Investigation of Material Softening and Increase of Deep Drawing Capacity of 22MnB5 during Press Hardening using CRP Technology

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Abstract. The cushion-ram pulsation (CRP) technology offers a significant increase in formability by the novel stepwise deep drawing with holding pauses. The influence of different incremental drawing depths and breaks on the deep drawability of 22MnB5 during press hardening with CRP is investigated for unheated and heated tools. Softening induced by the holding times during hot forming with CRP can play a relevant role in achieving higher drawing depths and is consequently described. The forming analysis is carried out by means of FE simulation and experiments. The influence of softening on the improved forming capacity can consequently be quantified and a recommendation for the CRP technology in press hardening can be determined.

1. Introduction

Developments on the use of servo-electric drives instead of conventional drives in all types of presses show that there is great potential in this form of drive. Investigations by Mauermann [1] on a screw press with servo-driven ram and cushion show that the formability of materials can be significantly optimized if the ram and cushion motions are carried out as discontinuous, time-shifted processes. Previous research on the cyclic interruption of deep drawing processes has focused on the velocity dependence of friction [2,3] and the material behavior due to the pause times [4,5] as well as the stress relief due to the interruptions [1,6]. It has been found that deep drawability can be increased by 20% for high strength steels if the deep drawing process is specifically interrupted [4]. An increase in formability occurs due to a more favorable material feed and improves the subsequent flow of the material near bottom dead center [7]. A specific method of highly dynamic deep drawing processes is cushion ram pulsation (CRP). The aim is to increase the drawing depth here as well. CRP differs from the standard process in that in conventional deep drawing the force is transmitted over the radius between the wall and the bottom of the deep drawn component until mechanical instabilities occur, the sheet thins out and cracks. In contrast, with the help of CRP, the total force to be transmitted is significantly reduced, which allows the drawing ratio to be significantly increased. By slightly opening the flange gap during the drawing process, the drawing forces can be reduced, stress peaks avoided and the material flow optimized. The wrinkles of the workpiece in the flange gap that form during this process are compensated by a counter motion of the drawing cushion on the sheet metal blanket. The ram motion...
must be interrupted during this process. The forming operation is stopped periodically. The motion between the cushion and the ram is synchronized and is path-controlled [1,8,9]. Further explanations that CRP is capable to increases formability focus on the tribological influence and the force reduction, since it is known that for larger deep-drawn parts the frictional forces can increase up to three times the required forming forces [1,10]. According to Mauermann, the main reasons are that CRP prevents the formation of local stress peaks on the drawing ring and reduces the formation of folds in the flange gap. The successful transfer of the CRP technology to the press hardening process shows that a significantly increased drawing depth can be achieved if the deep drawing process is discontinuous [11,12]. Among other factors, softening within the pause times is considered to be the cause, which has been proven by double compression tests under the conditions of different plastic strains and the forming temperatures. Thus, the soften kinetics occurred during the hot forming process were investigated for 22MnB5 in this study.

2. Experimental Procedure

2.1. Thermo-mechanical simulator test

The thermo-mechanical treatment was carried out on cylinder samples of the material 22MnB5. The chemical composition of this material is given in Table 1. The initial structure is equiaxed ferrite with globulitic pearlite.

| Table 1. Chemical composition of the investigated boron manganese steel 22MnB5 in wt %. |
|----------------------------------------|
| C          | Si      | Mn      | P        | S        | Al       | Ti       | Nb       |
| 0.2028     | 0.3712  | 1.162   | 0.0135   | 0.00196  | 0.05718  | 0.0325   | 0.00308  |
| B          | Cr      | Cu      | Mo       | Ni       | Ta       | W        | V        |
| 0.00146    | 0.2688  | 0.0301  | 0.03936  | 0.05882  | 0.00736  | 0.005    | 0.0045   |

The thermo-mechanical treatment is used to analyze the softening due to recrystallization of the material as a function of different process parameters. The focus is thereby on in which way the material softens dynamically and metadynamically after previous austenization. The compression specimens were machined so that the longitudinal axis of the specimen is in the rolling direction. The specimens have a diameter of 5 mm and a height of 10 mm. The BAEHR 805 A/D thermo-mechanical simulator was used to perform the experiments.

