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Increasing the Forming Limits in Hole Flanging of Dual-Phase (DP) 1000 Steel Using Punch Rotation

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Abstract. Dual-phase (DP) steels are widely used in sheet metal stamping. However, they are typically characterized by low hole expansion ratios. Since hole flanging is very often applied to sheet metal parts, solutions for improving hole flangeability are needed. In this study, high-speed punch rotation is applied in hole flanging of DP 1000 to generate frictional heat and increase formability. The flanges were formed using a punch rotating at 8000 rev/min and varying axial feeds. A maximum hole expansion ratio (HER) of 3.6 is obtained in the tests compared to ~1.58 in conventional hole flanging. The high formability is explained by the high temperature recorded in the process. The effects of temperature and strain rate on the formability of DP 1000 are examined by tensile tests conducted at different conditions. The tensile tests show an increase in formability at high temperatures. Optical microscopy at the flange edge reveals a change in the microstructure of the steel from the characteristic dual phase to a martensitic structure with elongated grains.

Introduction

The need to improve the fuel efficiency of vehicles has led to the increasing use of advanced high strength steels (AHSS) in structural applications to achieve lightweight construction, improve crashworthiness and decrease exhaust gas emission. AHSS usually have lower formability compared to conventional steels, which is indicated by their poor drawability, bendability [1] and stretch flange ability [2]. Poor formability can lead to early crack formation during forming and assembly of parts. The entire blank may be heated to improve the formability [3]. Alternatively, Löbbe et al. [4] explored local heating of blank portions with critical formability and design requirements to control grain growth and phase transformation. Formability in hole flanging is usually expressed by the hole expansion ratio (HER), which is the minimum diameter needed to form flanges without cracks divided by the inner flange diameter.

DP steels are a group of AHSS composed of hard martensitic and soft ferrite phases. Decohesion at the boundaries of the different phases of the material promotes crack formation. Low HERs were observed in hole flanging of DP steels (HER = 1.58) [5]. The HER in DP steels depends on the volume fracture of martensite and the difference in hardness between the martensite and ferrite phases [6]. A fine and even distribution of martensite colonies inhibits crack propagation and improves the HER [7].

Hot hole flanging operations have been conducted on AHSS because of their low stretch flange ability at room temperature. Cheng [8] performed one-step hot stamping to form flanges from high strength steel 15B22. The tensile strength and breaking toughness of the formed flanges increased by 7.4% and 33% compared to flanges formed by the cold working process. Motaman et al. [9] explored laser-assisted heating of the blank edge to increase formability. The blanks were heated to about 400°C and flanges with an HER of 3.3 were formed.

Besong et al. [10] introduced high-speed tool rotation to conventional hole flanging of 0.8mm thick Aluminum EN AW-6181-T1 blanks to reduce equipment cost and process time associated with heating the blanks in existing hot hole flanging process variants. The self-stabilising nature of axisymmetric tool rotation permits high-speed rotation with negligible kinematic effects acting on the machine tool. Round tools form flanges with higher formability compared to paddle-shaped tools. Optical strain measurements of flanges reveal that the lower formability observed in hole flanging by paddle forming is because of biaxial stretching [11]. In this study, round tools rotating at high speeds are used to form DP 1000 blanks. Frictional heat generated at the contact of the blank and punch causes a rise in blank temperature that in theory should lead to higher formability.

