Influence of the tool temperature increment on the coefficient of friction behavior on the deep drawing process of HSS

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Abstract. The use of High Strength Steels (HSS) in the deep drawing processes has an impact on the temperature that is achieved on the die surfaces. Due to the heat that is created through the deformation of the material and the friction itself, the tools temperature increase considerably up to approximately 100ºC. This temperature increment has an effect on both the wear of the surface and also the coefficient of friction (COF). In this work the influence of the tool temperature on the coefficient of friction is studied. For that, Strip Drawing Tests have been carried out at different tool temperatures with a DP780, High Strength Steel. Moreover, different contact pressures have been considered in the study to analyse the combined effect of the contact pressure with the temperature increment. It has been proved that the temperature increment has to be taken into account to predict accurately the behavior of the coefficient of friction between the sheet and the tool. This change in the coefficient of friction has a high impact on the prediction of the deep drawing process.

1. Introduction
The increasing use of High Strength Steels (HSS) has become common practice in the automotive industry. This growth is due to the global trend to reduce the CO₂ emissions to the atmosphere. Nevertheless, the processing of these materials has induced some drawbacks that have to be taken into account. The forming of these materials requires increased work and contact pressures [1], which is translated to high friction forces producing significant temperatures on the tool and blank surfaces. Moreover, due to the complexity of the final geometry of the majority of the automotive components, significant deformation levels have to be achieved. In order to achieve these levels of deformation, a remarkable plastic deformation energy is produced and as consequence high amount of heat is generated. In addition, the automotive industry requires high productivity of around 32 strokes per minute, which prevents the surfaces of the tools to dissipate the absorbed heat. The generated heat can increment the temperature of the surfaces up to 181ºC at some punctual moments [2].

Kim et al. [3] analyzed the temperature distribution of the sheet and the tools in a deep drawing process of a cylindrical cup and observed a maximum temperature of 85.5ºC on the sheet. Nevertheless, the study focusses on an isolated stroke regardless of the temperature rise effect during serial production. Hazra et al. [4] analyzed the temperature increment in big serial production of real components and concluded that modest temperature changes did not affect material properties but altered lubricant behavior. Pereira et al. [2] studied separately and coupled the influence of the frictional heating and the...
deformation-induced heating on the temperature rise of the tool surfaces. It was observed that the frictional heating is primarily responsible for the peak temperatures on the die surfaces.

Several researchers have observed the effect of the tool surfaces temperature increment on the deep drawing process. Kim et al. [5] showed that the formability of the High Strength Steels is affected by these temperature changes, particularly when shear fracture failure occurs. Sachnik [6] analyzed the zinc abrasion of the galvanized sheets that is produced in the deep drawing due to the achieved temperatures on the tool surfaces. Merklein et al. [7] tested a DX56-D+Z at different contact conditions, including different temperatures, but did not achieve temperatures over 60°C. Even though, as the tool temperature increased from 20 to 40 °C, the coefficient of friction experienced an increment of 6.5%. However, there has been noticed that a deeper research is needed in terms of the effect that the temperature changing has on the coefficient of friction.

The modelling of complex tribological conditions is one of the biggest goals to improve the accuracy in sheet metal forming simulations. Together with the blankholder force and the drawbeads restriction force, the coefficient of friction represents the restriction that the material has to overcome to flow through the surfaces of the tool. Furthermore, the deformation and stress distribution depends directly on the applied restriction to the material flow. The complexity of a precise definition of the friction coefficient lies on the number of variables which affect on it. The coefficient of friction is already known to be influenced by several factors within the forming processes as the sliding velocity and the applied contact pressure. But the influence of the temperature increasing at the tool surfaces caused by the forming of High Strength Steels on the coefficient of friction has not been analyzed yet.

In this work, the coupled effect of the applied contact pressure and the tool surface temperature on the tribological behavior has been experimentally investigated. A novel Strip Drawing test facility was developed to provide a temperature control on the tool. This equipment has been used to carry out Strip Drawing tests at different tool temperatures and contact pressures to show the influence of each parameter on the coefficient of friction of a DP780. The obtained results clarify the remarkable effect of the temperature increment on the tribological behavior in deep drawing processes of High Strength Steel components.