2.1.1. Dynamic recrystallization

Dynamic recrystallization (DRX) describes the formation of new grains during the deformation. For this purpose, flow curves were determined from isothermal compression tests, whereby various forming parameters were utilised. At the beginning, the samples were heated to 950 °C under vacuum with 3 K/s, and then remained at 950 °C for 300 s in order to austenitize completely. Subsequently, rapid cooling of the specimens with 25 K/s to a specified forming temperature is carried out. A short holding pause of 10 s ensures that there is no thermal gradient in the specimen. Subsequently, compression tests were carried out up to deformation grade \( \varphi = 1 \), with the strain rate being varied from 0.01 s\(^{-1}\), 0.1 s\(^{-1}\) to 0.8 s\(^{-1}\) in consecutive tests, as well as the forming temperature being adjusted to 800 °C, 850 °C, 900 °C and 950 °C. The compression tests were all performed in fully austenitized microstructure. Friction-corrected flow curves could be obtained from the values of the compression tests. Based on the measured slope, characteristic points of the flow curves, such as yield stress (\( \sigma_0 \)), the critical strain (\( \varphi_c \)) and stress (\( \sigma_c \)) of DRX, the peak strain (\( \varphi_p \)) and stress (\( \sigma_p \)), the steady stress (\( \sigma_{ss} \)) and the saturation stress (\( \sigma_{sat} \)) of DRV, that are essential to identify dynamic recovery (DRV) and DRX, were calculated. Based on the ratio of the measured yield stress (\( \sigma \)) and the idealized yield stress with only work hardening and dynamic recovery (\( \sigma_{WH,DRV} \)) as well as the difference of the saturation stress...
for DRV and steady stress of DRX, the recrystallized volume can be described according to equation 1, as also shown graphically in Figure 1 [13]. A profound calculation for DRX of 22MnB5 is given in [14].

\[
X_{\text{drx}} = \frac{\sigma_{\text{WH-DRV}} - \sigma}{\sigma_{\text{sat}} - \sigma_{\text{ss}}} \quad (\varphi \gg \varphi_c)
\]

\[
X_{\text{mdrx}} = \frac{\sigma_1 - \alpha_3 \cdot \log(t) - \sigma}{(\sigma_1 - \sigma_2) - (\alpha_1 - \alpha_2) \cdot \log(t)}
\]

**Figure 1.** Flow curve of DRXed material (red line) and calculated slope of only work hardened and recovered material (dashed line).

### 2.1.2. Metadynamic recrystallization

Metadynamic recrystallization (MDRX) considers the new grain formation after a previous dynamic recrystallization by growth of the nuclei formed by previous DRX, which occurs in the condition of that the critical plastic strain \( \varphi_c \) was exceeded in the previous deformation. The determination of the time dependence of MDRX was carried out with the help of stress relaxation tests. Similar to the compression tests for DRX, the specimens are heated in vacuum with 3 K/s to 950 °C followed by a holding time of 300 s. Subsequently, the specimens are quenched at 25 K/s to the defined forming temperature and held for 10 s in order to compensate the temperature. The subsequent isothermal forming at \( \varphi = 0.4, 0.6 \) or 0.8 at the temperature 800 °C, 850 °C, 900 °C and 950 °C is performed and the deformation degrees are significantly higher than the critical plastic strain. After successful forming, the stress relaxation test begins. In this process, the specimens are kept isothermal in the clamped condition and the stress relaxation as a function of time is measured, as shown exemplarily in Fig. 2. In this process, the softening goes through 3 stages, starting with recovery stage (I), MDRX stage (II) and finally grain growth stage (III). The respective stages are distinguished by changes in the kinetics of the stress relief. Based on the stress gradient, the MDRXed fraction is calculated according to Karjalainen [15] as shown in equation 2.

**Figure 2.** Stress relaxation curve (black line) and amount of MDRXed fraction (red line).

### 2.2. CRP test

The CRP tests were carried out using the DUNKES ESI-S4-80-30 servo screw press with 800 kN ram force and 300 kN cushion force. The maximum speed is 280 mm/s and the maximum acceleration 4,000 mm/s\(^2\). The mounted deep-drawing tool in Figure 3 forms circular cups with an inner diameter of 100 mm. The drawing edge radius at the die is 10 mm. The drawing die is attached to the press ram, the
blank holder is controlled by the cushion, and the punch is mounted on the press table without motion. The active parts can be heated and are thermally insulated from the rest of the tool. *Rovalma HCTS 130* and *Doerrenberg CP2M* are the tool steels used in tool active parts. Both have high wear resistance combined with good thermal conductivity. This is necessary to ensure specified cooling rates.

