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# The impact of strain rate on sheet metal formability at room temperature

## Vpliv hitrosti deformacije na preoblikovalnost pločevine v hladnem stanju

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## Abstract

It is known that in warm and hot forming the forming speed and with it combined strain rate has immense role on material flow in bulk and sheet metal operations. In contrast, the influence of the strain rate on the flow curve is only rarely analyzed at room temperature. Presented work analyzes the influence of strain rate on flow curve of DC04 deep drawing material obtained by the uni-axial tensile test. After the evaluation of the flow curves as a function of strain rate the deep drawing of box-shaped test specimen was performed with two drawing speeds. The influence of the forming speed on the forming force and onset of necking was analyzed.

**Key words:** sheet metal forming, deep drawing, strain rate, room temperature forming

## Izvleček

Hitrost deformacije je pri preoblikovanju v toplem in vročem stanju ključni parameter procesa tako pri preoblikovanju pločevine kot tudi pri masivnem preoblikovanju. Nasprotno od tega je vpliv hitrosti preoblikovanja le redko analiziran za preoblikovanje v hladnem. V članku je analiziran vpliv hitrosti deformacije na krivuljo plastičnosti jekla za globoki vlek kakovosti DC04, pridobljeno z enoosnim nateznim preizkusom. Po ovrednotenju krivulj plastičnosti v odvisnosti od hitrosti deformacije smo z dvema hitrostima izvedli tudi globoki vlek preizkusne pravokotne škatle. Opazovali smo potek preoblikovalne sile in lokalizacijo materiala v odvisnosti od preoblikovalne hitrosti.

**Ključne besede:** preoblikovanje pločevine, globoki vlek, hitrost deformacije, hladno preoblikovanje

## Introduction

In the last century many researchers have analysed forming velocity and with it connected strain rate effect on plastic deformation and flow curves of various materials. Rao & Doraivelu[1] in 1980 made comparison of earlier researches and conclude that different materials can be successfully processed with different speeds having different limits of the highest attainable strain rate. As a highest attainable was declared the strain rate where the material was still deformable without fast tearing. For example, steel and some aluminium alloys can be deformed in strain rate range from $2 \times 10^{-3}$ $s^{-1}$ to $3 \times 10$ $s^{-1}$, copper and brass in range from $10^{-3}$ $s^{-1}$ to $10^{-2}$ $s^{-1}$, steel at high temperature from 10 $s^{-1}$ to 103 $s^{-1}$, stainless steel in rate range from $5 \times 10^{-6}$ $s^{-1}$ to $3 \times 10^{-2}$ $s^{-1}$. Bailey, Haas & Shah[2] in 1971 made a research about velocity and temperature effect on flow curve of aluminium alloys. Obtained results have shown that required stress in tension necessary to obtain particular deformation is getting higher with increase of a strain rate at a constant temperature, and getting lower with increase of a temperature at a constant strain rate. Velocity effect of a deformation is getting more pronounced with increasing of temperature. Rao, Prasad & Hawbolt[3] in 1996 made a research on low carbon steel. On the basis of their results it can be concluded that with enhancement of strain rate and reduction of temperature, tensile strength is increasing and entire flow curve of material increase its level. Lee & Yeh[4] in 1997 made some experiments to determine dynamic relation between yield strength and deformation of steel alloy. Obtained results showed that yield strength is magnifying with increasing of strain rate or with decrease of the temperature. Odeshi, Al-Ameeri & Bassim[5] in 2005 investigated velocity effect of projectile impact on deformation speed of material and its flow curve. On the basis of experiments they determined that speed of projectile impact has an effect on the strain rate of the observed material. When the speed of projectile impact and also strain rate are higher, the higher is yield strength maximum. Tsao, Wu, Leong & Fang[6] observed flow curve behaviour of commercially pure titanium during the hot tensile deformation. In this case, level of flow curve is again increasing with increasing of strain rate and decreasing with changing of temperature. In order to obtain reliable data of the materials used in automotive industry Kim & Huh[7] have analysed deformability of two steels common used in body-in-white production. They have selected CQ (commercial quality) steel and dual phase ferite-martensite steel DP590. The common tensile test, used for analysis of the flow curve was not applicable for their research due to the large testing length of 80 mm or 50 mm. Since the strain rate is calculated from the deformation speed and the length of the specimen as

$$\varphi = \frac{d\varphi}{dt} = \frac{v}{l} \quad [s^{-1}] \tag{1}$$

the total deformed length should be as small as possible. In Equation 1 the $\varphi$ represents logarithmic strain, $v$ the deformation speed and the length of a specimen. For this purpose Kim & Huh have selected miniaturized tensile specimens – Figure 1. Good clamping of the specimen necessary to minimise dynamic responses of the entire testing system was assured by screwing of the specimen into the clamping head. They diminish with such clamping system also the sliding danger which may appear at high testing velocities.

