electronic system at intervals of 17ms.

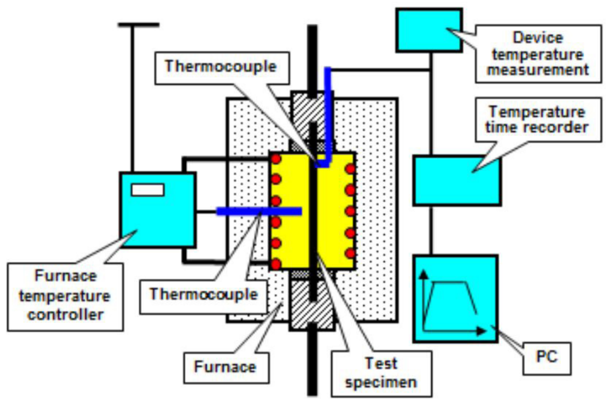

Figure 3. Temperature measurement and control system.

Table 1. Average results of the experiments showing cooling rates and cooling times

Cooling Condition	Cooling Rates (°C/s)		Temperatures (°C)		
	CR	MCR	T_i	T_f	(T_i-T_f)
Water Quenching	530	969	817	69	747
Oil Quenching	328	558	843	338	504
Die Quenching	112	164	871	442	429
Air Cooling	12	35	911	559	352

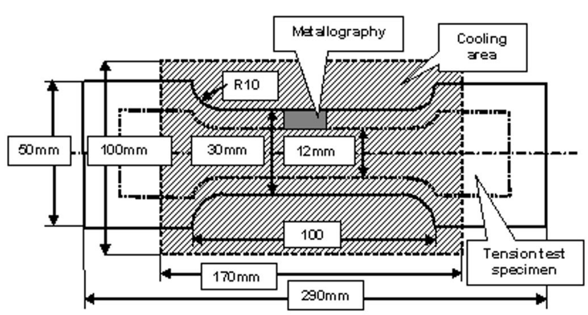

Figure 4. Test specimen details.

The material used in this study was an ultra-high strength 22MnB5 steel sheet supplied by Arcelor Mittal Vega with nominal thickness of 1.6mm, galvanized coating and ultimate tensile strength near 700 MPa. The chemical composition is shown in Table 1 and test specimen details are presented in Figure 4.

Before the test, a thin layer of a copper base paste was applied on the test specimen to inhibit oxidation during heating. The test specimen was attached to the mechanical testing machine by claws and heated to the test temperature (900°C) in a total cycle of 4 minutes. Next, the furnace was removed through vertical displacement and the cooler die was immediately introduced through horizontal displacement, promoting the test specimen quenching. This operation was conducted in a very fast time (3 to 5 s) to avoid excessive temperature loss.

The cooling curves "temperature x time" and "cooling rate x temperature" were obtained from temperature measurement and control system. These cooling curves were obtained by definition of the characteristic points "Ti" and "Tf" (initial and final temperatures) and "ti" and "tf" (initial and final cooling times), and by calculate the average cooling rates CR = (Ti-Tf)/(tf-ti) and setting the maximum cooling rates (MCR). Experiments were performed using the proposed experimental method as well as for samples cooled using water, oil and air. The objective was to compare the effect of cooling rate on the material properties when it is submitted to different quenching conditions. At least three experiments were carried out for each experimental condition. After that, results were assessed by hardness measurements along the test specimen on average of 10 measurements per sample. Tensile resistance tests and microstructure analysis by standard metallographic sample preparation and scanning electron microscopy were also performed. Tests procedures were previously described in detail [16].

3 RESULTS AND DISCUSSION

The experimental results concerning cooling curves are shown in Table 1, while the results of mechanical tests are shown in Table 2.

