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TAILOR TEMPERING AND HOT-SPOTTING OF PRESS HARDENED BORON STEELS

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Abstract

Hot forming processes are becoming a successful solution when complex geometrical components with high mechanical properties are desired. In fact, automotive structural components with tensile strengths higher than 1500MPa are being nowadays industrially produced. The technology is based on the forming and quenching of the sheet inside the forming tool using boron steels.

Aiming at boosting the advantages of this technology, car manufacturers have started to demand structural components with different mechanical behavior areas in order to improve the impact response of the auto-motive passenger compartment: the so called tailor tempered components. The basic idea is to obtain final parts with different properties like it has been successfully done using tailored welded blanks. Although different solutions exist, one of the most common strategy is to use partially heated tooling, which influences the cooling of the sheet and consequently the local properties.

At the present work, a special tooling with independent heated and cooled areas has been developed in order to evaluate the final properties achievable in the tailored tempering process. High and low conductivity alloys have been used to find the process limits and compare them to classical tool steels. Hardness values, Ultimate Tensile Stresses and microstructures are shown for different steels, tool temperatures and contact pressures.

Furthermore, and in the last part of the paper, the results covering the hot spotting process are presented. Different air gap diameters have been used to evaluate the possibility to create soft spots that will enable an easier cutting of geometrically accurate holes and a more suitable and ductile joint between different components by using the spot welding technology.

Key words: Hot Stamping, Boron Steels, Tailor tempering, Hot Spotting

1. INTRODUCTION

Hot formed components are becoming increasingly popular in the automotive industry and the mechanical properties of these materials has led to their application in chassis components such as A/B-pillar reinforcements, bumpers, door beams, roof rails, and other structural members. Hot formed components are manufactured by austenizing boron steel blanks in a furnace and then simultaneously forming and quenching them within a cooled tool. As the blank is quenched within the tool at a rate greater than 30 ◦C/s, the austenitic microstructure transforms into martensite (see figure 1). A fully martensitic microstructure is generally desired due to very high tensile strengths of approximately 1500 MPa and Vickers hardness values bigger than of 425 HV.

The hot stamping process is a mature technology and currently exists in two different main variants: the direct and the indirect hot stamping method. In the direct hot stamping process, a blank is heated up

236 – 244 ISSN 1641-8581

in a furnace, transferred to the press and subsequently formed and quenched in the closed tool. The indirect hot stamping process is characterized by the use of a nearly complete cold pre-formed part which is subjected only to a quenching and calibration operation in the press after austenitization (see figure 2) (Karbasian & Tekkaya, 2010).

