TiN Coating on Drawing Force and Friction Coefficient

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The influence of various process parameters on the deep drawing process is a current research topic in sheet metal forming technology. Starting from the application of the previously constructed original testing device, an original tribological model was developed based on the process of sheet metal strip sliding between flat contact surfaces under variable pressures. A complex experiment was executed using an Al alloy sheet, tool contact surfaces of different roughness, two types of lubricants and variable contact pressures.

Keywords: Al alloy ; TiN coating ; flat die deep drawing process ; contact pressure ; coefficient of friction

1. Introduction

There are only a few factors that influence the deep drawing process—the effect of contact pressure on the thin sheet flange and the action of the draw beads at the point of contact with holder. In most of the previous research on this topic, the pressure within a die was considered (or set) as constant. This was achieved by continuous pressure setting during the sliding process via theoretically pre-set functions of pressure variations in terms of time. Thus, the influence of variable contact pressure was the actual subject of this research for the purpose of defining yet another factor to control the forming process. The other influential factors (the die, the contact conditions or material) were not considered.

Out of the many developed physical–tribological models of the forming process, the most-studied one is the flat die sliding model [1][2][3][4][5]. The authors of the relevant papers considered models of the deep drawing process using a thin sheet flange at the flat contact surfaces between the holder and a die. The created tribological models took into account all the influential factors (material, die, contact conditions) to be able to monitor variations in the friction coefficient and the drawing force with the application of tools of various surface roughness. The contact conditions were realized with the use of various types of deep drawing lubricant and thin sheets with different coatings. In some experiments, the authors reported variation in the thin sheet sliding speed as well [6][7][8]. The objective was always how to control the output process parameters in order to reduce the friction coefficient and drawing forces (as much as possible), while simultaneously obtaining the desired geometry of the forming product without wrinkles at the flange [9][10][11].

2. TiN Coating on Drawing Force and Friction Coefficient

“The ultimate aim of applied research is generation of knowledge relevant to production processes. A vital first step in acquiring such knowledge is the choice of experimental methodology” [12].

An experimental evaluation of the friction coefficient during thin sheet strip sliding is presented by Frattini et al. (2006) in [1]. The authors developed a simple measurement system that aimed to reproduce the process conditions occurring during the typical sheet metal stamping operation. It recorded the force variation on the specimen with the set contact conditions. The used samples included cylindrical dies and strips from different sheets, with or without coating. The obtained results were sufficiently reliable to be used in the forming processes of thin sheets with similar sliding conditions.

Szakaly and Lenard (2010) reported the application of a different apparatus, more massively built; this massiveness was explained by an intention to minimize the dispersion of the test results [2]. Their results confirmed that at higher sliding speeds and higher contact pressures, the friction coefficient values decreased. Higher die roughness did not always guarantee higher values for the friction coefficient.

Figueiredo et al. (2011) investigated thin sheet friction effects using two different techniques to assess friction [3]. The obtained results revealed that using the cross-sliding test, one can obtain the reduced friction, which was attributed to slightly increased contact pressure. The friction coefficient decreased with the number of realized slidings, which was probably caused by the surfaces’ running-in effect.

Coello et al. (2013) studied sliding between the flat surfaces of thin sheets made of high-strength steel and coated with zinc [4]. The roughness of the contact surfaces was in the form of asperities, which cause the creation and retaining of micro-pockets of lubricant. This resulted in more favorable friction conditions. Different lubrication regimes may be present in a sliding system. Furthermore, certain lubrication regimes could vary during the forming process. Thus, the sheets could be subjected to different tribological conditions in different process stages. The friction coefficient dropped with increases in sliding speed and contact pressure. The applied lubricant layer’s thickness had no effect on the test results.

Yanagida and Azushima (2019) considered the influences of lubricant, temperature and contact pressure on the friction coefficient [5]. They used a tribo-simulator in dry conditions. The obtained coefficients of friction were applicable for use in numerical simulations with finite element analysis.

Manoylov et al. (2013) studied the elasto-plastic contact of nominally plane parallel surfaces [6]. The local separation of surfaces is significantly influenced by surface roughness. In the mixed lubrication, the lubricant film was not sufficiently thick to prevent contact between the working surfaces. Thus, the influence of surface roughness on the pressure distribution became significant. Large pressures were generated in the interaction regions of the most prominent surface asperities.

Kondratiuk and Kuhn (2011) analyzed hot-dip-aluminized and electro-plated Zn–Ni coatings on manganese boron flat steel for hot forming applications [7]. The coatings’ tribological behavior in hot strip drawing tests was examined. The experiments were conducted with two different loads and tool geometries and included obtaining the coefficient of friction and wear characteristics.

Ghiotti and Bruschi (2010) considered the tribological behavior of diamond-like carbon (DLC) coatings for sheet metal forming tools [8]. Improper lubrication policies may have a negative impact on the environment. The reason is the use of unhealthy degreasing agents to wash the formed parts. The test results show that in lubricated conditions, the friction coefficient was not significantly influenced by different coatings. The DLC coatings exhibited low friction values in dry conditions only.

Lee et al. (2002) proposed a new model of friction caused by lubrication and surface roughness in sheet metal forming [9]. The experimental results were obtained on a manufactured friction tester. The objective was to find the effect of the lubricant’s material properties and viscosity on the frictional characteristics of both coated and uncoated metals. The friction coefficient was inversely proportional to lubricant viscosity. The FEM analysis with the authors’ model more accurately approximated the experimental results than the FEM analysis using the conventional friction model.