The cooling curves "temperature x time" superposed on a continuous-cooling-transformation diagram 22MnB5 steel [2] are shown in Figure 5a. It is possible to observe that none of the curves of different quenching conditions (die, oil and water) crosses the start line of phase transformations in the diagram,

Table 2. Average results of the cooling rates and mechanics tests to different cooling conditions utilized in this study

Cooling Media	*Cooling Rate (oC/s)*	*Hardness (HV)**	σ_{yield}	σ_{max}	σ_{rup}	*Elongation (%)*
				(MPa)		
Air	12	208 (08.3)	313	536	386	12.3
Cooler	112	478 (12.0)	1595	1742	1376	6.7
Oil	328	501 (10.8)	1185	1586	1259	9.2
Water	530	542 (23.3)	1157	1684	1416	9.0

*values in brackets indicate standard deviations.

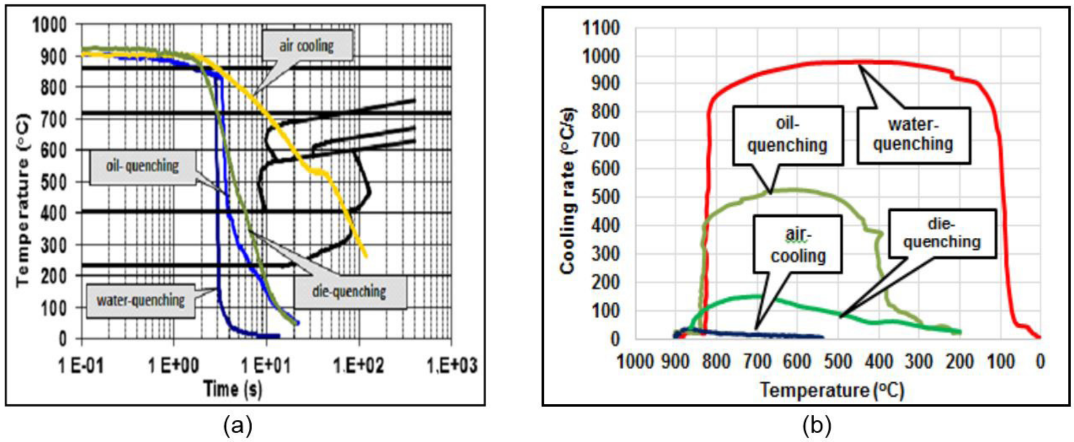

Figure 5. Cooling curves, (a) "temperature x time" superposed on a 22MnB5 CCT diagram; (b) "cooling rate X temperature" for different experimental conditions.

indicating the occurrence of full quenching. The cooling rate (CR) in water quenching condition was the fastest, followed by oil and die quenching. In the air-cooling the CR was only 12°C/s while in the die-quenching was 112 ° C/s, in oil-quenching was 328°C/s and in water-quenching was 530°C/s. In Figure 5b the cooling curves "cooling rate X temperature" for different experimental conditions are shown and it can be seen that there are very significant differences when comparing the quenching curves. In the case of water-quenching the maximum cooling rate (MCR) was 969°C/s and remained near this value during almost the whole cooling process. In the case of oil quenching the maximum cooling rate was virtually half, around 558°C/s and less prolonged. In the die-quenching it was lower (around of 164°C/s) and shorter. In the air-cooling it was inexpressive.

Figure 6 shows the correlation of hardness with average cooling rate. It is possible to observe a significant hardness increase with cooling rate change from 0 until 110°C/s, reaching a hardness of 478 HV with die-quenching. For higher cooling rates the hardness increase were less pronounced, reaching a maximum value of 542 HV with a cooling rate of 530°C/s, which corresponds to the water quenching. It can be noted that the hardness obtained with water quenching (542 HV) is significantly higher than the hardness obtained with the die quenching (478 HV). Similar results, i.e., hardness of 462 HV using a flat cooler die as opposed to more than 500HV with water-quenching, allowing a cooling rate of about 1000°C/s during forced cooling were reported by Nishibata and Kojima [4]. This hardness difference may be explained by undercooling below to M_s temperature which is directly proportional to the cooling rate.