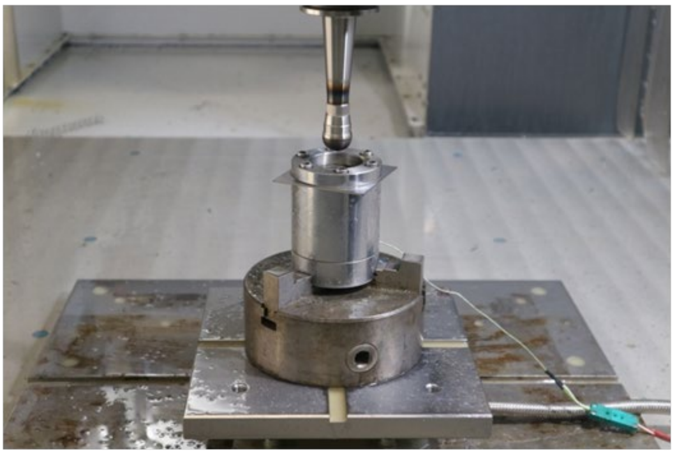
Hole Flanging Process Setup

The hole flanging with punch rotation was conducted on a 3 axis CNC router GR-510 machine center, manufactured by HAAS Oxnard, USA. The DP 1000 blanks were clamped by a die set, as shown in Fig.1a. The blanks were machined using a 5 mm flat end mill cutter to vary the blank thickness (0.1 mm, 0.1 mm, 0.7 mm, and 0.9 mm) and determine the effect of blank thickness on the maximum HER. Thermocouples were welded close to the flange bend to measure the temperature increase caused by tool rotation, see Fig 1b. The experiments were conducted at a tool speed of 8000 rev/min and tool feeds between 150-750 mm/min. The process time was less than 2 s. The approximate strain rate was between 0.2 – 1.8s^{-1} and is estimated from the change in the major strain divided by the process time. High tool speeds were used in the experiments based on the gain in formability reported in [11]. The tool had a diameter of 25 mm and was made from 1.2210 cold work steel alloyed with chromium and vanadium. Raziol CLF 100 cold forming oil was used as a lubricant. The chemical composition of the blanks is presented in table 1.

Table 1: Chemical composition of DP 1000 (wt%) [12]

Element	C	Si	Mn	P	S	Al	Nb
wt%	0.15	0.50	1.50	0.010	0.002	0.040	0.015

(a)



(b)

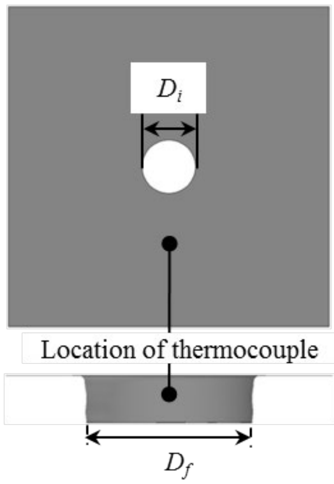


Fig. 1. (a) Set up of hole flanging experiments. (b) Position of the thermocouple before and after the forming process.

To determine the general effect of temperature and strain rate on the formability of DP1000, tensile tests were performed at strain rates of 0.01s^{-1}, 0.1s^{-1}, and 1s^{-1} at 25°C, 400°C, 500°C and 600°C. The tests were conducted in the rolling direction of the blank. The gauge lengths and widths of the specimens were 10 mm and 2 mm. The experiments were conducted on a dilatometer DIL805A/D at 10^{-4} bars of vacuum. Thermocouple elements were welded to the middle section of the specimens to monitor the specimen temperature. The microstructure of a flange was examined on a VHX 7000 digital microscope manufactured by Keyence, Osaka, Japan.

Results of Hot Tensile Tests

The tensile tests revealed an increase in the maximum true strain (elongation at break) from ≈ 0.12 to 0.18 as the blank temperature increased from 20°C to 600°C at a strain rate of $0.01s^{-1}$, see Fig. 2.a. The elongation at break reduced as the strain rates increased from $0.01s^{-1}$ to $1^{-}s$ at 25°C and 400°C. However, the strain rate does not significantly affect formability at 600°C.