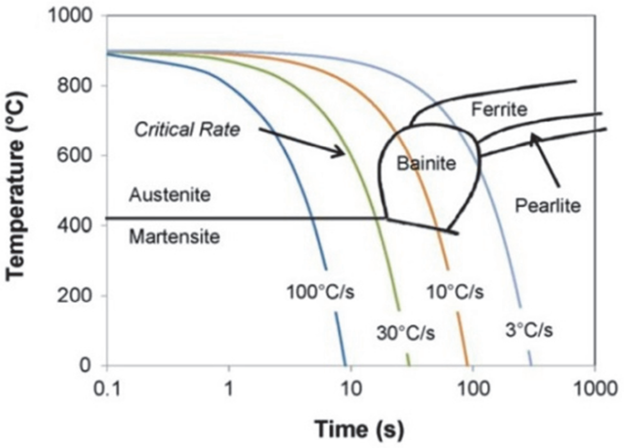

Fig. 1. *CCT for Usibor® 1500P.*

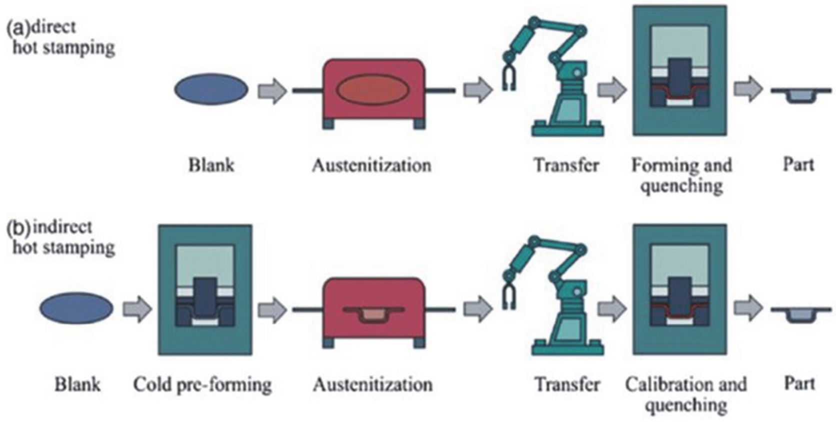

Fig. 2. *Hot stamping process chains (Karbasian & Tekkaya, 2010).*

Fully martensitic hot formed part exhibits very low levels of ductility and are rarely used in energy absorbing structures. For some applications, such as B-pillars and other automotive components that may undergo impact loading, it may be desirable to create regions of the part with softer and more ductile microstructures. The novel process, usually called the tailored tempering, allows doing this by suppressing the martensitic transformation in those zones of the sheet located under heated parts of the tools.

Bardelcik et al. (2010) examined the strength and strain-rate sensitivity of Usibor® 1500P subjected to various cooling rates both above and below the critical rate of 30 ◦C/s. They showed that quenching below 30 ◦C/s results in suitable mechanical properties for improving the crash performance of this material. Aiming to achieve these cooling rates in industrial dies, mainly four techniques have been used to produce tailored parts: 1) post-tempering of the fully hardened parts 2) differential heating within the furnace 3) tailor-welding blanks with different grades of steel and 4) tool tempering using locally heated tools or different tool materials with varying thermal conductivities.

The work of Wilsius et al. (2011) examines differential heating within the furnace of production-scale B-pillars. They reported a UTS of approximately 700 MPa in the tailored region compared to a UTS of approximately 1600 MPa in the fully hardened region. Stöhr et al. (2009) performed similar differential furnace heating techniques and they achieved a UTS of approximately 1600 MPa in the fully hardened region and 1100 MPa in the tailored region. Ghiotti et al. (2009) indicated that the use of a furnace with areas kept at different temperatures and the employment of resistance heating are two possible approaches for differential heating. When using differential heating, the material properties differ in different zones and this effect influences the forming step. If the minium temperature is too small, big springback differences could cause strong geometrical deviations among different zones.

Múnera et al. (2008) developed components using tailor welded blanks comprised of both hot forming steel and steel which is not as easily hardened, thus providing regions of very high strength and others with reduced strength. They demonstrated that is possible to reduce the total mass of a component by 20% while maintaining similar energy absorption characteristics.

Casas et al. (2008) examined new tool materials with varying levels of thermal conductivity to control the heat extraction from the blank during forming and quenching. Using tool steel in the tailored region with approximately 90% lower thermal conductivity than tool steel in the fully hardened region they have been able to achieve tensile strengths of 600 MPa and 1500 MPa, respectively.

Using tool tempering techniques, Lenze et al. (2008) indicated that is possible to create a part with areas of very high strength for intrusion protection, and others regions with increased ductility for energy absorption. The selected tool temperature influences the cooling rate during quenching and the final phases of the material. Therefore, the material properties of the parts can be selectively adjusted by means of the different tool temperatures. With a similar approach, Banik et al. (2011) produced a component with a hardness of approximately 200 HV in the tailored region and 425 HV in the hardened region with no indication of the heated die temperature. Merklein and Svec (2010) performed similar in-die heating studies with heated die temperatures up to 500 ◦C and have achieved hardness levels of 240 HV in the heated region and 420 HV in the cooled region.

Graff et al. (2011) performed studies using in-die heating techniques up to 500 ◦C with quench durations of 25 s and they showed a decrease in strength of approximately 50% when compared to fully quenched material. Ertürk et al. (2011) used the in-die heating technique with tool temperatures up to 550◦C and quench durations of approximately 20–25 s. They showed a similar decrease in the strength of the material of approximately 50% compared to a fully martensitic condition.