The correlation of the ultimate tensile strength with the cooling rate is shown in Figure 7. It is observed that strength values tend to stabilize when the cooling rate is higher than 100°C/s and for all quenching conditions it was higher than 1600 MPa including low closing pressure die-quenching. The high values of the ultimate tensile strength suggest that

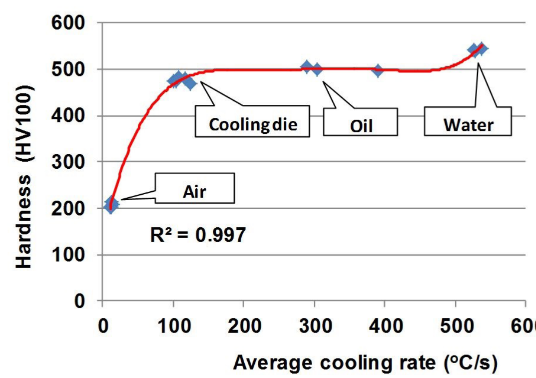

Figure 6. Correlation of hardness with average cooling rate.

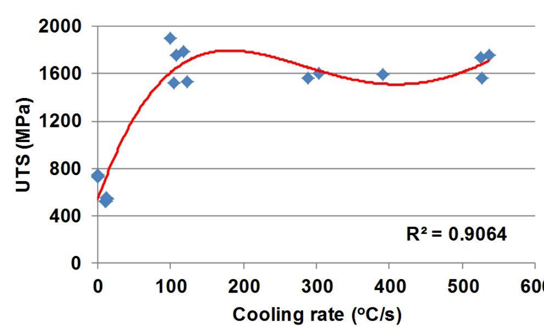

Figure 7. Correlation between ultimate tensile strength and cooling rate.

for all quenching tests, even for the proposed experimental set up, the final temperatures of cooling were very close to the Ms temperature, resulting in the formation of a fully lath-martensite structure. This observation is confirmed by Figure 5a, where it can be observed that none of the conditions of quenching hit the diagram curves, preventing the formation of bainite or even pearlite. The micrographs shown in Figure 8 have confirmed a full lath-martensite microstructure to all quenching conditions.