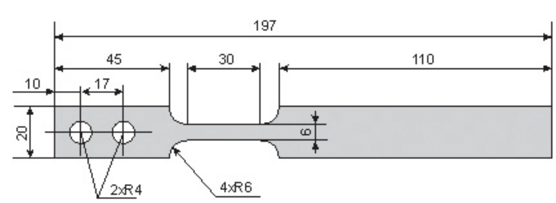


**Figure 1:** *Specimen for testing at high strain rates [7].*

The selected steels CQ and DP590 have shown that also at room temperature the flow curves are increasing with the increase of the strain rate. The authors have selected large testing range of the strain rates from 0.001 $s^{-1}$ to 100 $s^{-1}$ with an increment of one decade. The obtained flow curves for the rolling direction (RD) are presented on Figure 2.

For both steels it can be observed that the yield stress and the level of the flow curve increases with the strain rate. Considering the CQ steel, this phenomenon is more emphasized at lower strains up to the $\varphi_e$ = 0.1 while at DP590 steel quality the increase of the flow curve is more emphasised at strains above $\varphi_e$ = 0.1. On the other hand the behaviour regarding the total elongation is similar: it is increased from 0.1–100 $s^{-1}$ while at quasi-static strain conditions below strain rate of 0.1 $s^{-1}$ the total elongation is smaller and the material rupture at lower equivalent strains. Kim & Huh have analysed also the forming limit diagram under quasi-static loading at strain rate of 0.001 $s^{-1}$ to 0.0018 $s^{-1}$ and at strain rate of 60–120 $s^{-1}$. For both materials, there is no significant decrease in the forming limit curve (FLC) and only minor difference between the static and dynamic loading. The difference between both strain rates ranges is to observe only at the range between bottom and upper FLC line determining the reliability band of the FLD. The narrowing of this bend is more emphasized in the case of the dual phase steel DP590 – Figure 3.