![Diagram of deep drawing process](image)

**Figure 3.** Deep drawing for cylindrical cups to perform CRP tests.

In order to perform the CRP tests, blanks with a diameter of 170 mm and 1.5 mm sheet thickness of the material 22MnB5 are heated to 950°C for 10 minutes. Within this time, the microstructure changes from previously ferritic-pearlitic to austenitic. The austenitized circular blank is then manually transferred to the press, followed by immediate start of the deep drawing process. During the forming process, contact with the die results in quenching and consequently in martensitic transformation of the material. After the forming process is completed, the deep-drawn cup is removed from the tool. The maximum drawing depth that can be achieved is 40 mm as a consequence of the 170 mm diameter of the circular blank. The CRP process itself can be divided into 2 periods, as shown in Figure 4. Within the first interval, the deep drawing process is performed by the motion of the die. The blank holder performs the same motion simultaneously. Due to the equal speed of the cushion and the ram during the forming process, the flange gap is constant but larger than the sheet thickness, in this case 3 mm, in order to minimize the blank holder forces during the drawing process. As soon as the ram stops and turns into a holding phase, period 2 begins. The blank holder moves in the opposite direction and minimizes the flange gap to sheet thickness. This reduces wrinkles that have formed in the flange gap during period 1. A CRP cycle is then completed when the blank holder moves back to the originally set flange gap. The subsequent drawing step starts again with period 1. The forming process takes place step by step, interrupted by holding phases in the die, during which the blank holder performs a counter motion.

![Diagram of position-time curve](image)

**Figure 4.** Position-time curve of the drawing die and the blank holder for a single CRP cycle.

![Diagram of position-time curve](image)

**Figure 5.** Position-time curve of the drawing die, the blank holder and the punch at full CRP.

Within the scope of the investigations, several parameters of the CRP technology are varied in order to evaluate the respective influence on the drawing depth. The varied parameters are the incremental...
drawing depth with 5 mm and 10 mm, the ram holding time with 0.5 s, 1 s and 2 s, as well as the temperature of the active parts of the tool, with room temperature and 250 °C. All parameter combinations were investigated.

In comparison with the CRP tests, conventional press hardening tests were performed with the same flange gap of 3 mm. Here, the tests were carried out with the unheated tool and heated tool set at 250 °C. The conventional tests were performed at a constant ram speed of 25 mm/s. In CRP tests, the drawing speed varies continuously as a function of the drawing depth and as a result of the acceleration and braking of the drawing die. The continuous velocity represents a low velocity at CRP.

2.3. FE simulation
The FE simulation is used to determine the plastic strain and the temperature range that occur as a result of the CRP process. For this purpose, *Simufact Forming V14* was used. The analysis is divided into two parts and takes into account the manual transfer of the austenitized sheet into the tool as well as the subsequent forming by means of CRP or conventional deep drawing. The material model was calculated using *JMatPro V7.0* software based on the chemical composition given in Table 1. The workpiece is composed of 24688 hexahedral elements.

3. Results and Discussion

3.1. Influence of forming conditions on dynamic recrystallization
The proportion of the DRXed microstructure shows a sigmoidal curve as a function of the plastic strain until the microstructure is completely recrystallized, as it can be seen from Figures 6 and 7. The dependence of DRX on the forming temperature in Figure 6 shows that the transformation kinetics increase with increasing temperature. The reason for this is the grain boundary mobility, which depends on temperature and time due to diffusion. Consequently, this also explains the dependence on the forming rate. With decreasing forming velocity, the time for grain boundary mobility increases, whereby DRX takes significantly longer and thus more microstructure recrystallizes, as shown in Fig. 7.

![Figure 6. DRXed phase fraction as function of plastic strain and temperature.](image)

![Figure 7. DRXed phase fraction as function of plastic strain and strain rate.](image)

3.2. Influence of forming conditions on metadynamic recrystallization
Regardless of the variation of the forming parameters, a sigmoidal curve can be observed for time dependence of MDRX. The MDRX onset is slow, then increasingly accelerates to reach the maximum transformation rate at half of the MDRXed microstructure. Subsequently, the recrystallization kinetics reduces to finally stop at 100% MDRXed microstructure.