2. Methodology

The developed temperature controlled Strip Drawing Test consist of two blocks which have been modified to be able to be heated up to a defined temperature. The block temperatures were maintained at the commanded temperature by means of a cartridge die heater (Hasco). In each block two cartridges are placed to heat the material while a thermocouple is measuring the current temperature, see figure 1. The temperature control was realized by a closed-loop which received the current temperature from the thermocouple. As the thermocouple was located at a certain distance from the surface, there was a difference between the measured temperature at the thermocouple and the one at the block surface. So first, these differences were measured to know which consign had to be defined to reach each block surface temperature.
These blocks are located in a biaxial machine installation at the Mondragon University. Once that the temperature of the blocks surfaces is stabilized at the commanded value, a cylinder applies a determined contact pressure to the sheet and then another cylinder pulls the sheet in the transversal direction to the contact pressure overcoming the friction force that is produced between the surfaces. Both the applied contact pressure and the sheet pulling force are measured during the whole test for the posterior calculation of the coefficient of friction. The schematic illustration of the test is presented in the figure 2. The material of the blocks was GGG70 and it was followed exactly the same procedure to get the surfaces which were in contact with the sheet as the die manufacturers standards. There was no extra lubrication applied to the sheet apart from the lubrication that the sheet brings itself.

The biaxial machine provides the possibility to vary the contact pressure in a wide range. In this study, a contact pressure range between 1 and 16 MPa has been defined. The contact pressure values have been obtained from a numerical simulation of a B-Pillar reinforcement from a DP780 sheet where the above presented range was shown. In addition, four different temperatures have been defined: 20ºC (room temperature), 50ºC, 80ºC and finally 100ºC.

3. Results and discussion

As it has been mentioned before, the sheet material is a DP780 High Strength Steel. The analyzed material was covered by 50 microns of zinc coating in each sheet surface. The obtained experimental results are shown in figure 3.
Figure 3. Strip Drawing Test results and the fitted model curve at a) 20 ºC, b) 50 ºC, c) 80 ºC and d) 100 ºC. One test was carried out at each condition.

The experimental results have been fitted by the model proposed by Filzek et al. [8], where the coefficient of friction is represented in function of the applied contact pressure. This model represents the tribological behavior of the sheet by the equation (1),

$$\mu = \mu_0 \left( \frac{P}{P_0} \right)^{n-1}$$

where $\mu_0$ and $P_0$ are reference values and $n$ is an exponent defined within the range $0 < n < 1$. The results have shown that the tool temperature affect in the stability of the coefficient of friction. As the temperature increases, the coefficient of friction has a greater variation. Except from the experimental results carried out at 100 ºC, the general tendency of the coefficient of friction is to decrease as the contact pressure increases. However, this tendency seems to be reduced as the tool temperature increases. The most evident case is at 100 ºC where there is not a clear tendency of the coupled influence between the temperature and the contact pressure. The author suggest that as Merklein et al. stated [7], the change of the tribological behavior comes from the alteration that the viscosity of the lubricant suffers due to the temperature increment on the tool surfaces.

In figure 4 it is presented the comparison between the different tendencies that the experimental results showed in each thermal condition.
These results showed that the temperature increment has the major effect on the tendency of the coefficient of friction when different contact pressures are applied. As the temperature increases, the tribological behavior showed a lower dependency on the contact pressure variations. In fact, at 100ºC the value of the coefficient of friction maintains almost constant independently to the contact pressure that was applied.

4. Conclusions
These results add another extra deal to take care of when forming High Strength Steels components. The heat that is generated due to the high energy required to deform the material plus the high friction forces is transferred to the tool surfaces altering the viscosity of the lubricant and as consequence the tribological behavior between the tool and sheet surfaces. As it is known, the definition of the coefficient of friction is a key factor to predict accurately the deformation and stress distribution along the sheet and its direct impact on the springback and final geometry of the part. As consequence the temperature increment of the tools caused by the continuous production of High Strength Steels components is not a negligible parameter from the point of view of the coefficient of friction response.

The most remarkable conclusions obtained from this work are listed as follows:

- It has to be taken into account that the major temperature increment happens in tool areas where high deformations and contact pressures appear as die shoulders, punch radius or drawbeads zones. The results show at higher pressures than 11 MPa that the coefficient of friction is higher as the temperature increases. This effect can result in galling problems at those areas apart from inaccurate predictions in terms of deformation and stress distribution in the sheet.
- The inhomogeneous distribution of the temperature of the surfaces of the tools hinders the correct definition of an equal coefficient of friction model for all the different areas.
- A cooling of the tools which would be able to maintain the tool surfaces at the same temperature may facilitate the adequate establishment of a unique coefficient of friction model for the whole contact along the sheet.
- The obtained results demonstrate the necessity of using a friction model which considers the coupled effect of the temperature and the applied contact pressure. However, this model would
require a numerical simulation software able to predict the heating up of the tool surfaces along the deep drawing processes.

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