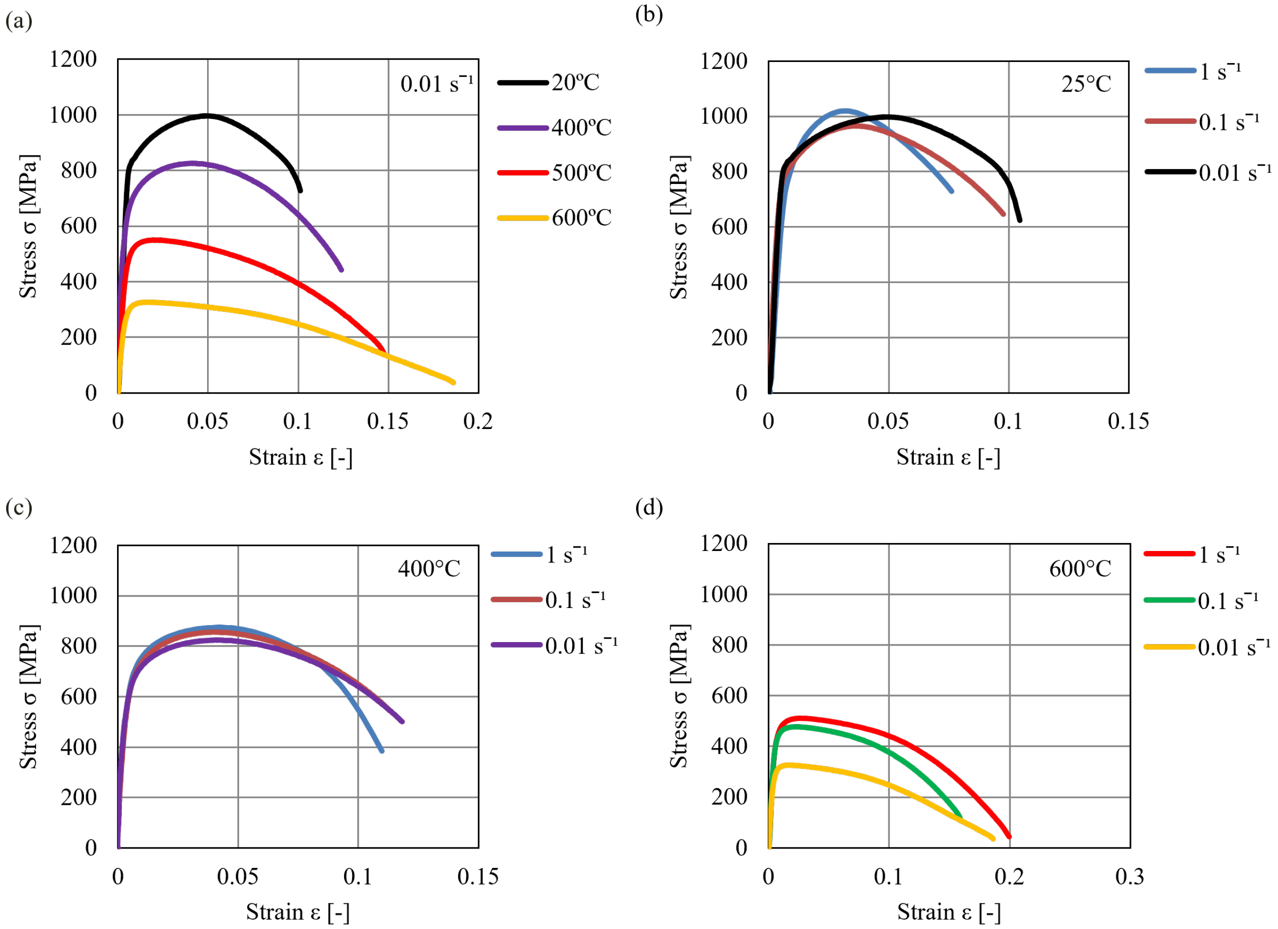


Fig. 2. Variation of the true stress-strain with temperature and strain rate. (a) Flow stress at different temperatures. (b) Flow stress at 25˚C. (C) Flow stress at 400˚C. (b) Flow stress at 600˚C.

Results of hole flanging

Temperature evolution. The temperature was measured at position B close to the flange bend, as shown in Fig. 3a. A maximum temperature of 1050 ±9°C was recorded in hole flanging at a feed of 750 rev/min, see Fig. 3b. The flanges were 0.5 mm thick and had initial hole diameters of 15 mm. The temperature measurements are similar and show that the process is reproducible in production environments.

