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Effect of Necking Behavior and of Gap Size on the Cooling Rate in Hot Stamping

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In this study, a tailored die quenching experimental method using low closing pressures and an aluminum flat die was developed in order to evaluate the effects of the gap size on the cooling rate in the hot stamping process of a 22MnB5 steel grade. Initially, the necking behavior in hot stamping was investigated by deforming the specimens to different strain levels and subjecting them to quenching in order to assess this effect on the gap profile formed between the die surface and the sample. Next, a controlled gap was promoted in the central region of the aluminum cooler using aluminum spacers (simulating the gap) with different thickness (0.06/0.15/0.40/0.70mm). Then, its effects on the cooling rate and on the hardness after quenching were evaluated. The results showed that the cooling rate is very susceptible to gap size, that the ideal situation occurred when there was no gap, good heat transfer and higher average cooling rates of 120°C/s were achieved, and that when the gap was wider than 0.20mm the average cooling rates were lower than 20°C/s, consequently below the critical 22MnB5 steel cooling for quenching, which is 28°C/s.

Keywords: *hot stamping, cooling rate, 22MnB5 steel, necking, gap effect, quenching*

1. Introduction

In the stamping process the blank is subjected to a plastic deformation which, depending on component geometry, operational conditions and strain level, can generate a local deformation or a necking, which is considered a plastic instability. In the hot stamping process this phenomenon is even more sensitive for two reasons: the deformation takes place at high temperatures in the metastable austenitic phase with the face-centered cubic (FCC) structure, resulting in changes to the mechanical properties of the material. Also, it is due to the fact that the material is hot formed in a face-centered cubic (FCC) structure and simultaneously quenched to room temperature, in order to obtain a component with good dimensional accuracy and high mechanical resistance[1]. In this case the necking causes a sheet thickness reduction generating a gap between the surfaces of the stamped component and the stamping die, thus affecting the efficiency of heat transfer. This gap, depending on its shape and intensity, can affect the cooling rate to the point of damaging the microstructure, reducing the mechanical properties of the material. This effect, along with the effect of reducing the section, can be considered critical, since it increases the localized weakness, affecting component performance. Diffuse necking can be acceptable, whereas localized necking is undesirable, because it results in localized deformation and instability that can lead to breakage of the component. Several theoretical and experimental studies were conducted in order to investigate the effect of localized necking and contact conditions on the heat transfer in hot stamping process[2-8]. In most of these studies it was found that the condition of contact between the tool and the material during hot stamping interferes significantly in cooling condition. It was noted that when there is a perfect contact between the tool and the blank surface the heat transference occurs preferably by conduction and the temperature decreases rapidly. It was also noted that when the contact between the surfaces is inadequate, even at high working temperatures, a coarse martensitic structure or even an upper bainite is generated, reducing mechanical properties. Salomonsson[9] has proposed that the heat transfer is lower with materials with greater roughness, resulting in a smaller contact area between the surfaces. Different authors[10-13] have investigated the effects of localized gap in the cooling behavior of hot stamped automotive components and have found that the gap between the tool and the blank significantly affects the heat transfer coefficient. Despite the gap being considered a harmful effect, it may be interesting in particular cases. In some situations the existence of differentiated mechanical characteristics in different regions of the component is necessary, in order to meet some specific requirements. This can be achieved through the development of tailored die quenching. It is possible to establish a control of the cooling process, allowing a better control over the resulting microstructure[14-17]. This is accomplished by using localized grooves on the forming tool surface, creating a controlled gap between the surfaces of the tool and of the blank, enabling heat extraction coefficient control and a cooling rate below the critical speed required for formation of a fully martensitic structure. Despite this, the effects of the gap size in the

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cooling rate and their consequences to the final hardness of hot stamped components have not sufficiently been studied yet. In this study, a tailored die quenching experimental method, using low closing pressures and an aluminum flat die, was developed in order to evaluate the effects of the gap size on the cooling rate in the hot stamping process.