Under variation of the forming temperature, it can be observed according to Figure 8 that the MDRX kinetics increases with increasing forming temperature. This is to be expected since MDRX involves thermally activated diffusion processes. Consequently, a higher forming temperature can produce a
larger proportion of MDRXed microstructure in a defined period of time. The influence of the plastic strain from the previous deformation is relevant, since with increasing plastic strain the reaction kinetics decreases, as it is obvious from Figure 9. It can be assumed that the reason is proceeded DRX at increased plastic deformation, which significantly declines the driving force for MDRX. An increased strain rate of the previous deformation has a positive effect on the acceleration of recrystallization, as is evident from Figure 10. The reason for this is the increase in stored energy introduced by high strain rate, which leads to an increase in dislocation density and consequently more nucleation sites are available for recrystallization.

![Figure 8](image1.png)  
**Figure 8.** MDRXed phase fraction as function of relaxation time and temperature.  

![Figure 9](image2.png)  
**Figure 9.** MDRXed phase fraction as function of relaxation time prior applied plastic strain.  

![Figure 10](image3.png)  
**Figure 10.** MDRXed phase fraction as function of relaxation time prior applied plastic strain rate.

### 3.3. Influence of the forming parameters on the maximum drawing depth for CRP

The advantage of CRP technology can only be shown in direct comparison to conventional deep drawing under test conditions that are as similar as possible in order to give a qualitative conclusion about the advantages of CRP. Since the CRP technology is exposed to continuous acceleration and braking, it is difficult to assume that the drawing speed is constant. Consequently, for continuous deep drawing, the drawing speed was defined as constant at 25 mm/s. As a result of the deep drawing tests with the same flange gap of 3 mm only 17.95 ± 0.05 mm maximum drawing depth could be obtained at room temperature and at 250 °C tool temperature only 15.5 ± 0.2 mm.

When performing the CRP experiments, a high dependence on the forming parameters can be observed. For example, the CRP experiments with a non-heated tool and incremental drawing steps of 5 mm show no significant improvement in the drawing depth, regardless of the duration of the pause time, as shown in Figure 11. However, the influence of the CRP technology is different for incremental drawing steps of 10 mm. Obviously, a significant improvement of the drawing depth can be observed even at low

![Figure 11](image4.png)  
**Figure 11.** CRP experiments with a non-heated tool and incremental drawing steps of 5 mm.
pause times. In addition to the incremental drawing depth of 10 mm, if the pause time is extended from 0.5 s to 2 s, the maximum drawing depth can be achieved for the given blank diameter. The influence of holding time and incremental drawing depth is different when the tool is heated to 250°C, as can be seen in Figure 12. Thus, no fundamental improvement of the drawing depth can be achieved by higher increments. Although the drawing depth is higher at 0.5 s holding time and 10 mm increment than at 0.5 s holding time and 5 mm incremental depth, this changes for the 1 s and 2 s holding times. With the 5 mm increment and the 2 s holding time, the maximum drawing depth of 40 mm can be achieved. The reason for this could be the long dwell time in the heated tool, which avoids rapid cooling of the workpiece and ensures improved formability.

3.4. Simulative comparison of the CRP technology

The FE simulation is based on the material model of 22MnB5 and is used to estimate the occurring plastic deformation, holding times and related temperatures in the workpiece. Figure 13 shows the distribution of the plastic strain over the deep-drawn cup. In the illustrated simulation, the tool is not heated and the incremental drawing depth was 10 mm with 1 s holding time between drawing increments. It is obvious that the maximum plastic strain is in the area of the cup wall with about \( \varphi \approx 0.5 \). In the area of the wrinkles, the plastic strain increases, but this zone is not considered. The reason is that the finished press-hardened structural parts should be wrinkle-free and, in principle, the wrinkles are cut off in a further step after press-hardening. Consequently, the areas with wrinkles do not matter for the final part.

