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Friction behavior under magnetorheological lubricant in sheet metal forming process

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Abstract. The increasingly high standards required in sheet metal forming industry, both geometrical and aesthetical, lead to continuous search of solutions to control the metal sheet flow during deformation. As alternative to traditional draw beads or hydraulically controlled segmented dies, the possibility of locally varying the material tangential speed by adapting the surface tribology at the interface between the blank and the blank holder represents a still unexplored scenario. The paper presents the feasibility analysis of the use of magneto-rheological (MR) fluids as lubricants in stamping, exploiting their ability to vary their rheological behaviour in response to external magnetic fields. To this aim, a new strip drawing test bench was developed to investigate the friction behaviour of MR fluids under different magnetic fields. The cold stamping of DC05 steel sheet was taken as reference case to investigate the influence of typical process parameters such as contact pressure, sliding speed and magnetic field.

Introduction

Magneto-rheological (MR) fluids are materials capable of reacting to applied magnetic fields by reversibly modifying their rheological behaviour and, typically, this change is manifested by an increase in the yield stress as an applied magnetic field increases [1]. MR fluids are basically made of three elements: the carrier fluid, iron particles and the stabilizing additives. The iron particles are dispersed in the carrier fluid and, if exposed to a magnetic field, they are aligned in chain structures that determine an increase in yield and a consequent greater resistance to wall-sliding in case of laminar flow. The additives are introduced to control the viscosity, the settling rate and the friction between the particles and avoid the thickening of the MR fluid after a defined number of off-duty cycles [2].

A review of the scientific literature reveals that MR fluids are mainly used in dampers for vibration control in civil structures [3], and automotive semi-active components, such as suspensions [4, 5], brakes [6], clutch [7] and differentials [8]. Despite their versatility and adaptability, MR fluids have seen few applications in metal forming, most of them related to the development of damping devices or actuations. In [9] MR fluids are applied to overcome the reverse load phenomena in blanking [9], while in [10] the same Authors demonstrate the possibility of enhancing the surface quality of the sheared surface in the final part. With regards to the capabilities of damping the dynamic phenomena, an MR device is implemented in turning of hard materials to suppress the cutting tool vibration, making the system stable and free from regenerative effect of the cutting process [11]. Moreover, MR dampers demonstrated their performances in reducing chatter phenomena during the cutting of thin-floor parts [12] and, consequently, improving the surface integrity of the final surfaces. With regards to deep drawing, a commercial MR damper was implemented in [13] and tested experimentally to retain constant the blank holder force during the process, defining the control system and his performance characteristics, in terms of response time and force errors. Recent studies proposed novel control algorithms [14, 15] capable to adjust the blank holder force with respect of the sheet draw-in to control the material flow.

The present paper aims at presenting a new approach for the control of the material flow in deep drawing, by using the MR fluid as lubricant and controlling the friction behaviour at the interface between the blank holder and the part. The effect of the tribological characteristics of the MR fluid was investigated by using a novel apparatus specifically designed and manufactured to exert different magnetic fields and evaluate the friction coefficient. The paper is organized into four parts: the former presents the characteristics of the selected MR fluid and the materials properties for both metal sheet and dies. The second part deals with the description of the magnetic tool design and numerical analysis to evaluate the magnetic field exerted to the MR fluid. The third part describes the overall experimental apparatus and the experimental plan. Finally, the last section presents the results of the experiments.

Material

The MR fluid selected for the test is the ARUS AMT-SMARTEC$^{+®}$. It is a synthetic-based fluid with high yield strength to take up heavy loads and dissipate the energy with minimal consumption of power. The principal nominal characteristics are reported in Table 1.

Table 1. Properties of ARUS AMT-SMARTEC$^{+®}$.

Viscosity (Pa*s) at 40 °C, calculated as sloop between 0-1200 s^{-1}	0.37
Density (g/cm$^{3)}$	2.90
Solid content by weight (%)	81
Yield shear stress (kPa) at 140 kA/m	69
Operating temperature range (°C)	-20 - 150
Flash point (°C)	> 180

Table 2. Nominal chemical composition of AISI 1040 steel.