George et al. (2012) performed experiments with a full-sized B-pillar with two individual heating zones up to 400 ◦C and one cooling zone (see figure 3). They measured Vickers hardness of 250–270 HV with a 500 ◦C tool and a decrease in tensile strength of approximately 50%. Ghiotti et al. (2009) have presented a paper for the accurate simulation of the tailor tempering process comprising material characterization, numerical analysis and forming of semi-industrial profiles with varying properties (George et al., 2012).

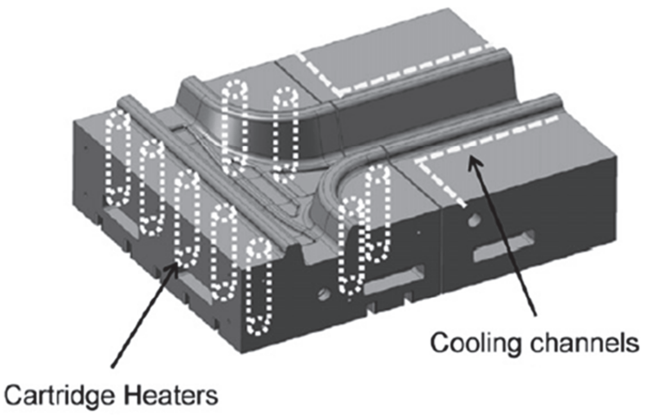

Fig. 3. *Segmented tool design by George et al. (2012).*

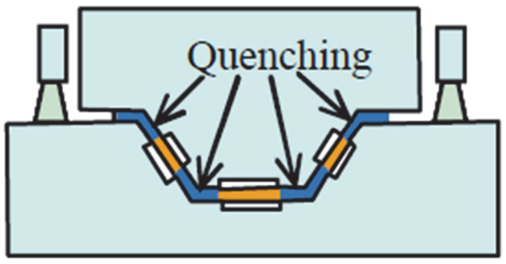

Fig. 4. *Tool with air gaps by Mori and Okuda (2010)*

Although the work presented by Mori and Okuda (2010) has not gain the attention of the industry it is a very clever and simple method to create different properties along the part. In the study, air pockets were used to avoid the fast cooling of certain areas where soft properties were desired (see figure 4).

2. MOTIVATION AND RESEARCH APPROACH

The motivation of the present work has been to verify the industrial applicability of three different approaches of tailor tempering and their advantages. The different selected processes have been the following:

1) The tailored quenching using varying thermal conductivity tool steels without heating cartridges for the soft zone, which its validity is not totally clear with the current available studies for in industry available special tool steels
2) The tailored quenching using different tool temperatures and high and low conductivity tool steels, with the specific objective to study if it is possible to lower the heated zone's temperature in comparison to conventional tool steels
3) The hot spotting using air gaps to study the possibility to produce local soft circular areas for their easy cut in the post forming operations and for their spot welding to create more ductile joins

For that, two special industrial tool steels having very different thermal conductivities have been used and a tool system having two thermal zones and an incorporated joule effect heating device for the heating of the sheet has been developed.

In order to study the applicability of the hot spotting, air gaps with different diameters have been machined in the above mentioned tool plates.

3. TAILOR TEMPERING TESTS

3.1. Tooling development

The cooling rate of a hot blank that is quenched within a cold tool is driven, principally, by the difference in temperature between the two surfaces in contact, the heat conductivity of the materials, and the contact pressure, among others. As the aim of the paper is to study the industrial applicability of the tailored tempering using three different approaches, a segmented tool system has been built up to create a low conductivity and a high conductivity area.

Tool steels in contact with the sheet are changeable for using different steel grades. In the present work, a special tool steel ROVALMA GTCS-550 has been used for the low conductivity zone and a ROVALMA HTCS-150 high conductivity tool steel for the high conductivity zone. Thermal conductivities of both steels are shown in table 1.