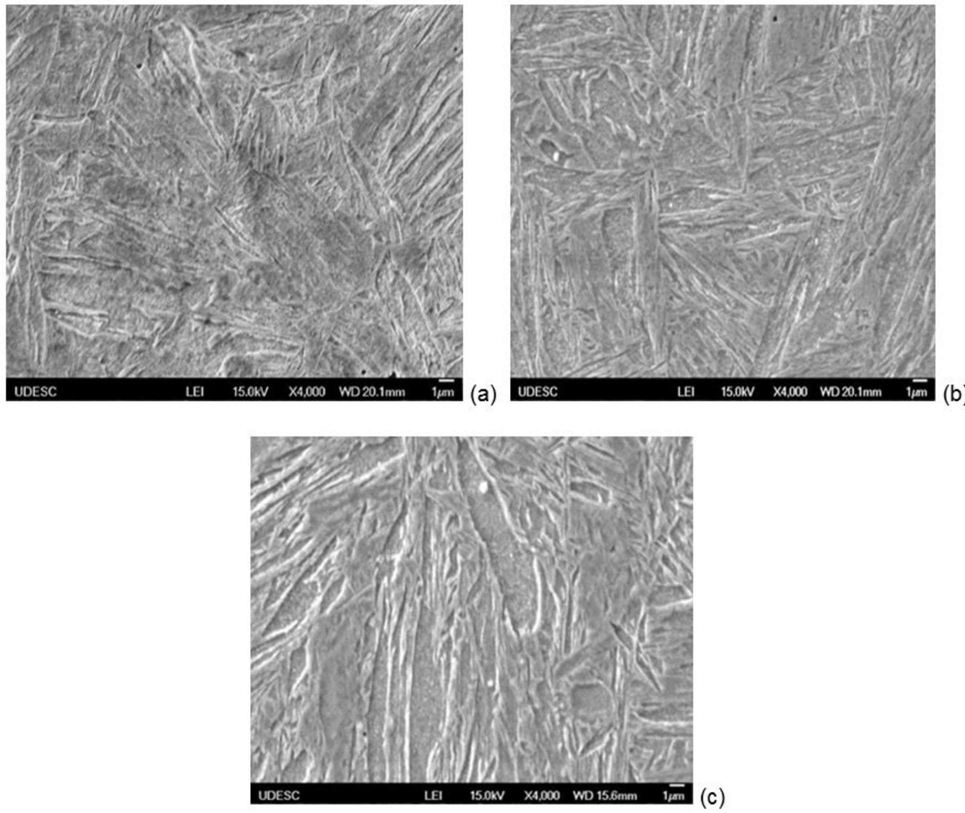

Figure 8. MEV micrographs to different quenching conditions: (a) water (cooling rate 528 °C/s); (b) oil (cooling rate 304 °C/s) and (c) die (cooling rate 108 °C/s).

These results are in agreement whit Nishibata and Kojima [4] who compared the hardenability of boron-containing steel cooling in the water-quenching with a flat dies. He determined that the cooling rate of the die is smaller than in the water-quenching, mainly below 400°C, generating hardness minor than 500HV with the tool-quenching, i.e., 462 HV as opposed to more than 500HV with water-quenching where the average cooling rate during forced cooling is about 1000°C/s. In this study it was observed that, in the case of water-quenching, the microstructure was formed by a more refined lath-martensite (Figure 8a) compared with the microstructures obtained in oil quenching (Figure 8b) and die quenching (Figure 8c) samples.

Concerning ductility, it is noted that for quenching conditions there is a significant increase of average elongation with the cooling rate from 6.7% (die quenching) to 9.0% (water quenching). This could be justified by the higher undercooling that generated a refined lath-martensite in the water quenching. This refinement of the martensite structure has influenced not only the ultimate tensile strength, but affected the hardness and elongation too.

The results of ultimate tensile strength and hardness tests presented a high correlation, as shown in Figure 9. It was observed that the higher the hardness the higher the strength is. What happens is that for steel 22MnB5, in order

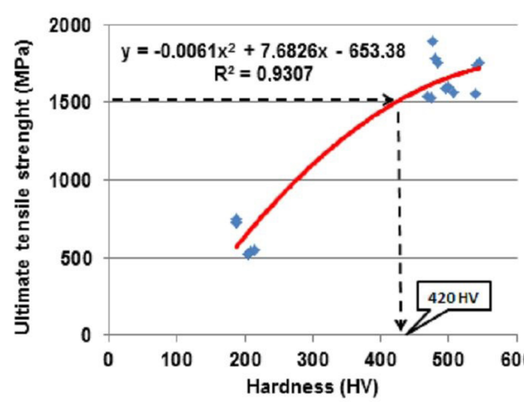

Figure 9. Correlation between the ultimate tensile strength and hardness.

to obtain a tensile strength higher than the 1500 MPa, which can be considered a suitable condition for all applications of this steel, a minimum hardness of 420 HV is necessary. These values could be obtained with this proposed experimental method, indicating their effectiveness. It is also important to note that the value of the correlation coefficient exceeds 0.90 thus showing that the hardness can be used to predict the ultimate tensile strength. Cui et al. [9] correlation was quite similar to the BR1500HS steel.

4 CONCLUSIONS

Results in this study showed that the proposed method allowed obtain values of hardness and ultimate tensile strength normally obtained in hot stamping processes and that the cooling rates were well above the minimum rate required for obtaining a fully lath-martensitic microstructure, indicating the effectiveness of the method.