Chemical compositions in wt%							
C	Si (max)	Mn	P (max)	S (max)	Cr (max)	Ni (max)	Mo (max)
0.37 - 0.44	0.40	0.50 - 0.80	0.045	0.045	0.40	0.40	0.10

The punch was manufactured by using quenched AISI 1040 steel, which has a nominal surface hardness of 210 HB. Table 2 report the nominal chemical composition of the AISI 1040 steel while Fig 1a) and Fig. 1b) show the punch geometry. During the tests, the punch was in contact with the specimen through the active area, whose has an extension of 500 mm^2 (20 x 25 mm^2 surface). The active area was measured by means of an 3D surface profilometer to quantify the surface roughness. The profilometry of the measured area is reported in Fig. 2a), giving an average surface roughness S_a of 0.100(±0.012) µm.

The material of the specimen was the DC05 grade steel provided in 1 (±0.05) mm thick sheet, which is a low carbon steel commonly used in deep drawing processes. The chemical composition of the DC05 grade steel is summarized in Table 3, while Fig. 1c) shows the specimen geometry. The punch was made to slide in the central part of the testing zone, which was measured by a 3D surface profilometer, returning an average roughness S_a equal to 1.256 (±0.008) µm. The profilometry of the sheet surfaces is reported in Fig. 2b).

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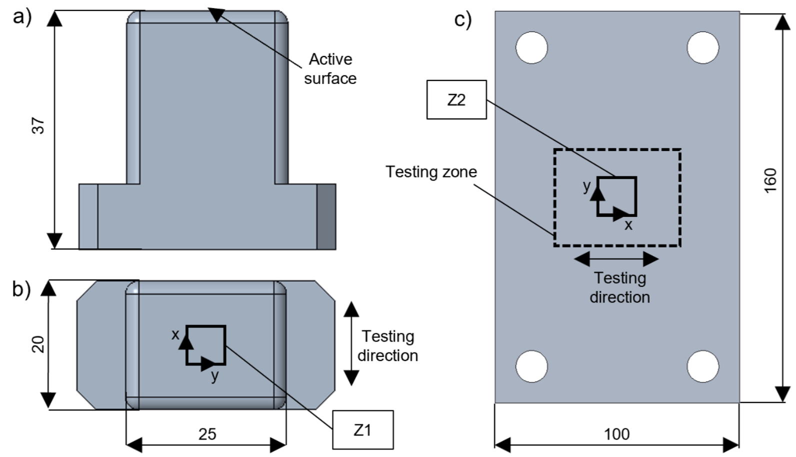

Fig. 1. Punch and specimen geometries: a) punch front view; b) punch plant view; c) specimen.

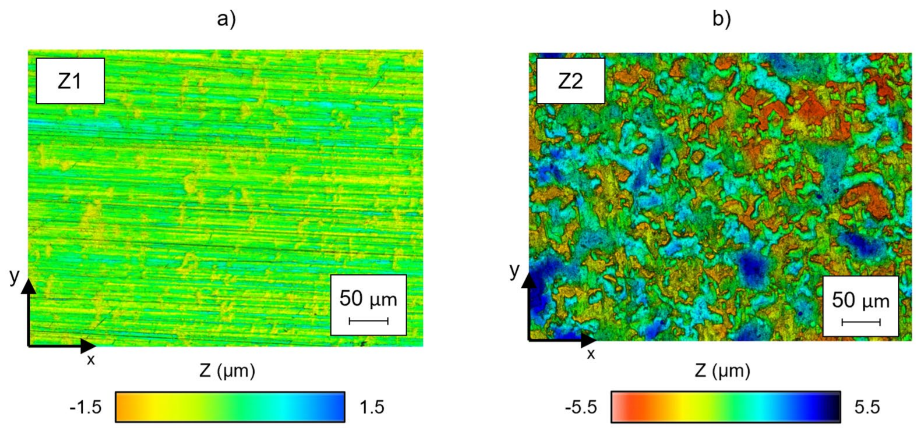

Fig. 2. Punch and specimen surface topographies: a) punch topography; b) specimen topography.