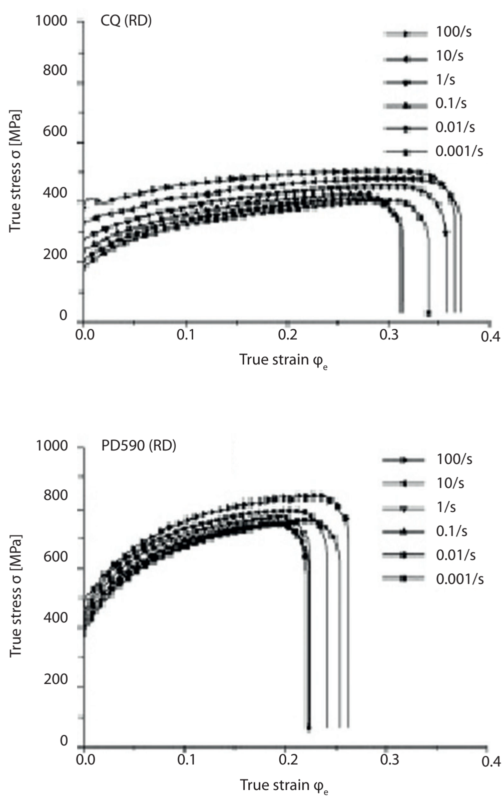


**Figure 2:** *Flow curves of CQ and DP590 steel at various strain rates [7].*

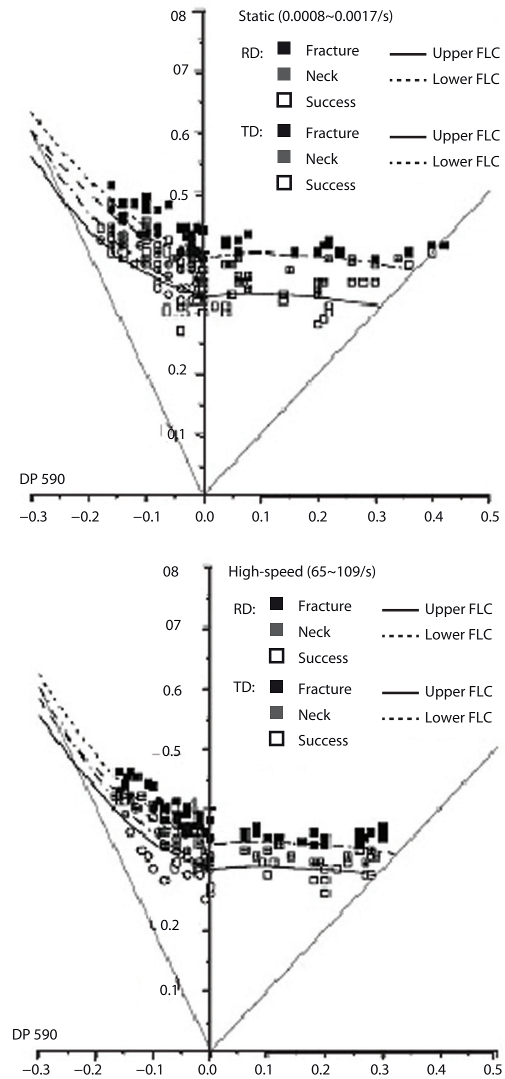


**Figure 3:** *Forming limit curves of DP590 at different strain rates [7].*

Jie et al.[8] have analysed the influence of strain rate on aluminium killed steel (AKDQ). They have also selected downscaled specimen with similar dimensions as Kim & Huh, however they have used for experiments the multipurpose Interlaken servo press with 260 kN nominal force. They have found out that with the increase of the strain rate the flow curve and yield point of the material are also increased. The forming analyses of magnesium alloy AZ31 done by Lee et al.[9] at elevated temperatures between 250 °C and 400 °C has shown that the increase of the strain rate also here increase the level of the flow curve but on the other hand the forming limit curve decreases at higher strain rates. While Lee et al. made forming analyses of sheet metal Kobold et al.[10] analysed the AZ80 bulk material in compression stress state. Similar to Lee et al. they also observed increase of yield stress with increase of the strain rate.

## Material properties of deep drawing steel DC04

The household appliance industry, some applications of automotive sector as well as other industrial sectors implement various grades of common DC deep drawing steel qualities, mostly suitable for painting after the forming. Since the companies are also in this sector forced to shorten the production times the analyses of the material DC04 on various strain rates were performed. Two speeds of the tensile testing machine were selected resulting in a strain rate of 0.002 5 $s^{-1}$ and 0.02 $s^{-1}$. In order to improve the accuracy of the measurements of the uni-axial tensile test the standardized 80 mm × 20 mm specimens were selected despite lower attainable strain rates. The selection of the forming velocity at testing machine was adapted to the performances of the hydraulic press Litostroj HUO-2-250-400 with punch speed of 0.02 m/s where the deep drawing tests of box-like specimens were performed. The formability of the material was analysed in three directions regarding the rolling direction: longitudinal, transverse and at 45°. The thickness of analysed sheet metal was 0.6 mm. The flow curves at both analysed strain rates for all three directions are presented on Figure 4. Five experiments were performed in each direction. Figure 4 represents the average values of flow curves for the analysed material in various directions regarding the rolling direction.
Differences between the flow curves obtained at both strain rates are clearly visible. The highest increase of the flow curve can be observed perpendicular to the rolling direction where material expresses also the highest elongation at fracture. The material of DC04 quality expresses at observed strain rates only minor decrease of the total elongation at strain rate 10 times higher as the standardised one.

