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Experimental and numerical study on High Speed Impact Trimming(HSIT) process for UHSS sheets

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Ultra-High Strength Steel (UHSS) sheets have been widely used for lightweight structure design because of their high specific strength characteristic in the automobile industry. However, the final stages of the manufacturing process, such as trimming and hole piercing of formed parts, lead to tool damage issues due to a subsequent increase in high yield stress. Conventional mechanical trimming techniques have some problems with UHSS because punch and die wear out and work hardened parts often cannot be trimmed. High-Speed Impact Trimming (HSIT) can be an alternative in this case. The basic principle of the HSIT process is that the high-speed trimming punch can cut off the scrap within a few microseconds leading to adiabatic conditions within the narrow shear band. In this study, the sheared edge quality using the HSIT under large clearance is investigated for CP1180-1.2t steel sheet with numerical and experimental methods. In order to consider the physical effects in numerical condition, Johnson-Cook hardening and damage models were employed so that the strain hardening, rate hardening, and thermal softening is reflected in simulation results. The experimental results show that high punch speed makes straight trimmed edge compared to conventional trimming under the same large clearance. The numerical simulation results also show that the faster punch speed of HSIT causes a deformation mode close to pure shear in the shear band, enabling more effective trimming with a good sheared edge quality.

1. Introduction

Ultra-High Strength Steel (UHSS) sheets with excellent specific strength have been widely used for vehicle components, such as door side impact beams, pillars, chassis, etc., which are directly connected to passenger protection with very high stability. Due to technological maturity and enormous demand, applications have been extended to affordable car models. Even though the forming process of UHSS has difficulties due to low elongation and high strength, it can be handled through alternative processes such as hot stamping [1-2]. However, work hardening of deformed parts and/or martensitic structure after hot stamping makes the mechanical trimming process very difficult. So, laser processing has been widely performed for trimming high-strength steel sheets but this method spends high power energy and causes excessive manufacturing time and product costs. Trimming after local heating using infrared light has also been recently proposed [3]. As an alternative, High-Speed Impact Trimming (HSIT) has been studied by increasing its efficiency and fast production. Schmitz et al. (2020) reported that high-speed blanking for high-strength steel sheets can make a smooth cutting surface and it results from adiabatic conditions making materials softened [4]. Gu et al. (2020) performed trimming experiments with two high-strength steel sheets with a variety of clearance and punch velocities [5]. They showed that trimming velocity has a critical role in sheared edge quality from small to large clearance conditions. HSIT process usually progresses from micro- to milli-second scale.

In this work, the effect of high-speed trimming on the quality of the shear edge of UHSS has been studied. HSIT experiments were performed under large clearance conditions to analyze velocity effects compared to the conventional trimming process. For simulation, LS-Dyna explicit S/W was used with Johnson-Cook hardening and damage models to consider multi-physical effects. Finally, stress triaxiality was analyzed during the whole trimming process through-thickness direction to discuss the velocity effects.

2. Numerical model

The HSIT process proceeds with tens of- or hundreds of millisecond scale and strain rates are very high in the severely deformed region. And also, a very short time process prevents heat generated by inelastic work from diffusion with neighbors. Therefore, material behavior should be defined together with strain hardening, strain rate hardening, and thermal effects. Here, the Johnson-Cook hardening model was used to include multi-physical effects.

$$\bar{\sigma}_{\theta}(\bar{\lambda}) = \left[A + B\bar{\varepsilon}^{pn}\right] \times [1 + C\dot{\varepsilon}^{*}] \times [1 + T^{*m}] \qquad (1)$$

Where A, B, C, and m are material constants. In addition to strain hardening, strain rate effect and thermal softening are also included as given

$$\dot{\varepsilon}^{*} = \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \qquad (2)$$

$$T^{*} = \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right) \qquad (3)$$

Where $\dot{\varepsilon}$ denotes strain rate and $\dot{\varepsilon}_0$ denotes reference strain rate set
to 0.01/sec. T means temperature, T_{ref} and T_{melt} are room and melting temperature, respectively.