Table 3. Nominal chemical composition of the DC05 grade steel.

Chemical compositions in wt%			
Si (max)	Mn (max)	P (max)	S (max)
0.06	0.35	0.025	0.025

Table 4. Nominal chemical composition of the AISI 1015 steel.

Chemical compositions in wt%				
C	Si	Mn	S (max)	P (max)
0.13 – 0.18	0.15 – 0.35	0.30 – 0.60	0.045	0.045

Magnetic die

With the aim to expose the MR fluid to a controllable magnetic field, the die was designed and analyzed by means of ANSYS Maxwell software to evaluate the amplitude of the magnetic field *H*, which interests the MR fluid, see Fig. 3a).

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It was made of a die base in annealed AISI 1040 steel on which a groove was manufactured. Tree magnetic cores with winding coils were mounted on the groove to produce the magnetic field when the winding coils are excited by an input current. The magnetic cores were manufactured in annealed AISI 1015 steel, whose chemical composition is reported in Table 4, while the winding coils were made of 70 turns each of enameled copper wire with a nominal diameter of 1.5 mm. The sheet specimen was mounted on the magnetic die and fixed with the blocker plate. The blocker plate used to fix the specimen during the test acted as a pool for the MR fluid. The blocker plate was manufactured in non-magnetic AISI 304 steel, to concentrate the magnetic field in the magnetorheological fluid volume.

Fig. 3b) and c) show the magnetic field distribution in the MR fluid along the longitudinal direction, for an input current respectively of 2.5 A and 5 A. The contour plots reveal an almost horizontal iso-line distribution of the magnetic field, with the higher values near to the surface of the specimen.

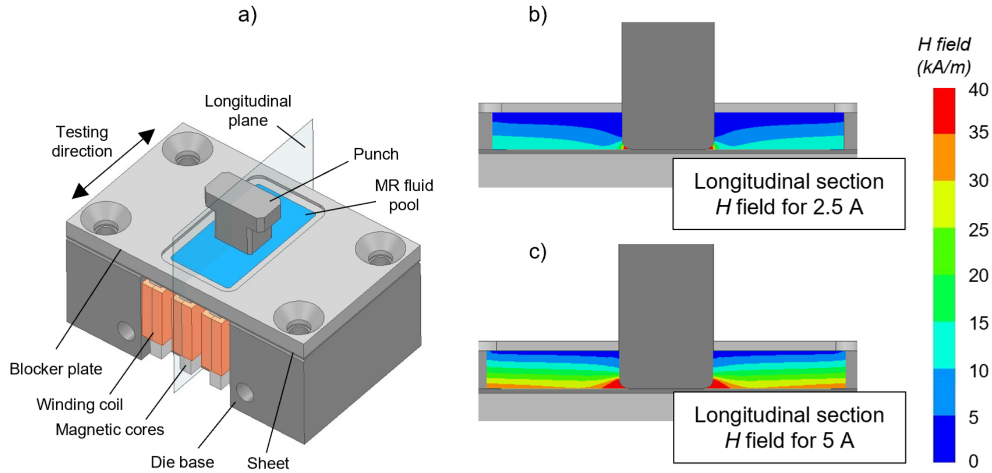

Fig. 3. Numerical model of the magnetic die and result: a) geometry implemented in ANSYS Maxwell; b) contour plot for an input current of 2.5 A; b) contour plot for an input current of 5 A.

Experimental

Fig. 4a) shows the overall experimental equipment, while Fig. 4b) reports a magnification of the magnetic die mounted on the equipment and connected to the power supply. The normal force F_N exerted by the punch was applied with a screw mechanism that embedded a piezoelectric load cell to monitor the normal pressure acting on the specimen.

During the test, the strip-sheet was fixed on the magnetic die and is made to slide against the punch. The sliding movement was transmitted to the carriage by using an electric actuator. The carriage is mounted on a linear roller guide with a negligible rolling friction coefficient, to avoid any disturbance in the tangential force F_T measurements. A load cell was mounted between the electric motor and the carriage to measure the tangential force F_T. The magnetic die was clamped on the carriage by means of a non-magnetic steel table, to avoid leakage of the magnetic field lines in the carriage material, hence enhancing the magnetic field applied to the MR fluid.