2. Experimental setup and test procedures

The experimental apparatus was composed of three systems: an electrical resistance heating furnace, a mechanical testing machine and a water cooled aluminum flat die with a force multiplier system that promoted a 0.33MPa closing pressure on the test specimen. Figure 1 shows a schematic representation of the experimental set up. Test procedures were previously described in detail[18]. Temperature evolution was controlled using a type K thermocouple located inside the furnace 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 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 2. A thin layer of high temperature resistant paste was applied over the test specimen in order to inhibit oxidation during heating.

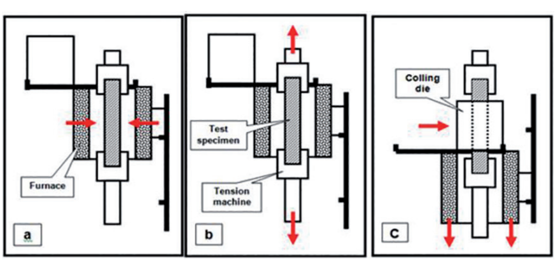

Figure 1: Schematic diagram of the experimental apparatus (a) heating system (furnace), (b) deformation system (mechanical test machine) and (c) cooling die.

In order to investigate the necking effect, specimens were heated to 930°C/4minutes and subjected to different axial deformations (0, 6, 15, 28, 38, 46, and 53%) using a deformation rate of 100mm/s. Then, the furnace was removed through a vertical displacement system and the cooler die immediately introduced through horizontal displacement, promoting test specimen quenching. This operation was conducted in a very fast time (3 to 5s) to avoid excessive temperature loss. Next, the thickness and the hardness profile along the test specimen were measured.

In the study of the localized neck effect, both size and location of the gap were controlled, which had not been possible in the experiment described above since the contraction in the test specimens happened at random. To evaluate these effects aluminum spacers (simulating the gap) with 40 mm width and different thickness (0.06/0.15/0.40/0.70mm) were deployed in the central region of the aluminum cooler (Figure 3). A thermocouple was fixed in the no cooling region in order to obtain cooling curves. The specimens were heated at 930°C/4minutes and afterwards were quenched by the aluminum cooler. This cooling curves were obtained by defining the characteristic points "Ti" and "Tf" (initial and final temperatures), "ti" and "tf" (initial and final cooling times), and by calculating the average cooling rates CR = (Ti-Tf)/(tf-ti)[18]. Results were assessed by hardness measurements along the test specimen and metallographic analysis using scanning electron microscopy.

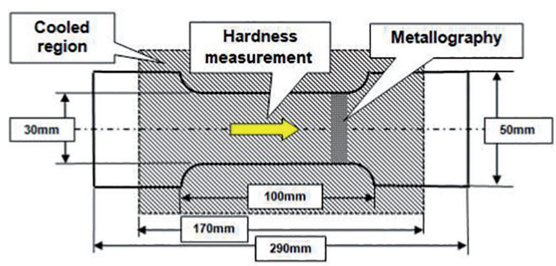

Figure 2: Test specimen showing cooling region and sampling details.

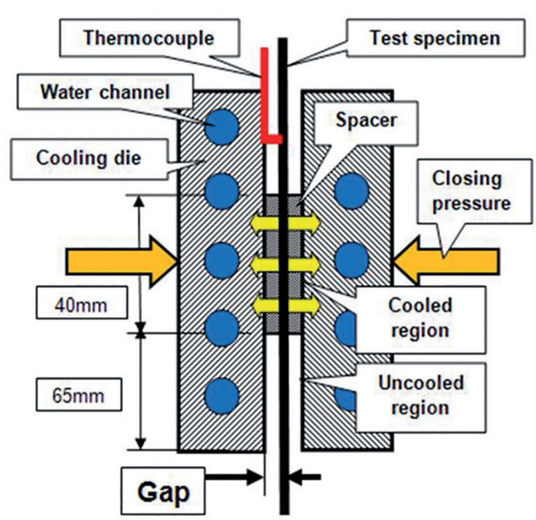

Figure 3: Detail of the experimental arrangement for cooling of the samples.

Table 1: Chemical composition of 22MnB5 steel (source: Arcelor Mittal).