Table 1. *Thermal conductivities of the special tool steels.*

Tool Steel	Thermal Conductivity (W/mK) at 42 HRc			
	25ºC	200 ºC	400 ºC	600 ºC
GTCS-550	5.66	8.05	10.03	13.53
	Thermal Conductivity (W/mK) at 50 HRc			
	25ºC	200 ºC	400 ºC	600 ºC
HTCS-150	55	53	47	--

One half of the tooling is equipped with internal heating from cartridge heaters and cooling using chilled water recirculation was used in the other half. A schematic of the tooling is shown in figure 4, indicating the location of the cartridge heaters and cooling channels. The cartridge heaters have been divided into two separate PID controls to improve the temperature uniformity across the heated zone of the tool. Temperature control thermocouples have been placed 10 mm below the surface and additional 12 thermocouples have been used to monitor thermal uniformity in the exchangeable tool steels at 2.5 mm from the contact surface.

The sheet is directly heated in the tool using a joule heating device in order to avoid heat loses during the transport and to assure repeatability between the different tests.

To insulate the two halves of the tool, a 5 mm thick layer of structural ceramic insulation has been used between the two halves of the tool and a 20 mm ceramic insulation has been placed in the upper and bottom part of the die to minimize heat loss from the tool to the press. Insulation has been demonstrated to be very efficient and maximum temperature of 50ºC is measured in the cooled part when 550ºC are reached in the heated zone, where maximum temperature gradient is of 25ºC.

As it is shown in figure 5, the selected final geometry of the part is a flat sheet. The exchangeable tools have been machined and polished following industrial procedures of collaborative industrial partners.

Final industrial experimental set-up is shown in figure 6.

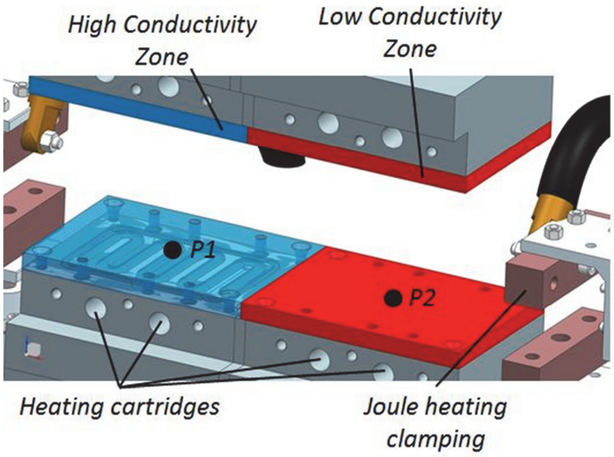

Fig. 5. *Tailor tempering tooling schema.*

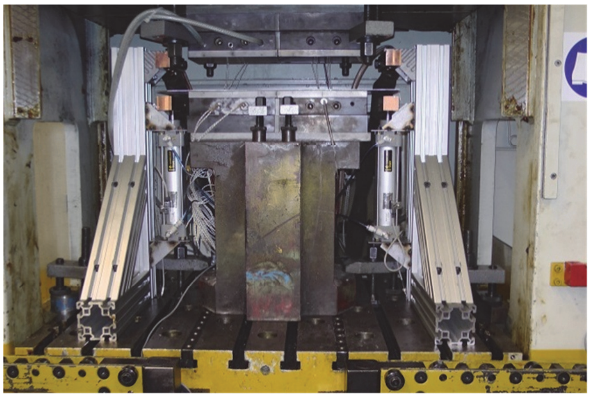

Fig. 6. *Experimental set-up.*

3.2. Material description

The material used for this study has been the Usibor® 1500P which is manufactured by ArcelorMittal. It is a boron steel developed specifically for the hot forming process which is pre-coated with an aluminum–silicon coating for oxidation protection. The blanks have a nominal thickness of 1.8 mm.

3.3. Experimental method and results

Tailor quenching experiments were performed using the above mentioned tool as out-lined in the test matrix presented in table 2.

First of all a baseline tempering test was performed cooling both sides of the tools (temperatures near 25ºC) to study the effectiveness of using very different thermal conductivity tools. In a second step, low conductivity tool temperature was varied from 150ºC to 450ºC to study the influence of this parameter in the final properties of the resulting part.

