Analysis of microstructure and mechanical properties of different boron and non-boron alloyed steels after being hot stamped

M. Naderi\textsuperscript{a}, M. Ketabchi\textsuperscript{a}, M. Abbasi\textsuperscript{a}, W. Bleck\textsuperscript{b}, a*

\textsuperscript{a}Amirkabir University of Technology, 424 Hafez Ave, Tehran, Iran.
\textsuperscript{b}RWTH-Aachen University, Aachen, Germany.

Abstract

Hot stamping is a non-isothermal high temperature forming process, in which complex ultra high strength parts are produced, with the goal of no springback. Boron alloyed steels, especially 22MnB5, have been the point of focus for the materials choice in hot stamping. In this paper four high strength non-boron alloyed steels as well as five boron alloyed steels were hot stamped using water and nitrogen cooling media. Microstructural analyses as well as tensile tests of hot stamped samples were performed. Boron alloyed steels obtained fully martensitic or bainitic microstructure while microstructure of non-boron alloyed steels was consisted of some ferrite phase in addition to martensite and bainite phases. The results showed that boron alloyed steels attained yield and tensile strength values of about 650-1370 MPa and 850-2000 MPa, respectively, while those related to non-boron alloyed steels were, in order, about 600-1100 MPa and 900-1400 MPa.

Keywords: Hot stamping; Boron alloyed steels; Non-boron alloyed steel.

1. Main text

Due to the demand for reduced vehicle weight, improved safety, and crashworthiness qualities, the need to manufacture automobile structural components from ultra high strength steels is apparent. However, unacceptably high stresses during forming of high strength steels and significant springback phenomenon...
makes traditional sheet metal forming technologies unsuitable [1]. The possibility to perform stamping operations at elevated temperatures represents a solution to these problems, allowing lower loads on tools and higher accuracy of formed components [2]. In the industrial process, the blank is heated in the range between 850 and 950 °C and then transferred to the press where the whole deforming phase should take place in fully austenitic conditions [3]. Boron alloyed steels, especially 22MnB5, are the most commonly used steel grades in hot stamping processes. Merklein and Lechler [4] indicated that with the application of 22MnB5 steel, hot stamping process can result in production of components with tensile strength more than 1500 MPa due to changes in microstructure. Naderi et al. [5] analyzed microstructural and mechanical properties of different B-bearing steels after being hot stamped.

In the present research, different boron and non-boron alloyed steels were hot stamped by application of a water or nitrogen cooled punch and resulted microstructures and mechanical properties were compared.

2. Materials and methods

2.1. Chemical composition

Chemical compositions of studied steels are represented in Table 1. Carbon equivalent of investigated steels was calculated according to Ito-Bessyo equation [6]. In Table 1, boron and non-boron alloyed steels are introduced by B and N letters, respectively. While the first letter of symbols for boron alloyed steels is B, those for non-boron alloyed steels is N.

2.2. As-received properties

As-received microstructures of studied steels as well as their thickness and initial mechanical properties are presented in Table 2. It comes from Table 2 that microstructure of boron-alloyed steels consisted of ferrite and pearlite phases while those for non-boron alloyed steels contained different phases.

Table 1 Chemical composition of studied steels.

| Steel | C   | Si  | Mn  | Cr  | Ni  | Al  | Ti  | B   | N   | Ceq |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| B-A   | 0.07| 0.21| 0.75| 0.37| 0.01| 0.05| 0.048| 0.002| 0.006| 0.148|
| B-B   | 0.16| 0.40| 1.05| 0.23| 0.01| 0.04| 0.034| 0.001| 0.246|
| B-C   | 0.23| 0.22| 1.18| 0.16| 0.12| 0.03| 0.04 | 0.002| 0.005| 0.320|
| B-D   | 0.25| 0.21| 1.24| 0.34| 0.01| 0.03| 0.042| 0.002| 0.004| 0.350|
| B-E   | 0.33| 0.31| 0.81| 0.19| 0.02| 0.03| 0.046| 0.001| 0.006| 0.400|
| N-A   | 0.15| 0.57| 1.45| 0.01| 0.03| 0.04 | 0.003 | -   | 0.003| 0.243|
| N-B   | 0.14| 0.12| 1.71| 0.55| 0.06 | 0.02 | 0.002 | -   | -   | 0.258|
| N-C   | 0.19| 0.55| 1.61| 0.02| 0.05 | 0.04 | 0.003 | -   | 0.006| 0.291|
| N-D   | 0.20| 1.81| 1.48| 0.04| 0.03 | 0.04 | 0.006 | -   | -   | 0.337|

2.3. Heat treatment
Different austenization temperatures and soaking times were examined. Due to resulted microstructures and hardness profiles, optimum austenization temperature and soaking time for each grade was selected which are represented in Table 3.