For the damage model, the Johnson-Cook model was applied because it can consider hardening, strain rate, and temperature rise at different stress triaxiality states.

$$\varepsilon_f = [D_1 + D_2\, exp(D_3\sigma^{*})] \times [1 + D_4\dot{\varepsilon}^{*}] \times [1 + D_5 T^{*}] \qquad (4)$$

$$\sigma^{*} = \frac{\sigma_m}{\bar{\sigma}_{eq}} \qquad (5)$$

D_1 - D_5 denote material constants. σ^{*} denotes stress triaxiality defined as the ratio of hydrostatic stress to isotropic equivalent stress. $\dot{\varepsilon}^{*}$ and T^{*} are the same as equations (2) and (3). The material constants used in hardening and damage models are tabulated in Tables 1 and 2, respectively. Note that for both models, material constants were fitted by a geometrically optimization process and not fully verified by experimental data. To get exact calibration, further experiments are needed.

Table 1. Johnson-Cook hardening material constants for CP1180-1.2t

A [Mpa]	B [Mpa]	n [-]	C [-]	T_{ref} [°C]	T_{melt} [°C]	m [-]
1180	510	0.28	0.014	298	1833	1.03

Table 2. Johnson-Cook damage material constants for CP1180-1.2t

D_1 [-]	D_2 [-]	D_3 [-]	D_4 [-]	D_5 [-]	T_{ref} [°C]	T_{melt} [°C]
0.015	0.2	-3	-0.07	0.12	298	1833

3. Trimming condition

3.1 Experimental setup

High-speed trimming was conducted using AIRAM pneumatic press machine with Max. 60psi pressure capacity as shown in Figure 1. CP1180-1.2t blank was positioned between die and holder and a punch speed of 1.1m/sec was controlled with a pneumatic pressure setting of 40psi in the air tank. Clearance was fixed to 16 % of thickness during the process.

3.2 Finite analysis setup

The finite element (FE) modeling is shown in Figure 2. Tools were made to the elastic body and the radius was set to 0.1mm. The minimum element size of the blank was configured as 0.02mm to express sheared edge effectively.

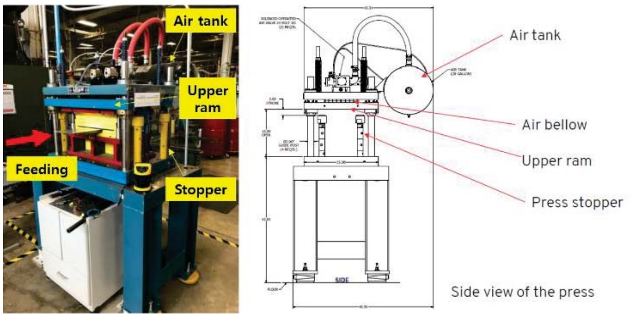


Fig 1. AIRAM pneumatic press and main configuration

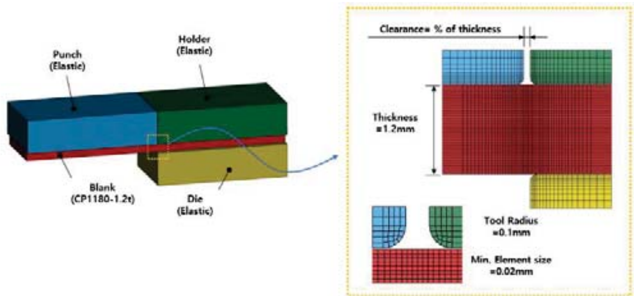
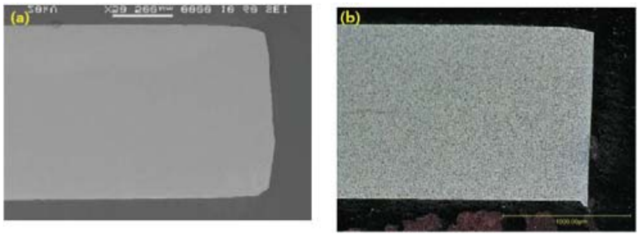


Fig 2. Schematic of HSIT FEM modelling

4. Results

Figure 3 describes the trimmed edge of CP1180-1.2t at different conditions. Conventional trimming shown in Fig. 3 (a) was performed with a speed of 5mm/sec under 8% clearance. The trimmed edge presents the roll-over, burnish, and fracture parts, as in traditional trimming processes. In addition, the uneven sheared edge can be found with distinct ductile fracture characteristics. However, high-speed trimming in Fig. 3 (b) represents a different configuration. In this case, the distinction between the roll-over, burnish, and fracture parts almost disappear, and a very sharp cross-section is shown.