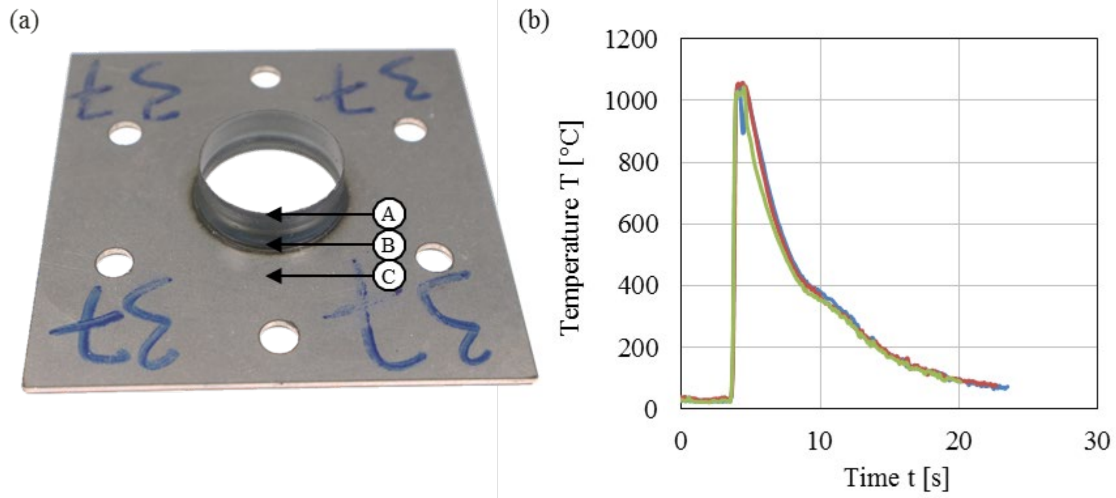


Fig. 3. (a) Flange formed at a feed of 750 mm/min. (b) Temperature evolution of point B.

Microstructure analysis. The microstructure at the flange edge (point A) should change because of the high temperatures measured in the experiments. The short cooling time from the temperature at which austenite is formed implies that the steel transforms to martensite on cooling. Negligible or no change is expected towards the bend of flange and non-deformed blank (points B and C) because of lower temperature change. The blank was examined at 3 points (Fig. 3a) along the flange length to reveal changes in the microstructure due to the forming process. At the flange edge, the microstructure was composed of elongated martensite grains, which is caused by the rapid cooling of the material from austenitic temperatures to room temperature. Close to the flange bend, there is a transition in the microstructure. In the non-deformed part of the blank (point C), the characteristic dual-phase structure of DP 1000 steel is observed as shown in Fig. 4c.

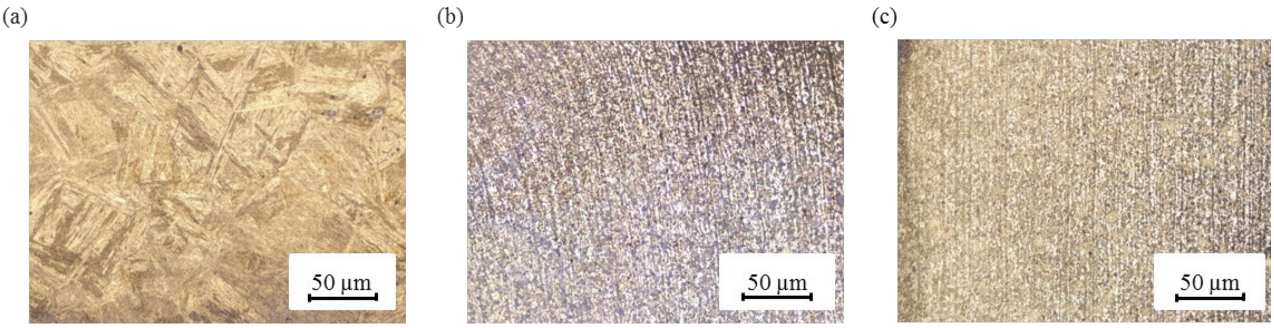


Fig. 4 Microstructure of DP1000. (a) Flange edge. (b) At the transition area. (c) Non-deformed blank.