Table 2 As-received properties of studied steels.

| Steel | Thickness (mm) | As-received microstructure (+/5) | Y.S (MPa) | U.T.S (MPa) | Elongation (A25) (%) |
|-------|----------------|--------------------------------|-----------|-------------|---------------------|
| B-A   | 3.5            | 96F-4P                         | 447       | 520         | 28.5                |
| B-B   | 2.7            | 75F-25P                        | 505       | 637         | 16.8                |
| B-C   | 2.8            | 73F-27P                        | 473       | 695         | 25                  |
| B-D   | 3.0            | 70F-30P                        | 478       | 720         | 23.8                |
| B-E   | 3.0            | 47F-53P                        | 580       | 810         | 20                  |
| N-A   | 1.5            | 30F-70M                        | 734       | 1046        | 8.6                 |
| N-B   | 1.5            | 90F-10P                        | 400       | 640         | 26                  |
| N-C   | 1              | 10F-90M                        | 1313      | 1493        | 6                   |
| N-D   | 1              | 66F-34A                        | 514       | 836         | 26.6                |

2.4. Mechanical properties

Determination of the mechanical characteristics were carried out using tensile test for thin sheet metals as represented in DIN 50114 standard [7] at room temperature. The measuring gauge length was 25 mm, which was adjusted by an accurate imaging system, thus total elongation, A25, was determined.

3. Results and Discussion

3.1. Microstructure

Microstructure of studied steels after hot stamping process using nitrogen and water coolant is presented in Table 3. As it is seen in Table 3, microstructure of boron alloyed steels is consisted mostly of martensite phase, while microstructure of non-boron alloyed is a combination of different phases. Presence of boron in composition of boron alloyed steels increases the hardenability and correspondingly high amount of martensite phase is constituted in the microstructure [5]. Very low carbon value of B-A steel grade, despite containing boron, causes no formation of martensite (Fig. 1a and Fig. 2a). Low hardenability of non-boron alloyed steels brings the possibility to constitution of bainite and ferrite phases other than martensite. Among the non-boron alloyed steels the lowest and the highest hardenability relate to N-A and N-D steel grades, respectively. While the former can be related to silicon, the latter can be respected to high value of C eq. Si alloying according to Krauss [8] stabilizes ferrite and extends ferrite phase area and increment in content of C eq about 0.1, reduces austenite to ferrite temperature about 20 °C according to formula presented by Atkins [9]. As it comes from Table 3, for all steel grades as cooling
rate during hot stamping enhanced, using nitrogen as coolant, volume fraction of martensite phase was also scaled up.

Table 3 Microstructure of studied steels after hot stamping process using nitrogen and water coolants.

| Steel | Austenization | Microstructure |
|-------|---------------|----------------|
|       | Temperature (ºC) | Time (min) | WCP | NCP |
|       |                |             | M   | B   | F   | M   | B   | F   |
| B-A   | 950           | 10          | 100 | -   | -   | 100 | -   | -   |
| B-B   | 950           | 10          | 90  | 10  | -   | 90  | 10  | -   |
| B-C   | 950           | 15          | 97  | 3   | -   | 100 | -   | -   |
| B-D   | 900           | 20          | 96  | 4   | -   | 100 | -   | -   |
| B-E   | 900           | 10          | 100 | -   | -   | 100 | -   | -   |
| N-A   | 950           | 20          | 40  | 30  | 30  | 64  | 26  | 10  |
| N-B   | 950           | 10          | 42  | 55  | 3   | 60.5| 36.5| 3   |
| N-C   | 950           | 15          | 55  | 30  | 15  | 67  | 25  | 8   |
| N-D   | 950           | 15          | 70  | 17.5| 12.5| 78  | 15  | 7   |

Fig. 1 Microstructure of two steels after being hot stamped using water cooled punch, (a) B-A steel; (b) N-D steel.

Fig. 2 Microstructure of two steels after being hot stamped using nitrogen cooled punch, (a) B-A steel; (b) N-D steel.
Table 4 Mechanical properties of studied steels after hot stamping process.

| Steel | WCP | NCP |
|-------|-----|-----|
|       | Y.S (MPa) | U.T.S (MPa) | A25 (%) | Y.S (MPa) | U.T.S (MPa) | A25 (%) |
| B-A   | 751  | 882  | 9.5     | 777     | 905     | 9.7     |
| B-B   | 967  | 1354 | 4.7     | 992     | 1350    | 7.6     |
| B-C   | 987  | 1493 | 8.1     | 1050    | 1490    | 7.4     |
| B-D   | 1097 | 1611 | 4.4     | 1137    | 1630    | 5.9     |
| B-E   | 1378 | 2040 | 2.5     | 1378    | 2010    | 1.6     |
| N-A   | 600  | 910  | 9.3     | 894     | 1278    | 3.6     |
| N-B   | 916  | 1260 | 3.7     | 936     | 1287    | 2.5     |
| N-C   | 800  | 1150 | 4.3     | 926     | 1292    | 3.8     |
| N-D   | 787  | 1190 | 5.3     | 1110    | 1400    | 2.0     |