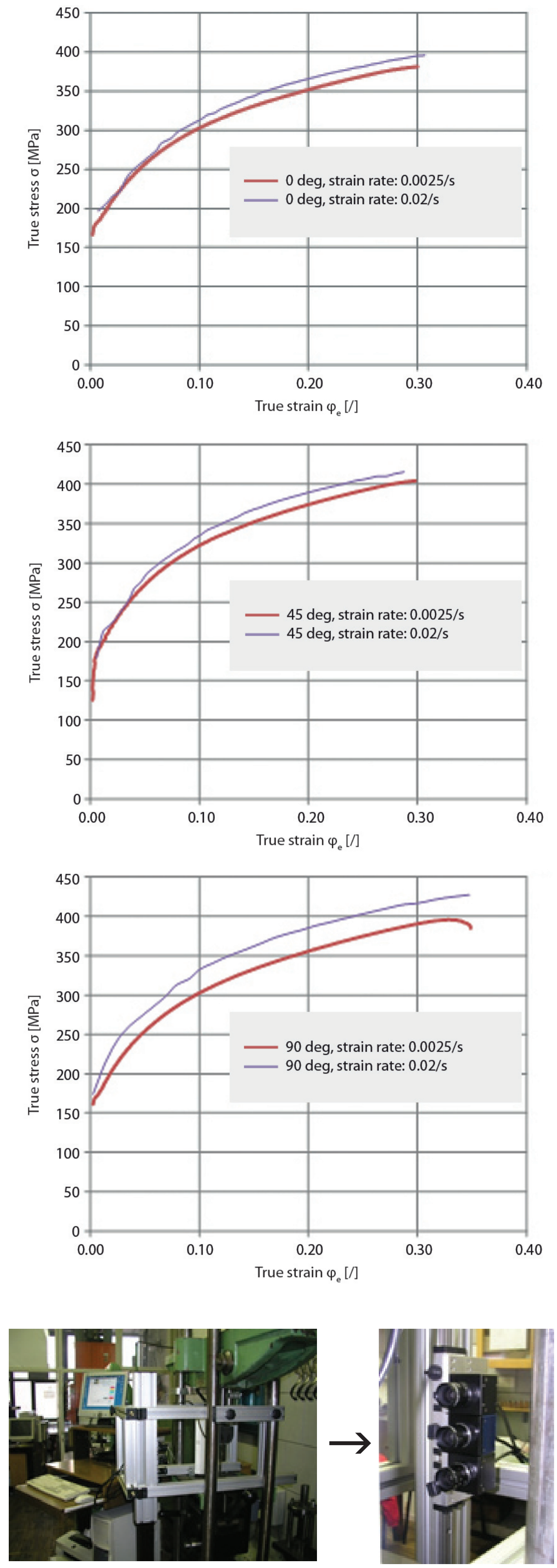


**Figure 4:** *Comparative flow curves for different directions regarding the rolling direction of the sheet metal (top and bottom left) and measurement equipment for acquisition of the tensile test (bottom right).*

## Analyses of deep drawing of a rectangular box

The forming of a rectangular box has served for comparative determination of necking and tearing limit for analysed material DC04 at two different strain rates. The forming speed was set to quasi-static forming with punch speed of 5 mm/s and at 4-times higher speed of 20 mm/s being the press maximal speed. The blank has dimensions of 165 mm × 145 mm with 20 mm trimmed corners while the drawn box has dimensions of 70 mm × 100 mm with radii of 5 mm, 8 mm, 11 mm and 15 mm on its circumference, bottom radius of 5 mm and a flange radius of 7 mm – Figure 5. Different drawing depths ranging from 24 mm to 31 mm were selected in order to determine the necking and fracture limit of the drawn box. The drawing depth was incremental increased from 24 mm by 1 mm until the onset of necking or tearing was observed. The onset of necking followed by corner tearing appears at the smallest box corner. Since the flow curves of the DC04 material have shown the sensitivity on the strain rate it was to expect that the forming force should be also higher at higher forming speeds. The acquisition of force versus punch travel diagram did not prove this assumption. The course of the forming force was almost identical for both forming speeds.
Onset of necking appears at punch speed of 4 mm/s at the drawing depth of 25.3 mm while the fracture of the smallest corner appears at drawing depth of 27.7 mm. On the other hand, the necking range of the smallest corner at drawing speed of 20 mm/s is wider having a spread from drawing depth of 27 mm to 34 mm and the box tearing appears at drawing depths above 34 mm.

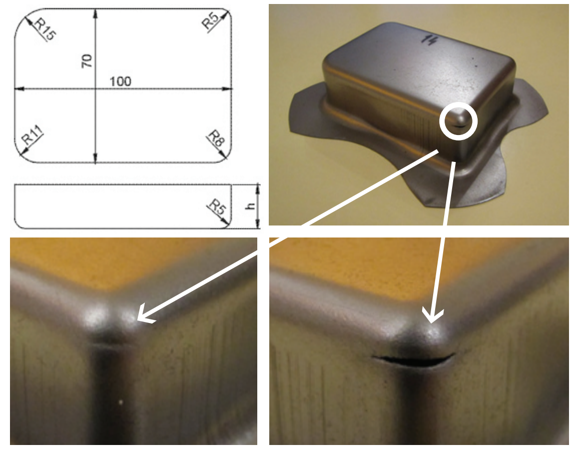


**Figure 5:** *Specimen geometry (left) and specimen formability limit with tearing (bottom left) and necking (bottom right).*

## Conclusions

The strain rate and temperature have immense influence on flow curves and forming limit diagrams at warm and hot forming. At room temperature the strain rate influence is less emphasised and therefore less known in industrial practice. With drastically decrease of production times in stamping operations the strain rate influence cannot be neglected. Recent works have shown that in some cases also at room temperature the increase of the yield stress and flow curves is observed with increase of the strain rate. The flow curves of DC04 material were analysed at two strain rates; 0.002 5 $s^{-1}$ and 0.02 $s^{-1}$. The first strain rate is prescribed by the standard for uniaxial tensile test while the second one was calculated according to the maximal punch speed of the press used for deep drawing experiments. Flow curves in three main directions according to the rolling direction have shown increase of the flow curve level at a higher strain rate without any decrease of the total elongation at fracture. The deep drawing test on the other hand has shown interesting phenomenon where the localisation on the critical corner of the specimen appear earlier at small forming speed of 4 mm/s as at five times higher forming speed of 20 mm/s.
With further research work the FLD need to be determined for both forming speeds to gain deeper overview of the DC04 material behavior at various strain rates. Finally, with gained material and formability data the FEM simulations of the deep drawing of the test box need to be performed.

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