The FE simulation results are represented in Figure 4 with effective plastic strain distribution. In this figure, strain distributions do not form narrow and straight but are connected in a diagonal direction from punch corner to die corner. The trimming line does not follow the direction of the shear band but keeps a straight line through-thickness direction. For more discussion, stress triaxiality was analyzed during the trimming process from points 1 to 5 in Figure 5. For the deformation path, point 1 has negative triaxiality around -0.1 at initial deformation, which means that the element has slightly experienced compression to make the roll-over region. At middle regions of thickness including points 2 and 3, mateial points were evolved keeping stress triaxiality close to zero, almost pure shear mode. For lower regions, points 4 and 5, they experience compression at initial deformation and then change their modes to slightly tension mode following pure shear mode. This implies that fracture strains are not affected by the magnitude of effective plastic strain solely but together with strain rate and stress triaxiality; in other words, it implies that even a smaller effective plastic strain level can



reach the fracture limit near points 2 and 3 leading to the good edge quality.

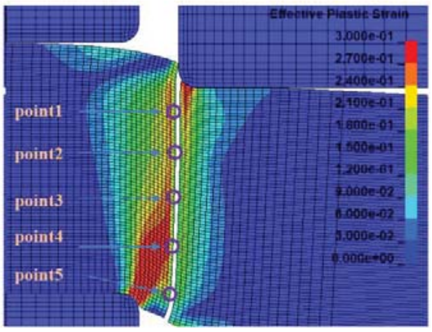


Fig 3. Trimmed edge of CP1180-1.2; (a) conventional trimming (b) high-speed trimming

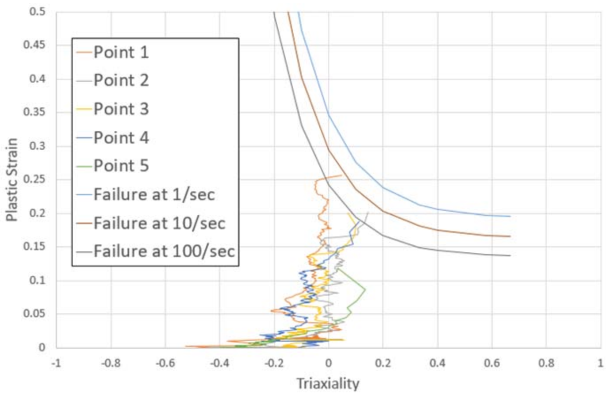


Fig 4. shows numerical results for effective plastic strain distribution with a similar edge profile after the process completion.

Fig 5. Johnson-Cook failure curve and triaxiality change through-thickness direction during the whole deformation

4. Conclusions

In this work, high-speed trimming was studied with a UHSS sheet by experiments and numerical analysis. HSIT process showed the improved sheared edge line compared to conventional process even in more wide clearance condition. Details are summarized as follows:

1. Under the large clearance condition, high punch velocity represented smooth sheared edge profiles. However, conventional trimming even in a smaller clearance formed uneven sheared edges including roll-over and fracture angles.
2. The FEM model was successfully set up to include strain rate effects in the hardening model and damage model simultaneously, and describe the trimmed edge.
3. Stress triaxiality analysis shows that fracture is affected by both stain, strain rate and stress modes. From the analysis, it is found that HSIT was able to have straight edges, small roll-over, and burr height even with a small plastic strain.
4. For more accurate verifications, further experiments (e.g. hardness tests, fracture test at different stress triaxiality, and microstructure analysis) will be carried out.

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