ZESZYTY NAUKOWE POLITECHNIKI RZESZOWSKIEJ – MECHANIKA
SCIENTIFIC LETTERS OF RZESZOW UNIVERSITY OF TECHNOLOGY – MECHANICS
94 (2022), s. 51-61

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ANALYSIS OF THE FRICTION MECHANISMS OF DC04 STEEL SHEETS IN THE FLAT STRIP DRAWING TEST

Abstract: This article presents the use of a specially designed flat strip drawing tester in order to assess the change in surface topography of DC04 steel sheets. The flat strip drawing test simulates friction conditions in the sheet metal-blankholder interface during deep drawing processes. Experimental tests were carried out at various nominal pressures and in dry friction and lubricated conditions. Two widely available gear and engine oils were used in the study. It was found that, in the range of pressures investigated between 3 and 12 MPa, 80W-90 gear oil provided a greater reduction in the value of the coefficient of friction (COF) than 5W-30 engine oil. Gear oil reduced the COF by an average of about 13.4 [%]. The lubrication efficiency depends on the pressure values; the greater the pressure, the lower the lubrication efficiency. A lowering of the value of the main amplitude surface roughness parameters Sa and Sq was generally observed. SEM analysis showed that even under lubrication conditions there was intense flattening of the roughness asperities of the sheet metal.

Keywords: coefficient of friction, friction, sheet metal forming, surface topography

1. Introduction

In the deep drawing process, several areas can be distinguished in terms of the stress state, deformation state, sliding speed and friction conditions: the flange of the drawpiece, the area of the edge of the punch and die, the wall and bottom of the drawpiece. Different friction conditions prevail in these zones due to

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different sliding velocities and values of normal pressures. The unfavourable effects of friction include, for example, non-uniformity of the drawpiece deformation, increased pressure exerted by the punch and deterioration of the surface finish of the drawpiece (Recklin et al., 2018; Vyboch et al., 2011). Only the friction of the sheet against the surface of the punch is a positive phenomenon because it increases the maximum forming force. The unfavourable phenomenon of friction can be counteracted by, among others factors, using appropriate lubricants, texturing the surface of the tools and applying self-lubricating coatings to the surface of the tools (Antoszewski et al., 2008; Kirkhorn et al., 2012; Sniekers & Smits, 1997). Correct selection of the lubricant is essential to obtain a product with the appropriate surface finish. The lubricant directly influencing the value of the coefficient of friction is a key parameter that determines the maintenance of the lubricating film at elevated temperature, which may occur in the contact zone.

The flange surface under the blankholder is one of the largest areas of friction in the deep drawing process. Too much friction in the flange area can cause the drawpiece to crack prematurely. So, knowing the friction conditions that prevail in this zone is crucial to assuring the appropriate friction conditions. The strip drawing test is used to experimentally determine the value of the coefficient of friction existing in the flange of the drawpiece. This test involves pulling a sheet metal strip between two countersamples, most often of cylindrical (Roizard et al., 2009) or flat (Solfronk et al., 2018) shape. The parameters influencing the change of friction conditions are the countersample clamping force, lubrication conditions, sliding speed and surface roughness of the countersamples.

Over the years, the strip drawing test has been investigated by various researchers. Costa and Emmens (1997) investigated the effect of different contact areas on the friction coefficient, using a vertical strip drawing test. The found that tool length and the contact area has a high influence on friction. Hutchins (2009) studied the effects of die surface patterning on lubrication in strip drawing test. Dies composed of circular pockets and parallel grooves. When the grooves were oriented parallel to the drawing direction, the friction was much greater. On the other hand the grooves oriented perpendicular to the drawing direction greatly reduced the friction. Vollertsen & Hu (2006) studied the tribological size effect in sheet metal forming (SMF) of Al99.5 aluminium sheets using a strip drawing test. They concluded that with miniaturisation of process dimension the tribology within SMF will be greater. Severo et al. (2009) analysed experimentally the tribological behaviour of W–Ti–N coatings in semi-industrial strip-drawing test. The performance of the tester developed has been confirmed. With uncoated tools adhesion always occurred independently of the testing load. In lubricated conditions, the coefficient of friction was always lower with coated tools. Wang et al. (2013) investigated tribological behaviour of diamond-like carbon (DLC) film deposited on female die in strip drawing test. It was found that surface topography of specimen and the sample dimensions have a little effect on tribological behaviors of DLC film than castor oil. Evin et al. (2021) analysed the friction coefficient in different regions of the die during sheet metal forming in strip drawing test and cup test. DC05 steel sheets for the automotive industry were tested under various friction conditions. It was found that, with increased contact pressure on the contact surfaces, the effectiveness of Anticorit 3802-39 S lubricant with high-pressure EP additives improves. Tevares et al. (2021) analysed the friction mechanisms of thin hard PVD coated forming tools in strip drawing test. The experiments revealed that the VN and CrN/TiN coatings presented low and stable friction coefficient values. This has been attributed to the formation of relatively smooth and partially oxidized transfer layers on the tool. Filali et al. (2022) numerically predicted the galling of 6082 aluminium alloys in cold strip drawing test, with and without lubricant. The developed numerical model was able to predict the onset of galling. Schell et al. (2022) Investigation of oil-, wax-, polymer- and solid lubricants for aluminium warm and hot forming based on a strip drawing test. It was found that mixing different lubricants can greatly improve overall lubrication performance.