In all the tests, 20 MPa of contact pressure was used and the press velocity was set to 100 mm/s. Holding time after contact was 20 s. As explained before, the sheets were heated to 900ºC using a joule heating device being the heating time approximately 35 s.

Table 2. *Test matrix.*

Trial	High conductivity tool temperature (ºC)	Low conductivity tool temperature (ºC)
1 (base)	25	25
2	25	150
3	25	250
4	25	350
5	25	450

Figure 7 shows the temperature–time history of a blank that was heated to 900◦C and quenched using a nominal temperature of 450ºC at the low conductivity zone and 25ºC at the high conductivity one. After austenitization of the blank by joule heating, transfer and cooling of the sheet can be observed in the graph. The total time for this operation is approximately 1.5s before the press contacts the heated sheet. As it is observed in the cooling graphs, very different cooling rates are obtained in the heated low and cooled high conductivity zones resulting in tailored properties of the part.

After the hot forming experiments were completed at the various heated die temperatures, samples were cut from the quenched parts and prepared for micro-hardness testing, microstructure analysis and mechanical testing. The mechanical testing and microstructure analysis samples were taken from two different locations, one in the high conductivity zone named P1 and a second one in the low conductivity zone named P2 (see figure 5).

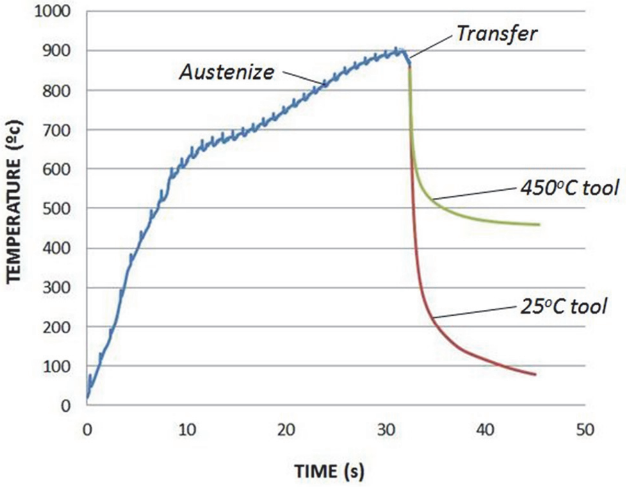

Fig. 7. *Temperature–time history of the blank.*

Figure 8 shows the different micro-hardness values obtained when different tool temperatures were used in the heated GTCS-550 zone. Each hardness data represents an average measurement of three through-thickness measurements from three different parts formed at the same conditions. It is clearly observed that minimum temperature to obtain tailor properties is 350ºC. The transition zone is about 40 mm long.

In figure 9, the stress-strain curves of the different samples cooled down using different tool temperatures are shown. Samples quenched at 25ºC using high conductivity and low conductivity tool material show similar behavior, although the high conductivity sample is slightly higher at low strains. Ultimate tensile stress decreases as temperature of the soft zone is increased.