A dedicated power supply excited the winding coils of the magnetic dies with a maximum current of 5 A, which correspond 7.5 V.

Table 5 shows the experimental plan and the ranges of experimental parameters, namely normal pressure, sliding velocity and input current.

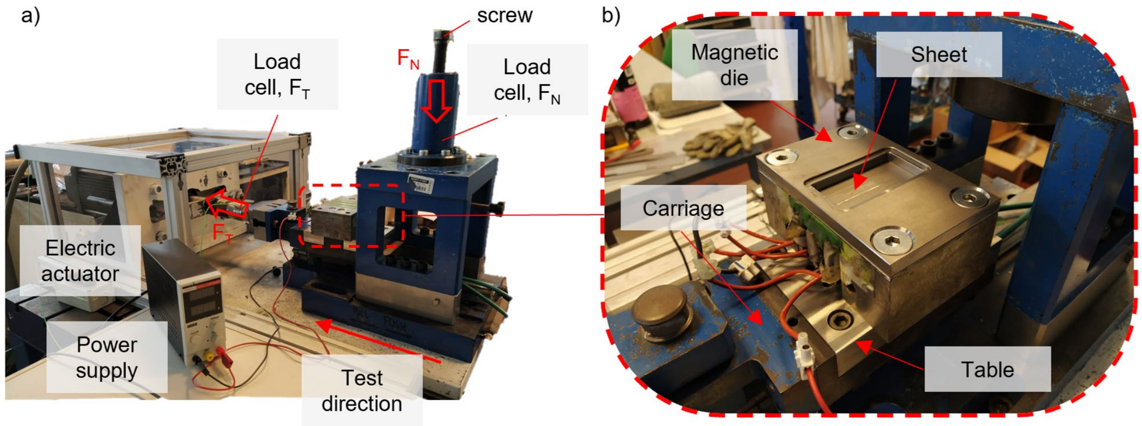

Fig. 4. Experimental equipment: a) overall view; b) detailed view of the magnetic die.

Table 5. Experimental plan for the strip drawing test

Normal pressure (MPa)	Sliding velocity (mm/s)	Input current (A)	Repeatability (-)
1, 5	5, 20	2.5, 5	3

Result and discussion

The coefficient of friction was calculated by using the Coulomb equation $\mu = F_T/F_N$ where F_T and F_N are respectively the tangential and normal forces measured by the embed piezoelectrical sensors.

Fig. 5 shows the experimental values of the friction coefficient with respect to the measured stroke for the investigated values of current, normal pressure and sliding velocity. The diagrams show an initial transit behavior for the first part of the stroke, then the coefficient of friction became stable after 10 mm. The exception is given in Fig. 5b), whereas the transit zone exceeds the first part of the stroke and the values of friction coefficient stabilize in the final part of the stroke. When the winding coils are powered with the input current, and the magnetic field is applied to the magnetorheological fluid, the coefficient of friction decreases from the initial values.

Fig. 6 shows the results of the friction coefficient according to the test parameters investigated in the experimental campaign. In the case of a sliding speed equal 5 mm/s and a normal pressure of 1 MPa the coefficients of friction are larger than the corresponding values investigated for a contact pressure of 5 MPa. For a normal pressure of 1 MPa, the coefficients of friction were respectively 0.294 (±0.021) at 0 A, 0.273 (±0.020) at 2.5 A, and 0.238 (±0.015) at 5 A. Rising the contact pressure up to 5 MPa, the coefficients of friction decrease to 0.280 (±0.017) at 0 A, 0.245 (±0.013) at 2.5 A and 0.215 (±0.016) at 5 A.