Kirkhorn et al. (2013) studied the influence of tool steel microstructure on friction in sheet metal forming [10]. They used several tooling materials with high-strength uncoated sheet material as a reference sheet material. The authors constructed a tribo-tester, based on flat-die strip drawing, characterized by full control of the applied normal force and the drawing velocity. The tested tools had extremely diverse microstructures. The variation in carbide content could not be directly correlated to variation in the friction coefficient.

Aleksandrović et al. (2011) presented experimental results on the investigation of a specific tribological system’s influence on the non-monotonous two-phase deep drawing process of low-carbon electro-galvanized steel sheets [11]. The first phase involved uniaxial tension in the strips until the elongation reached 10% of producing the blank. This was followed by the deep drawing. The drawing force and distribution of the main strains in the sheet plane were monitored. The authors stated that it was possible to use the concrete non-monotonousness method of forming to improve the process results.

Novotny et al. (2022) analyzed a new (composite) coating for deep drawing tools [13]. It consisted of micro-layers of TiAlN and TiAlCN, applied using high-power impulse magnetron sputtering (HIPIMS) coating technology. The drawing tool for the production of cartridges was made of STN 14109 steel. The objective was to relate the thickness of the layers and their connectivity with the underlying substrate. The authors found that this micro-coating, at a thickness of 5.8 μm, increased the repeatability of production strokes by 200%. This was confirmed by testing in real operation by a large manufacturing company.

Radwanski et al. (2021) analyzed the impact of the stretch leveling process of DC03 and DC04 steel sheets on their quality [14], meaning the waviness and state of internal stresses of the sheets. The achieved reduction values in sheet waviness were 88% and 96% in the cases of the DC03 and DC04 thin sheets, respectively. The residual stresses, after straightening, did not exceed 40 MPa. Thus, stretch leveling with a controlled elongation value resulted in a favorable and stable stress state in the sheets.

Szewczyk et al. (2022) considered the frictional characteristics of deep drawing quality steel sheets in the flat die strip drawing test of 0.8 mm thick DC04 steel sheets [15]. They conducted friction tests under different pressure and lubrication conditions. In the dry friction conditions, the average and the root mean square roughness decreased (in the normal pressure range of 3–6 MPa). Then, they increased due to ploughing mechanism intensification. The use of engine oil decreased the COF values only by 3.84 to 8.87%. The use of 80W-90 gear oil caused decreases in these values by 11.24 to 15.7%.

Dixit (2020) conducted a review of the metal forming modeling methods of various metal forming processes [16]. He emphasized that modeling micro- and nano-forming is quite different from modeling conventional metal forming processes. The scale effect comes into play, while the physical phenomena, which are insignificant at the macro-scale, could become significant at the micro- and nano-scales. Dixit concluded that fairly accurate models are available for predicting the forming load. However, that is not the case for residual stresses and surface integrity, so “the multiscale modeling of the metal forming process may be a viable panacea in future”.

The objective of Gill et al. (2016) was to show the influence of defining the pressure-dependent friction coefficient on numerical spring-back predictions of three steels [17]. The pressure-dependent friction models of each material were compared to the experimental results of a strip drawing test and used in the numerical simulation of an industrial automotive part drawing process. The results show important differences between defining a pressure-dependent or a constant friction coefficient.

Drossel et al. (2019) constructed a novel mechatronic system for measuring and controlling the normal force distribution in deep drawing based on the force measuring platform between the upper die and the press ram [18]. The systematic adjustment and measurement of the resulting force location present the new possibility of controlling the drawing process, as well as ensuring process reliability and drawn part quality.

Tiwari et al. (2022) conducted a review of studies on factors affecting the deep drawing process, including friction, blank holder force, lubrication, process temperature and the drawn part’s shape [19]. They stated that by optimizing the said factors’ influence on the process, one can predict the process’ results, i.e., obtain the required product without compromising its quality.

Ikumapayi et al. (2022) performed “a concise overview of deep drawing”, covering the process applications, merits and demerits of the deep drawing process [20]. The authors stated that there is a scarcity of information on the metallurgical features of warm deep drawing.

Hetz et al. (2020) considered so-called “spring-back” behavior in cross-profile deep drawing [21]. Such a behavior is a consequence of residual stresses that appear in semi-finished product. The authors proposed a novel approach to investigate the spring-back behavior of AA7020-T6 and AA7075-T6 via the spring-back angle. They also advised that it is important to study spring-back behavior at elevated temperatures.

Ma et al. (2015) examined the effect of the friction coefficient on the deep drawing of aluminum alloy AA6111 under three conditions of elevated temperature using finite element analysis and experimental investigation [22]. Their results indicate that the friction coefficient and lubrication position significantly influence the minimum thickness of the drawn piece, as well as its thickness deviation and the failure mode. They concluded that when the friction coefficient is 0.15, the formability is acceptable.

Dwivedi and Agnihotri (2017) conducted a study of deep drawing process parameters with the objective of optimizing the deep drawing process [23]. The considered parameters included blank holding force, friction and blank holder pressure. The authors concluded that for a successful deep drawing manufacturing process, a deep knowledge of all the parameters affecting the process “is a must”.

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