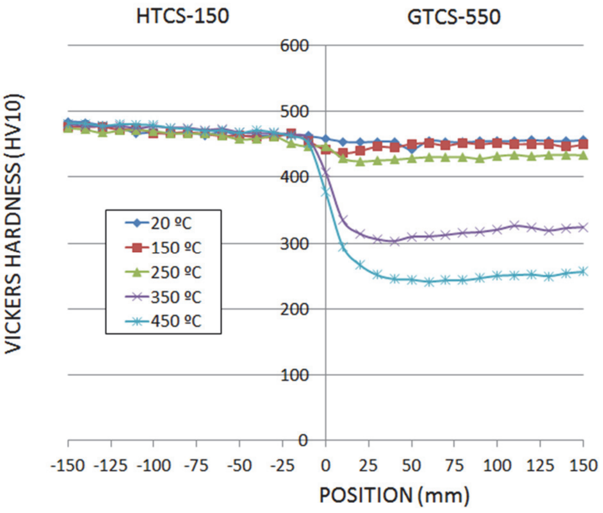

Fig. 8. *Hardness along the tailor tempered parts.*

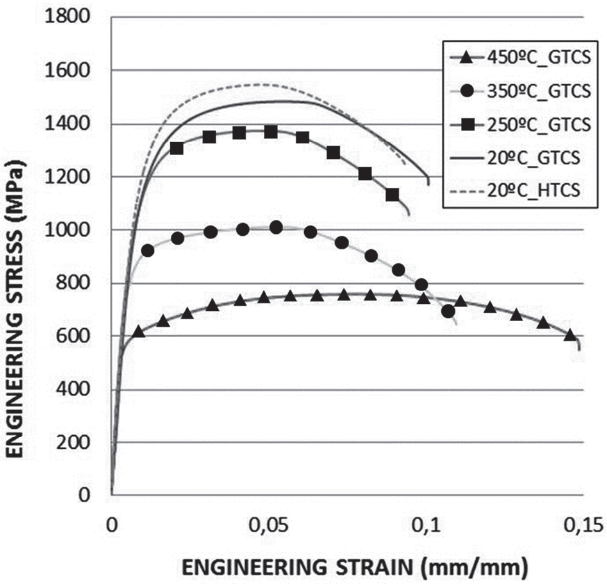

***Fig. 9.** Engineering stress vs. strain results.*

In figure 10 the different microstructures for very rapid cooling, slow cooling and intermediate cooling rates are shown. Fully martensitic structure has been found for all the high conductivity zone samples. Fully bainitic structure has been found in the soft zone for the sample quenched at 450ºC and using the low conductivity tool material. Combined martensitic-bainitic structure is present for the 250ºC and 350ºC tests.

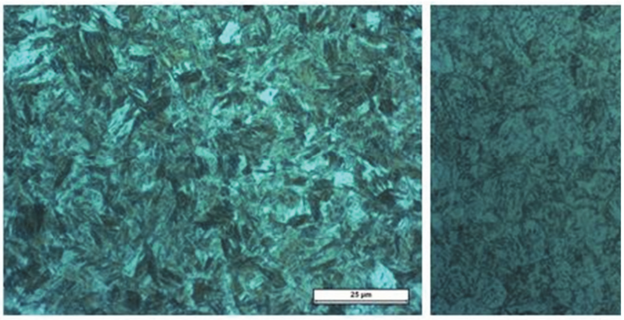

***Fig. 10.** Final microstructures of tailored quenched parts. a) fully martensitic (rapid cooling), b) fully bainitic (slow cooling) and c) combined martensitic-bainitic (intermediate cooling, bainite is highlighted with arrows).*

4. HOT SPOTTING TESTS

4.1. Tooling development

Aiming to verify if air pockets can be used for hot spotting and creating soft areas, the HTCS high conductivity tool inserts were machined using 1.0 mm depth pockets. Different size diameters ranging from 20 to 50 mm were used to identify the minimum size needed for lowering the material hardness in the soft areas. These soft spots enable a later easy cutting of holes with high geometrical accuracy and spot welding of different components having more ductile crash properties.

A schematic cross section of the tooling is shown in figure 11. The upper tool is symmetrical to the lower one and no contact exists between the sheet and the tool in the circular air gap areas resulting in a hot spot during the process. The real tool with a machining of 50 mm diameter is shown in figure 12.

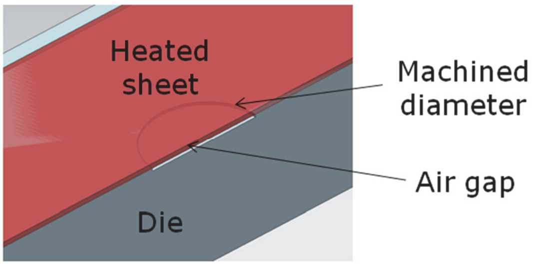

***Fig. 11.** Tooling schematic drawing.*

***Fig. 12.** Real tool with 50 mm diameter.*

4.2. Experimental method and results

The same USIBOR 1500 P material was used in the hot spotting experimental tests. The lower and upper tools were water cooled as explained before and the contact pressure was maintained at 20 MPa in all the tests and the closing speed of the hydraulic press was 100 mm/s.