Element	C	Mn	P	S	Si	Cu	Ni	Mo	Cr	Al	Ti	Bo
wt %	0.23	1.19	0.008	<0.001	0.24	0.03	0.02	<0.02	0.20	0.03	0.035	0.003

3. Results and discussion

3.1. Necking formation

The necking formation occurs when the specimen is subjected to axial deformation, creating a gap between the sheet surfaces and the die, affecting heat transfer when it is hot stamped, according to what is shown schematically in Figure 4.

Figure 5 presents the stress-strain curve showing the mechanical behavior of the 22MnB5 steel sheet heated at 930°C and deformed using a rate of 100 mm/s. The test specimen was subjected to different deformations (0, 6, 15, 28, 38, 46, and 53%) within the diffuse (ε_D) and localized (ε_L) necking fields, and after that, rapidly quenched through the cooler die.

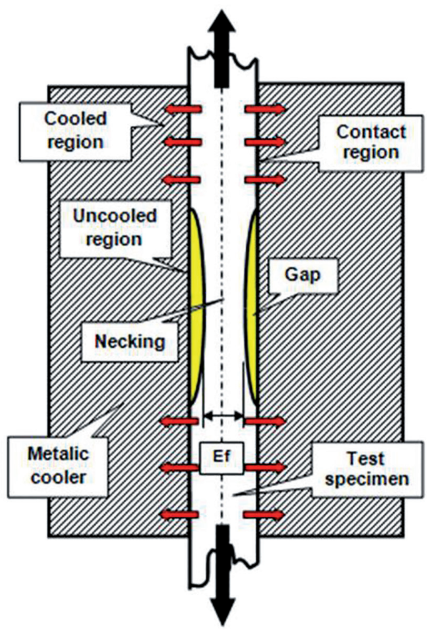

Figure 4: Necking and gap formation in hot stamping test using axial deformation.

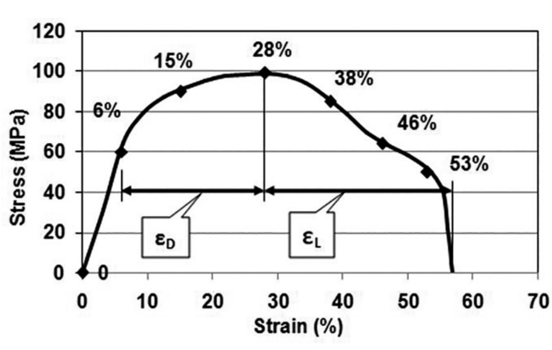

Figure 5: Stress-strain curve showing necking fields and applied deformations.

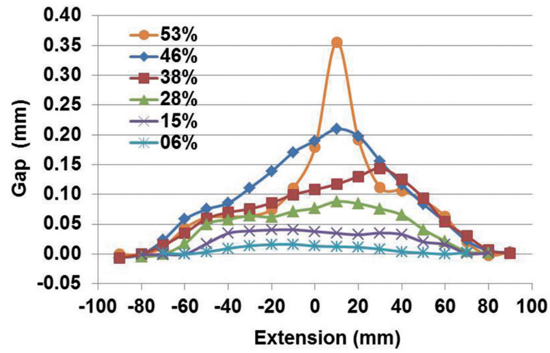

Figure 6: Gap profile along the test specimen as a function of axial deformation.

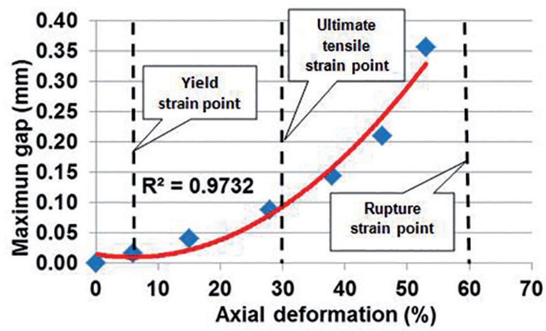

Figure 7: Correlation between maximum gap and axial deformation.