By applying closing pressures of 0.33MPa and using an aluminum water cooling die simulating the hot stamping process it was possible to obtain cooling rates of around 110°C/s as well as ultimate tensile strength higher than 1600 MPa, hardness exceeding 480 HV and elongation around 6.7%. It was also found that the more intensive cooling rate has an important impact on the properties of 22MnB5 steel, mainly on the hardness and elongation associated with the undercooling below start martensite temperature (Ms), which promotes a lath-martensite refinement effect.

Acknowledgements

The authors would like to thank Arcelor Mittal Vega for providing experimental material and Fapesc/Udesc for financial support (Process 1937/2014_Term 2015/TR 233).

REFERENCES

1 Karbasian H, Tekkaia AE. A review on hot stamping. Journal of Materials Processing Technology. 2010;210:2103-2118.

2 Gorni AA. Novas tendências no processo de estampagem a quente. Corte &Conformação de Metais. 2010;62:62-77.

3 Naderi M. Hot stamping of ultra high strength steels [master's thesis]. Aachen: Rheinish-Westfälischen Technischen Hochshule; 2007.

4 Nishibata T, Kojima N. Effect of quenching rate on hardness and microstructure of hot-stamped steel. Journal of Alloys and Compounds. 2013;577S:549-555.

5 Turetta A. Investigation of thermal, mechanical and microstructural properties of quenchable high strength steels in hot stamping operations [doctor thesis]. Padova: Univesita Degli Studi di Padova; 2008.

6 Bandyopadhyay PS, Kundu SK, Ghosh SK, Chatterjee S. Structure and properties of a low-carbon, microalloyed, ultra-high-strength steel. Metallurgical and Materials Transactions. 2011;42A:1051-1061.

7 Steinbeiss H, So H, Michelitsch T, Hoffmann H. Method for optimizing the cooling design of hot stamping tools Production Engineer. Research for Development. 2007;1(2):149-155.

8 Naganathan A. Hot Stamping of manganese boron steel [master's thesis] Ohio: Ohio State University; 2010.

9 Cui J, Lei C, Xing Z, Li C, Ma S. Predictions of the mechanical properties and microstructure evolution of high strength steel in hot stamping. Journal of Materials Engineering and Performance. 2012;21(11):2244-2254.

10 Geiger M, Merklein M, Lechler J. Determination of tribological conditions within hot stamping. Product Engineer Research Development. 2008;2:269-276.

11 Merklein M, Lechler J, Stoehr T. Investigations on the thermal behavior of ultra-high strength boron manganese steels within hot stamping. International Journal of Material Forming. 2009;2(1):259-262.

12 Ravindran D. Finite element simulation of hot stamping [master's thesis] Ohio: Ohio State University; 2011.

13 Hu P, Ying L, Li Y, Liao Z. Effect of oxide scale on temperature-depend interfacial heat transfer in hot stamping process. Journal of Materials Processing Technology. 2013;213(9):1475-1483.

14 Caron E, Daun KJ, Wells MA. Experimental characterization of heat transfer coefficients during hot forming die quenching of boron steel. Metallurgical and Materials Transactions. B, Process Metallurgy and Materials Processing Science. 2013;44B(2):332-343.

15 Bai Q, Lin J Zhan L, Dean T, Balint D, Zhang Z. A new method determining interfacial heat transfer coefficient and its application in hot/warm forming. In: Proceedings of the 14th International Conference Metal Forming; 2012; Krakón, Poland. Local de publicação: Editora Wenhein - Germany Editora: Wiley-VCH Verlag GmbH & Co. KGaA; 2012. p. 1035-1038.

16 Olah A No. Estudo do efeito da deformação plástica sobre a cinética de transformação de fase do aço 22MnB5 estampado a quente [tese de doutorado] Joinville: Universidade do Estado de Santa Catarina; 2015.

Received: 24 June 2016
Accepted: 25 Out. 2016