Forming limits. Blanks were formed at 8000 rev/min rotational speed and feed rates between 150-750 mm/min to keep the process time in the range of conventional hole flanging, see Fig. 5a. The blanks had a pre-cut hole diameter of 15 mm (HER = 1.67) and 0.5 mm thickness. The flange length increased from 4.73 mm to 5.85 mm as the feed increased from 150-350 mm/min and reduced for higher feed rates, as shown in Fig. 5b. The difference in the flange length may be explained by the tendency for the tool to stretch the blanks at high feed rates, which happens due to the increased friction at the contact surfaces. However, for feed rates higher than 350 mm/min, the drop in blank temperature due to fewer rotations made at the contact of the tool and blank leads to lower blank formability and hence shorter flanges. The feed of 750 mm/min (green star) was used in the rest of the tests because higher feeds may increase the process forces which adversely affect the machine tool since less heat is generated at high feed rates. In addition, the process time is short at a feed rate of 750 mm/min. Likewise the flange length is longer (5.70 mm) at a feed rate of 750 mm/min compared to 4.73 mm and 5.32 mm at 150 and 250 mm/min feed rates.

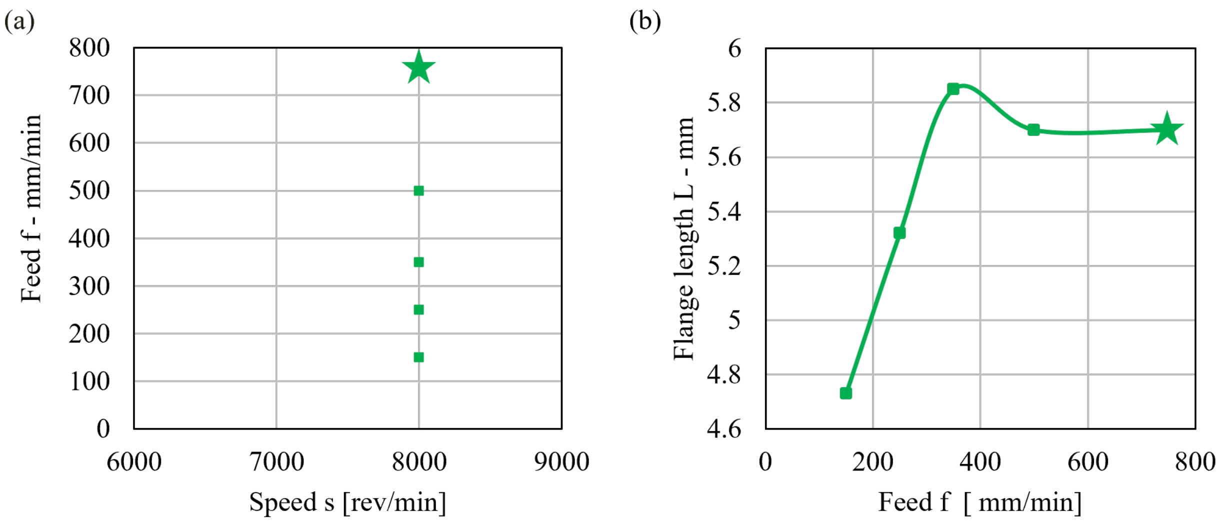


Fig. 5. (a) Flanges formed at different feeds at 8000 rev/min. (b) Flange lengths.

A maximum HER of 2.3 was obtained for the 0.1 mm thick blanks. The flange with a higher HER had cracks at the edge, see Fig 6a. For the flanges with initial blank thicknesses of 0.3 mm and 0.5 mm, the maximum HERs were 2.75 and 3.6, respectively. Flanges with lower HERs were successfully formed, see Fig. 6b. Similarly, the flanges with HER above 2.75 and 3.6 had cracks. The red dots in Fig 6c represent flanges with cracks while the green squares represent flanges without cracks. A maximum HER of 3.1 was obtained for a blank thickness of 0.9 mm. Flanges were not formed for blanks with higher thickness to avoid damage to the CNC machine tool due to high forces. Likewise, flanges with HERs above 3.1 were not formed for the 0.9 mm blank (see the blue diamond shape in Fig. 6c). The maximum HER increased with the blank thickness probably because more material is available for stretching before fracture. The region in which flanges without cracks were formed for the different blank thicknesses is shown in the shaded region in Fig. 6c.