Regarding the test conducted with a speed of 20 mm/s, the tests reveal an opposite trend, with the highest friction coefficients in the case of contact pressure of 5 MPa. For a normal pressure of 1 MPa, the coefficient of friction ranges from 0.258 (±0.016) for a null input current, 0.220 (±0.019) in the case of an input current of 2.5 A and 0.198 (±0.019) for an input current of 5 A, while, in the case of a contact pressure of 5 MPa, the coefficient of friction is equal to 0.266 (±0.01) for a null current, 0.243 (±0.015) for a current of 2.5 A and 0.230 (±0.018) for a maximum current of 5 A. In these cases, the increase in the coefficient of friction is sharper for the contact pressure of 1 MPa, while, arising the contact pressure to 5 MPa, the coefficient of friction remains almost constant for 0 and 2.5 A, then decrease with a maximum input current of 5 A.

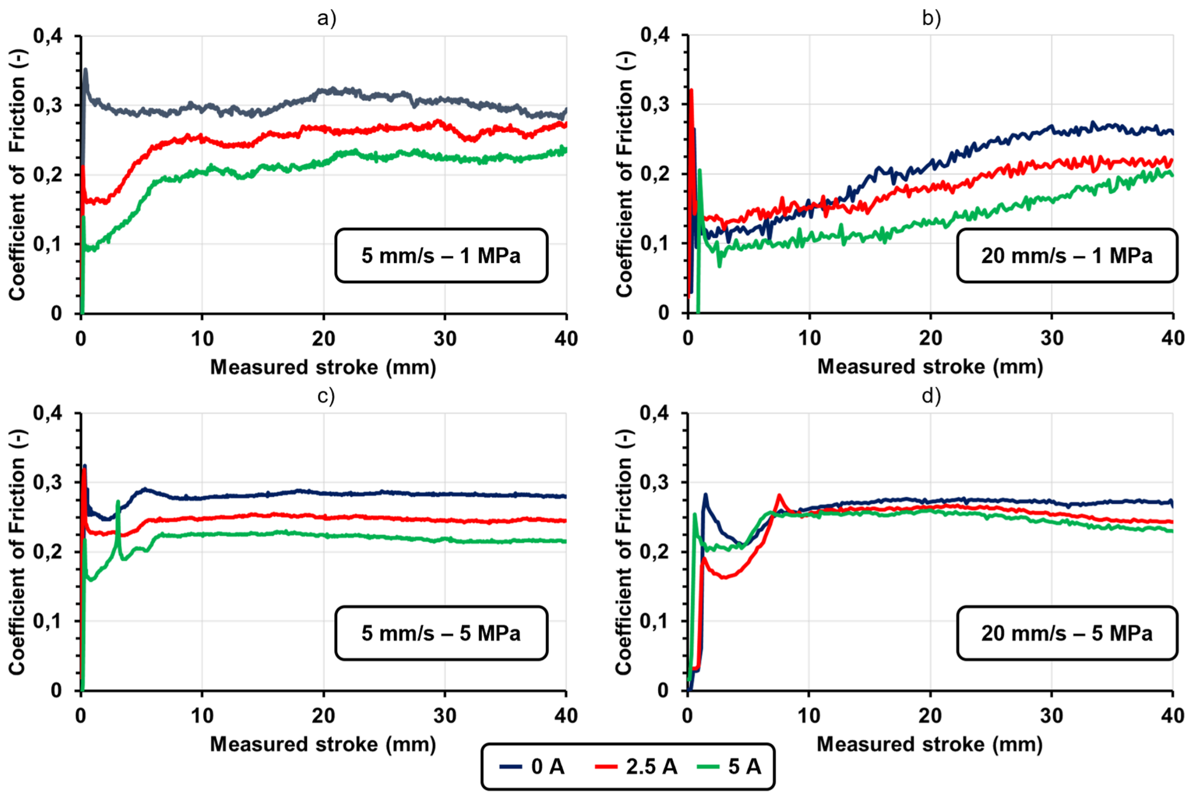

Fig. 5. Coefficient of friction vs measured stroke diagrams: a) 5 mm/s – 1 MPa; b) 20 mm/s – 1 MPa; c) 5 mm/s – 5 MPa; d) 20 mm/s – 5 MPa.