![Figure 13. FE-simulated distribution of plastic strain after CRP deep drawing of 22MnB5 with incremental drawing depth 10 mm and holding time 1s.](image)

In order to be able to estimate the plastic strain and the holding times that occur in certain temperature ranges, a particular element was selected which lies in the cup wall in the finished formed part, since the highest plastic strains are to be expected here according to Figure 13. Furthermore, a second element
was selected which lies in the area of the radius between wall and bottom of the finished formed cup. Here, the highest contact pressures between tool and workpiece and consequently the highest cooling rates can be expected. Figure 14 a) shows two selected points in the cross section of the deep-drawn cup. As can be seen from Figure 14 b) for cooling during forming, the highest cooling rates occur at point 1. After completion of forming, point 1 has a temperature of 358 °C and point 2 has a temperature of 656 °C. The vertical dashed line at 7 s indicates when the forming is complete and the sheet cools in the tool. In comparison, Figure 14 c) shows how the plastic strain increases during CRP forming at point 2, while the plastic strain remains constant at point 1 after the 2nd CRP cycles. The holding times between the individual forming stages are also obvious of 1 s each, which correspond to the holding times of the ram.

![Figure 14](image)

**Figure 14.** a) Position of analyzed points in cross-sectional view of the cup, b) simulated temperature-time slope of point 1 and 2, c) simulated plastic strain-time slope of point 1 and 2.

Using *JMatPro*, it is possible to calculate a CCT diagram based on chemical composition, the austenitization temperature of 950 °C and ASTM grain size 9.0, which is shown in Figure 15. Here it can be seen that the martensite start temperature is 400 °C for 100 K/s and 394 °C for 10 K/s. In comparison with the simulation results for cooling in Figure 14 b) and c), it can therefore be deduced that the forming temperatures and deformation induced are guaranteed to initiate recrystallization softening in austenitic state during CRP process, which results in enhanced formability. However, the influence of the deformation on the shift of the phase transformation was not considered, which means further investigations are required.

![Figure 15](image)

**Figure 15.** Calculated CCT diagram after austenitization at 950 °C and ASTM grain size 9.0.
4. Conclusion
In this paper, the dynamic recrystallization (DRX) and metadynamic recrystallization (MDRX) of 22MnB5 were investigated, and subsequently the effect on the forming parameters of the CRP technology evaluated. For DRX, the temperature parameters in the range of 800 °C to 950 °C, and the forming rate 0.01 s⁻¹, 0.1 s⁻¹ and 0.8 s⁻¹ were analyzed. For MDRX, the forming parameters temperature in the range 800 to 950 °C, plastic strain 0.2, 0.4 and 0.6, and forming speed 0.01 s⁻¹, 0.1 s⁻¹ and 0.8 s⁻¹ were investigated to determine their influence on the proportion of recrystallized microstructure. The CRP tests were performed with the tool unheated and heated to 250 °C. The incremental drawing depth was varied between 5 and 10 mm. The influence of the holding periods was tested in the range of 0.5 s, 1 s and 2 s. A simulative comparison of the CRP technology shows the plastic strain and temperature as a function of the process time. The following results were obtained:
1) The simulative comparison with Simufact Forming and JMatPro shows that maximum plastic strain \( \varphi \approx 0.5 \) is achieved in the cup wall. The holding times between incremental steps correspond to the pause times of the ram. According to the FE simulation, the material is in austenitic state during the CRP. However, deformation also affects the onset of phase transformation, which was not taken into account in the simulation and needs to be considered in further investigations.
2) DRX shows that recrystallized microstructure occurs in every case, but this strongly depends on the strain rate and forming temperature. At the simulated plastic strain of \( \varphi \approx 0.4 \), at least 20 – 30% would be recrystallized at the strain rate \( d\varphi/dt = 0.8 \). A reduced forming speed would increase the recrystallized fraction even more.
3) A lowered forming speed at CRP would increase DRX. However, this also reduces the forming temperature, which in turn lowers the DRX. An optimum process window of the interaction of forming speed and forming temperature must be defined.
4) MDRX can generate a recrystallized fraction above 25% by sufficiently fast forming at low forming rates and high temperatures. In particular, long holding times favor MDRX.
5) Long holding times at CRP lead to an increased MDRXed fraction, but at the same time the forming temperature decrease, slowing down the MDRX. An ideal process window needs to be defined.
6) The CRP tests show that the cooling rates have a significant influence in this case. Due to the lower cooling rate for the heated tool, the forming takes place at higher temperatures. The recrystallization would consequently take place to a higher extent.
7) The extended holding times have a positive influence on the maximum drawing depth with CRP, although the workpiece temperature decreases with increasing holding time. MDRX, which takes place within the holding times, may be relevant.

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