3.3. Mechanical Properties

Table 4 shows that strength values of boron alloyed steels has enhanced in order, while those for non-boron alloyed steels is non-ordered. As microstructure of boron alloyed steels is mostly martensite, the most effective parameter on mechanical properties of these steels is their carbon equivalent; the higher the Ceq, the higher the strength values. As it is also seen in Table 4, ductility value of boron alloyed steels has decreased when Ceq increased. For non-boron alloyed steels which contain different phases it seems that both Ceq value and microstructure have effective role on resulted properties. Low yield strength value of hot stamped N-D steel which has the highest value of Ceq among non-boron alloyed steels, in condition of using water as coolant, can be related to relatively high volume fraction of ferrite phase. It also comes from Table 4 that both strength and ductility values of boron-alloyed steels are almost higher than those of non-boron alloyed steels except for steel B-E which due to ultra high strength has a very low ductility. As composition of boron and non-boron alloyed steels differ largely in the amount of B element, the noted property can be respected to the effect of this element. It is known that boron enhances hardenability [8] and might also act as grain refiner which the former results in high strength and the latter may enhance the ductility. One important point in Table 4 is that the strength values of boron alloyed steels have changed remarkably while those for non-boron alloyed have not; however this can be respected to the wide range of carbon equivalent of boron alloyed steels. Vandeputte et al. [10], mentioned that the ability of a material to have both a good ductility or formability and a high strength is best quantified with the UTS×A25 value that is known as formability index value. Formability index values of all studied steels are represented in Fig. 3. It is observed in Fig. 3 that formability index values of non-boron alloyed steels in case of hot stamping using water coolant are more than those processed using nitrogen coolant, while for boron alloyed steels a general conclusion cannot be concluded. It is also observed that formability index values of B-alloyed steels are generally higher than of non-boron alloyed steels, except for B-E steel which has an ultra-high strength and very low ductility. The highest formability index values among boron and non-boron alloyed steels relate respectively to B-C and N-A steels, which both are hot stamped using water cooled punch and have appropriate ductility. Although due to martensitic microstructure of B-C steel, it has a high U.T.S value, too.

4. Conclusions

In this research, the effect of hot stamping process on mechanical properties and microstructure of boron and non-boron alloyed steels was investigated. The results showed that boron alloyed steels...
obtained mostly martensitic microstructure after hot stamping, while non-boron alloyed steels had microstructures consisted of different phases, however as cooling rates increased the volume fraction of martensite phase increased. It was also concluded that:

1- Boron alloyed steels due to presence of boron element obtained strength and ductility values higher than non-boron alloyed steels.

2- The effect of cooling rate on mechanical properties of non-boron alloyed steels was high, while for boron-alloyed which had a martensitic microstructure this effect was negligible.

3- Usage of water as coolant during hot stamping of studied non-boron alloyed steels resulted in higher formability index but poor homogeneity of microstructure. However the homogeneity improved when nitrogen was used as the coolant.

References

[1] Liu HS, Xing ZW, Bao J, Song BY. Investigation of the Hot-Stamping Process for Advanced High-Strength Steel Sheet by Numerical Simulation. J Mater Eng Perform 2009; 19: 325-334.

[2] Mori K, Okudo Y. Tailor die quenching in hot stamping for producing ultra-high strength steel formed parts having strength distribution. CIRP Ann-Manuf Technol 2010; 59: 291-294.

[3] Naderi M, Ketabchi M, Abbasi M, Bleck W. Analysis of Microstructure and mechanical properties of different high strength carbon steels after hot stamping. J Mater Proc Technol 2011, In Press, Corrected Proof.

[4] Merklein M, Lechler J. Investigation of the thermo-mechanical properties of hot stamping steels. J Mater Proc Technol 2006; 177: 452-455.

[5] Naderi M, Ketabchi M, Abbasi M, Bleck W. Analysis of microstructure and mechanical properties of different hot stamped B-bearing steels. Steel Res Int 2010; 81: 216-223.

[6] Patchett BM. CASTI metals blue book, welding filler materials. 4th edition. Alberta: CASTI Publishing Inc.; 2003.

[7] DIN 50114, Zugversuch an dünnen Blechen.

[8] Krauss G. Steels: Heat treatment and processing principles. New York: ASM International; 1990.

[9] Atkins M. Atlas of continuous cooling transformation diagrams for engineering steels. Leeds: Chorley & Pickersgill Ltd.; 1977.

[10] Vandeputte S, Vanderschhuern D, Claessens S, Martinez LT. Modern steel grades covering all needs of the automotive industry. 9th International conference on Steel Sheet Metal, Leuven, Belgium, 2001: 405-414.

Fig. 3 Formability index values of studied steels for two conditions of using water and nitrogen as coolant.