After the hot spotting experiments were completed samples were cut from the quenched parts and prepared for micro-hardness testing, microstructure analysis and mechanical testing. For this last task sub-size specimens were cut from the hot spot center of the different sheets with a gauge length of 6 mm (see figure 14). This length was defined after the micro-hardness measurements and is the maximum one to guarantee the testing of a quasi-homogeneous hardness material portion.

The microstructural analysis is not presented since the results were very similar to the ones observed in the tailor tempering tests. Fully martensitic microstructure was observed for the small diameters and combined martensitic-bainitic structures appeared as the air gap diameter was increased.

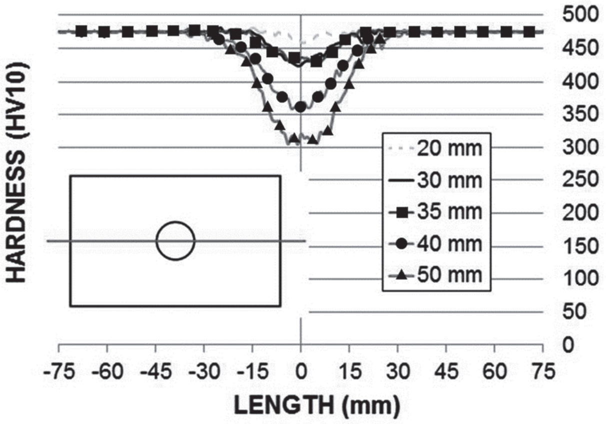

Fig. 13. *Hardness along the hot spotted parts.*

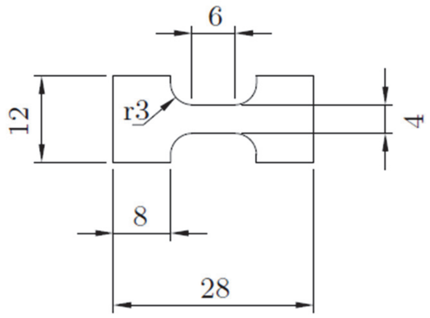

Fig. 14. *Sub-size specimen.*

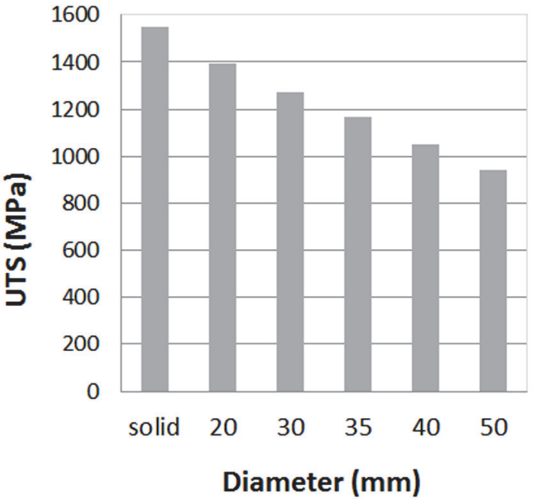

Fig. 15. *Ultimate Tensile Stress (UTS) for the different hot spots.*

In figure 13 the hardness distributions along the hot spots are shown for the different air gap diameters. A minimum diameter of 30-35 mm is needed to decrease the hardness of the material.

In figure 15, the Ultimate Tensile Stresses (UTS) of the different hot spots are shown. The stress decreases with the air gap diameter. Elongation at rupture is not included since the specimens are not following any standard.

5. CONCLUSIONS

The following key conclusions can be drawn from the present study:

It has been demonstrated that cooled low conductivity tool steels are not sufficient on their own for tailor tempering of boron steels. Temperature difference between the sheet and the tool is the main dominating factor to control the cooling rate. In comparison to conventional tool steels (Uddeholm Orvar Supreme steel for example) a slight improvement on final UTS is observed when using the Rovalma high conductivity HTCS steel. This could enable a shortening of the cycle time in industrial production but further research is needed using industrial production tools to confirm this evidence.