The thickness along the test specimen was measured and the gap profile formed as a function of axial deformation intensity determined (Figure 6). It was noted that the deformation in the diffuse necking field (6 to 15%) generated a low intensity and well distributed necking along the specimen length. From the maximum stress point (28%) the neck became more concentrated. From this point, within the localized necking field, it was noted that the increase of axial deformation of the gap was more intense and concentrated. This effect may be better observed in Figure 7, where the maximum gaps observed in Figure 6 were correlated with the axial deformation.

The hardness profiles along the test specimen for different deformation levels are shown in Figure 8 and it can be observed that there is a direct correlation with the gap profile (Figure 6). This shows important evidence that the gap interferes with heat extraction and affects the cooling rate, influencing the final microstructure and material properties.

3.2. Effect of the localized gap on the cooling rate

The cooling curves for different gaps are shown in Figure 9. It was noted that with no gap the cooling was very effective, achieving a maximum cooling rate of 150°C/s; however,

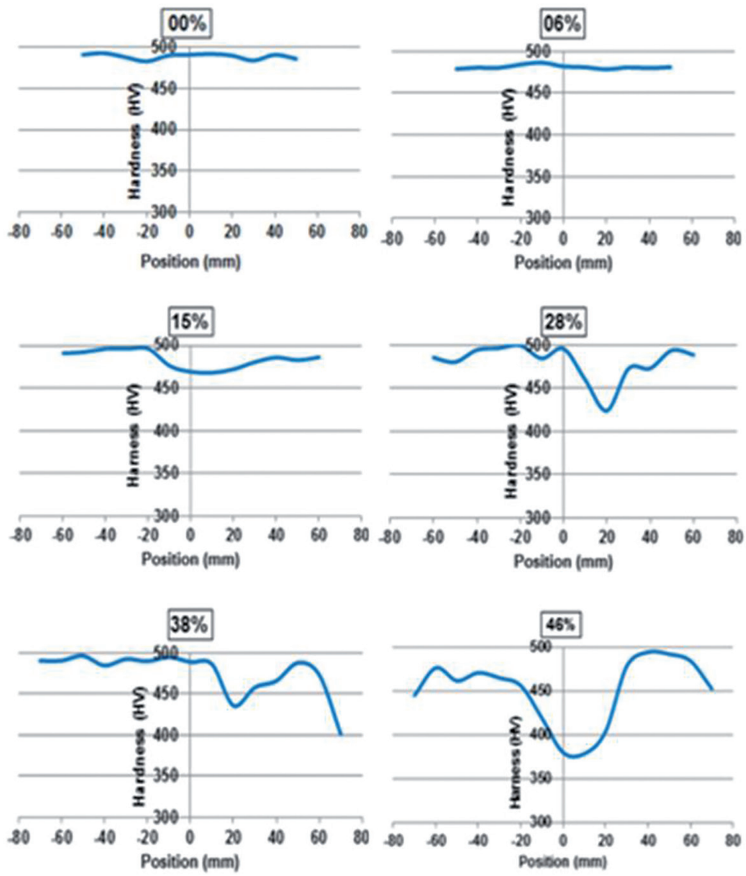

Figure 8: Hardness profiles along the test specimen for different axial deformations.

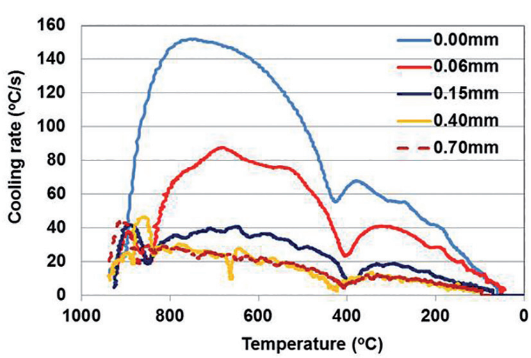

Figure 9: Cooling rate curves for different gaps.

with the gap increasing the speed was gradually reduced, reaching only a maximum of 40 ^{0}C/s for a 0.70 mm gap.