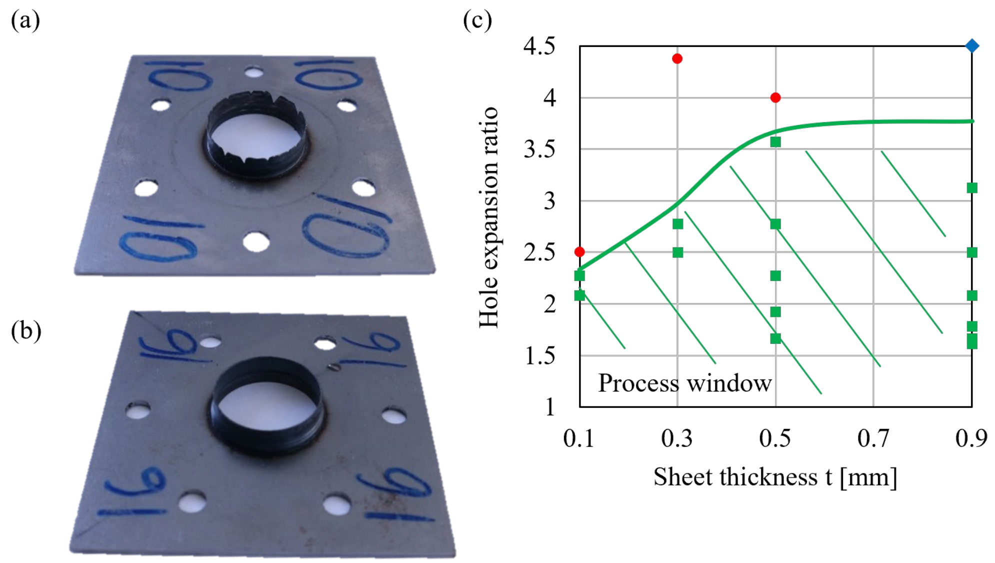


Fig. 6. (a) Flange with cracks. (b) Successfully formed flange (c) The maximum HERs for flanges with different initial blank thickness.

Discussion

A maximum temperature of 1050 ±9°C was recorded in the hole flanging tests. The hot tensile tests revealed that material formability increases with temperature, which agrees with the high forming limits observed in the hole flanging tests compared to an HER of approximately 1.58 for

1.2 mm thick blanks in conventional hole flanging. In addition to temperature rise, the contact between the punch and tool causes bending under tension and nonlinear strain paths that increase formability [13]. Shear due to tool rotation also increases formability [14]. This is demonstrated by a slight twist along the flange length and finite element analysis of the process [10]. The increase in formability of the steel at high temperatures is attributed to softening of the steel as the energy needed to activate slip planes within grains of the material is reduced and the material can be deformed without failure. Rapid cooling of the steel from temperatures at which the steel is in the austenitic phase causes the formation of martensite observed in the optical micrographs of the flange edge. Martensite formation as a result of high-speed tool rotation can also be implemented in partial heat treatment of blanks which is highly useful for lightweight applications.

Conclusion

This study was conducted to increase the formability in hole flanging of hard-to-form DP1000 steel. A maximum HER of 3.6 was obtained in the experiments compared to ≈1.5 in conventional hole flanging. The results of the hole flanging experiments revealed that formability increases with blank thickness. The maximum HER was 2.3 for 0.1 mm thick blanks and increased to 3.6 for 0.5 mm thick blanks. Hot tensile tests revealed an increase in material formability (elongation at fracture) with temperature, which explains the high formability in stamping with punch rotation compared to conventional hole flanging. The high process temperature altered the blank microstructure from the characteristic dual-phase steel to elongated martensite grains, which increases the strength of the formed flanges.

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