On the other hand, the use of cartridge heaters has proven to be effective to obtain tailor properties in hot stamped parts (minimum hardness of 240 HV). Joule heating device has been also successfully employed for in tool heating of the sheets leading to very fast heating times and reasonable hardness values. At the same tooling, the use of cooling channels and chiller for the high conductivity zone allows the total quenching of the blank resulting in a maximum of 484 HV hardness. Although low conductivity steels offer an advantage to reach slower cooling rates in the heated blank, the temperature difference between the sheet and the tool is the main governing process variable.

Hot spotting has been successfully applied to flat surfaces by using air gaps. The final hardness distribution depends on the gap diameter and a minimum of 30-35 mm diameter is needed to lower the material hardness. With smaller gaps, the neighbor material cools down the central area of the hot spot sufficiently fast to obtain the maximum hardness levels and a fully martensitic structure.

During the experimental tests, authors have observed that the different thermal expansion of the cooled and heated zones is crucial for a proper quenching of the part, since the gap must be tuned for the selected temperatures to assure a proper contact pressure between the tool inserts and the blank. A misalignment of the cooled and heated zones leads to an incorrect contact pressure in the high conductivity or cooled zone, resulting in very poor hardness values of the final product.

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ZRÓŻNICOWANIE WŁASNOŚCI I ZGRZEWANIE PUNKTOWE BLACH ZE STALI Z BOREM HARTOWANYCH W MATRYCY

Streszczenie

Procesy przeróbki plastycznej na gorąco są skuteczną metodą wytwarzania wyrobów o skomplikowanym kształcie i wysokich własnościach mechanicznych. Wytwarzane są obecnie elementy nadwozia samochodu o wytrzymałości na rozciąganie rzędu 1500 MPa. Technologia wytwarzania dla stali z dodatkiem boru wykorzystuje kolejne operacje kształtowania i hartowania w narzędziach. Aby w pełni wykorzystać możliwości tej technologii producenci samochodów wykazali zainteresowanie w komponentach charakteryzujących się zróżnicowaniem własności mechanicznych w ich różnych obszarach. Miało to na celu poprawę zdolności tych komponentów do akumulowania energii w razie kolizji samochodu i do zabezpieczenia kabiny pasażerów przez odkształceniem. Takie elementy posiadają różne własności w różnych obszarach (ang. tailored tempered components - TTC). Podstawową ideą technologii TTC jest uzyskanie komponentu o zróżnicowanych własnościach, tak jak to ma miejsce w przypadku stosowanych obecnie blach o różnych własnościach spawanych laserowo (ang. Tailored Welded Components). Chociaż znanych jest kilka metod uzyskiwania zróżnicowania własności to wydaje się, że najbardziej popularną jest zastosowanie częściowego podgrzewania narzędzi do tłoczenia, które pozwala na zróżnicowanie prędkości chłodzenia w różnych częściach wyrobu. W konsekwencji uzyskuje się zróżnicowanie lokalnych własności w wyrobie.

W ramach niniejszej pracy zaprojektowano specjalne narzędzia z możliwością niezależnego nagrzewania i chłodzenia poszczególnych obszarów. Wykorzystując te narzędzia przeprowadzono badania i wyznaczono lokalne własności wyrobów. Przebadano stale narzędziowe o niskim i wysokim współczynniku przewodzenia ciepła. Dla różnych stali, różnych temperatur narzędzia i różnych nacisków wyznaczono twardość i wytrzymałość na rozciąganie oraz mikrostrukturę gotowego wyrobu.

W dalszej części pracy przedstawiono wyniki badań dla procesu punktowego dogrzewania. Badano różne średnice szczeliny powietrznej aby ocenić możliwość wytworzenia w blasze miękkich obszarów, które pozwoliłyby na łatwe wycinanie dokładnych wymiarowo otworów oraz na tworzenie plastycznych połączeń metodą zgrzewania.

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