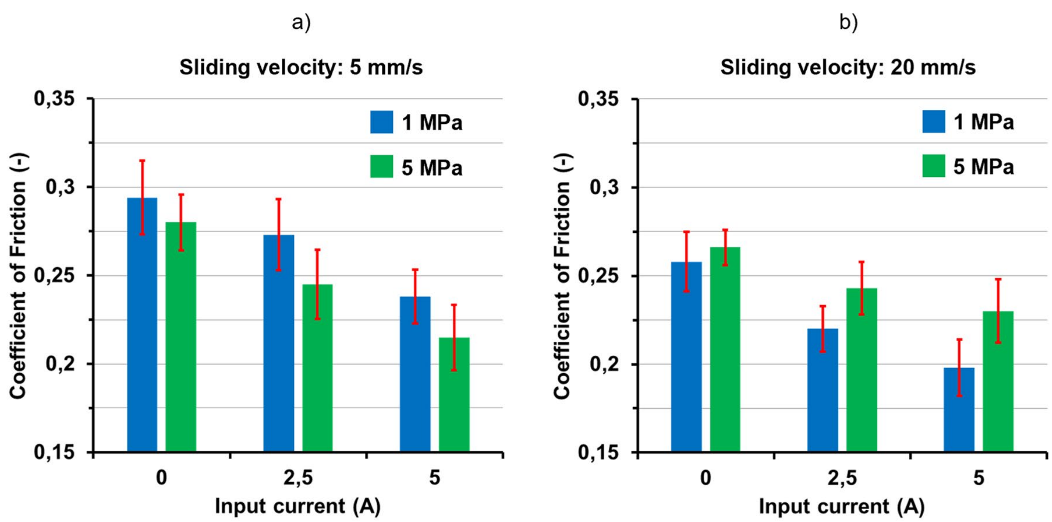

Fig. 6. Coefficient of friction values: a) at sliding velocity of 5 mm/s; b) at sliding velocity of 20 mm/s.

Finally, it is worth to notice how in both cases, higher values of applied DC led to lower COF. This can be related to the greater intensity of the magnetic field generated by higher DC, aligning the ferromagnetic particles dispersed in the ferrofluid with the magnetic lines, thus hindering the fluid flow between the tool and the sheet when the normal pressure is applied. In this way, the greater amount of lubricant at the interface can decrease the relative COF.

Conclusions

The present study aims at investigating the feasibility of using MR fluids as lubricants to vary the coefficient of friction in deep drawing. Moreover, by controlling the coefficient of friction becomes possible to adjust the restrain force on the blank during the draw-in. With this objective, a magnetic die was manufactured and installed in a strip drawing test equipment to apply controllable magnetic fields to the magnetorheological fluid.

To quantify the effects of the magnetic field on the MR fluid, the magnetic die was modeled in ANSYS Maxwell software. Two values of input current – respectively of 2.5 A and 5 A – were considered in the numerical analysis, to reproduce the test parameters.

From the experimental activities it was observed the dependency of the friction coefficient on the sliding speed and contact pressure. For the tests conducted at low speed, namely 5 mm/s, the coefficients of friction values were higher in the case of contact pressure of 1 MPa. The higher value equal to 0.294 was measured for a null current, and then it decreased as an input current was applied to the magnetic circuit, ranging to 0.273 and 0.238 respectively for an input current of 2.5 A and 5 A. By increasing the contact pressure up to 5 MPa, the values of the coefficient of friction became smaller. The coefficient of friction changed from 0.280 for a null current to 0.245 and 0.215 when a current of 2.5 A and 5 A was applied to the circuit. For the tests conducted at higher speed of 20 mm/s, the trend was opposite, with the lowest value in the case of contact pressure of 1 MPa. In this case, the coefficient of friction was equal to 0.258 for a null current, then increase to 0.220 and 0.2198 for input current of 2.5 A and 5 A. As the contact pressure was raised up to 5 MPa, the coefficient of friction was equal to 0.266 for a null current, 0.243 for an input current of 2.5 A and then decrease to 0.230 with a maximum input current of 5 A.

The results highlight a positive effect of a more intense magnetic field applied by increasing the coils supplied DC. A greater intensity of the applied magnetic field seems to hinder the lubricant flow under the dies improving the lubrication effects. Such results seem to open new possibilities for the in-process control of the sheet draw in applied to cold stamping processes.

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