It was found that with no gap the cooling rate was high during the whole cooling period until it reached lower temperatures. With the 0.06 mm gap there was a significant change in curve profile with the occurrence of a slight increase in speed close to 900^{0}C, as well as the reduction of the maximum cooling rate. Through increasing the gap to 0.15mm this modification was even more sensitive, but it was observed from this condition that the cooling rate curves showed a similar behavior, indicating that significant reduction in the cooling rate occurs from this gap. In all cases, cooling rate increase occurred when close to 900^{0}C, showing a pattern of behavior. This effect has not been investigated in detail, but it is believed to be associated with a more complex heat transfer condition which involves radiation and convection. Another observation obtained from the cooling rate curves is that close to the temperature of 400 ° C there was also the onset of an inflection. This effect may be associated with the start of the martensite transformation (M_s temperature) which, according to Ravindran[8], is 420^{o}C for 22MnB5 steel.

The Vickers hardness profiles along the test specimen for different gaps are shown in Figure 10, where it was observed that in the central region (cooled areas) the hardness was elevated and homogeneous, reaching values between 480 and 500HV in all experimental conditions. In the uncooled region the hardness was reduced appreciably depending on the spacer level, ranging from 480HV with zero gap to around 270HV with a 0.70 mm gap.

The microstructures were evaluated in three regions of 0.70mm gap test specimen, as shown in Figure 10. With no gap a high cooling rate was noted ensuring a fully martensitic

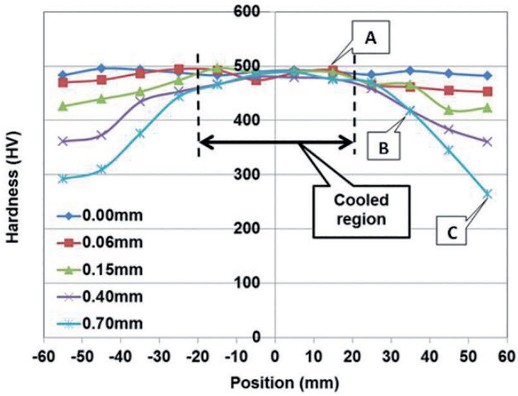

Figure 10: Hardness profile along the specimens for different gaps.

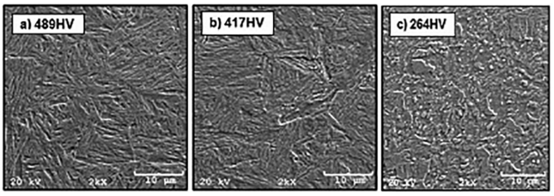

Figure 11: SEM observations showing microstructures of 0.70mm gap test specimen in different regions: (a) cooled region, (b) region near cooler, (c) region far from cooler.

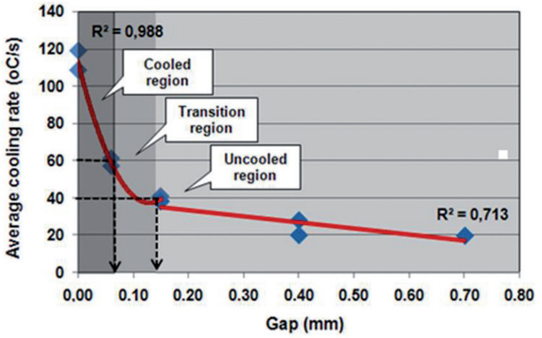

Figure 12: Effect of the gap size on the cooling rate showing different cooling conditions.

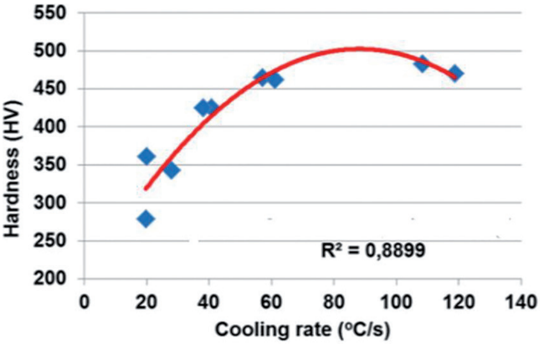

Figure 13: Correlation of hardness with cooling rate.

microstructure (Figure 11.a). In the region near the cooler (B), a microstructure martensitic was also observed (Figure 11.b); however, the hardness was slightly decreased, while in the region far from the cooler (C) a failure in the martensitic transformation (Figure 11.c) was observed.

The gap values were correlated with the average cooling rate (Figure 12), and it was found that when there is good contact between the surfaces (no gap) it is possible to obtain a high average cooling rate, around 120°C/s. In this case the heat transfer occurred only by conduction between the contacted surfaces. The presence of gap, even if it is a very small one (0.06mm), was sufficient to considerably reduce the cooling rate to 60°C/s, but it is higher than critical cooling rate for quenching the 22MnB5 steel, which is 28°C/s [19]. Therefore, this condition was sufficient to attain high hardness exceeding 450HV, as shown in Figure 13, in which the cooling rate values were correlated with the hardness. These results are in agreement with the study of Äkerston[20], which has found that 0.04 mm is the critical gap in order to ensure a fully martensitic microstructure.

With a gap between 0.15 to 0.20 mm the average cooling rate was reduced to 30-40°C/s**,** reaching a limit condition in order to ensure a martensitic microstructure with hardness around 400HV. In this condition the heat transfer occurs not only by conduction, but also by radiation through the air layer formed between the cooler and the test specimen surface. In spite of this, one should consider that this mechanism is temperature dependent and therefore efficient only at high temperatures. The heat transfer through convection is unwelcome, because in this case it fails to enable a favorable condition to promote enough air volume movement in the region formed between the surfaces. With a gap wider than 0.20mm the cooling rate becomes too low, of the order of 20 to 30°C/s, affecting hardness, which was reduced to 270HV. In this case, as the distance between surfaces becomes too large, the heat transfer mechanisms are no longer effective, thus affecting the cooling rate.

Hardness reduction with a gap is a very significant technological effect, especially when it is taken into consideration that there is a strong correlation between hardness and mechanical resistance[18]. In this study the hardness of 480HV, obtained in appropriate hot stamping conditions, corresponds to an ultimate tensile strength of approximately 1700MPa, while the hardness of 270HV corresponds to a resistance of only 900MPa, which is a low value, whereas in the steel sheet supplied the mechanical resistance of 22MnB5 steel is about 700MPa.

Relating the results obtained in this step (Figure 12) with the results obtained in the previous step (Figure 7), it can be noted that the maximum gap limit of 0.15 mm was achieved with an axial plastic deformation of the order of 38%, already within the localized necking field. Therefore, this should be the limit of axial deformation in order to avoid obtaining fragile regions in a hot stamped component.

4. Conclusions

Present results support the conclusion that when a specimen is hot stamped three different cooling conditions can take place as a function of the axial deformation intensity and its respective gap.

The ideal condition occurs when there is no gap, i.e., the tool and the specimen surfaces are in perfect contact. In this case the heat transfer occurs exclusively by conduction, good heat transfer and a high cooling rate are achieved, of the order of 120°C/s, ensuring high hardness around 480HV. This condition was achieved when the axial deformation suffered by the sample was too small, close to or little higher than the yield strain point, around 6%.

The intermediate condition occurred when there was a small gap, but the surfaces were still relatively close and the heat transfer happens by radiation through an air layer, which is less effective than through the conduction mechanism. When the gap was between 0.10 to 0.15mm cooling rates between 30 and 40°C/s could be obtained, which was enough to ensure a martensitic microstructure with high hardness (above 400HV). This could be achieved when the axial deformation applied on the specimen was not higher than 28%, indicating the beginning of localized necking field.

The undesirable condition occurred when the gap was wider than 0.15mm. In this case the heat transfer process was fully affected, reducing significantly the cooling rate to less than 20°C/s, consequently below the 22MnB5 steel critical cooling quenching rate that is 28°C/s, resulting in hardness below 270HV. This effect occurred when the axial deformation experienced by specimen was higher than 38%.

5. Acknowledgements

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