In this paper the flat strip drawing test was used to evaluate the coefficient of friction of DC04 steel sheets, commonly used in the automotive industry. Experiments were carried out at various nominal pressures and lubrication conditions. The main friction mechanisms were revealed based on scanning electron microscope micrographs and analysis of the surface topography.

2. Material and methods

2.1. Test material

Deep drawing quality DC04 steel sheet, commonly used in the automotive industry was used as a test material. The mechanical properties of the test material were determined at ambient temperature using a Zwick/Roell Z100 uniaxial tensile testing machine. Three specimens were tested and the average values of the basic mechanical parameters were determined (Table 1).

Table 1. Basic mechanical parameters of the DC04 steel sheet.

Yield stress, [MPa]	**Ultimate tensile stress, [MPa]**	**Elongation , [%]**	**Percentage reduction of area, [%]**	**Hardness HV5**
165.2	309.3	37.1	45.7	97

The basic height parameters of the geometric structure of the surface were determined using a Hommel-Etamic T8000RC stationary profilometer. The values of basic surface roughness parameters are as follows: arithmetical mean height Sa = 1.55 [µm], root mean square deviation Sq = 1.26 [µm], kurtosis Sku = 2.68, skewness Ssk = -0.0307, maximum profile peak height Sp = 8.02 [µm], maximum height Sz = 15.0 [µm] and maximum profile valley depth Sv = 6.93 [µm]. The topography of the sheet metal and the flat countersamples are shown in Fig. 1a and Fig. 1b, respectively.

a) b)

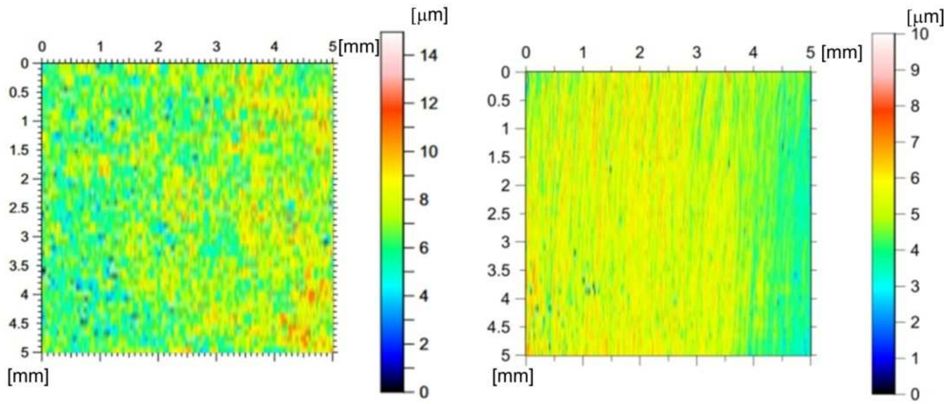

Fig. 1. Topography of the a) sheet surface and b) countersamples.

2.2. Procedure of friction testing

A tester which was specially designed to perform the strip drawing test is shown in Fig. 2. The strip drawing test consists in pulling a sheet metal strip between two countersamples made of 145Cr6 cold-work tool steel with a flat working surface. The device has the advantage that it is a simple structure with uncomplicated measurement of the force parameters during the test. The device was mounted in the lower grip of the Zwick/Roell Z100 testing machine. The upper end of the sample in the form of a sheet metal strip with dimensions of 130 (length) x 20 (width) [mm] was attached in the upper grip of a testing machine. The pulling force was recorded using the measuring system of the testing machine. The contact pressure was recorded by means of the Labview program on the basis of the indications of a Kistler type 9345B force sensor. Values of both friction and normal forces were correlated in the LabVIEW program based on a Megatron Series SPR18 potentiometric linear transducer. On the basis of the values of the pulling force (F_P) and clamping force (F_N), the value of the coefficient of friction was determined in accordance with the relationship:

$$\mu = \frac{F_P}{2F_N} \tag{1}$$

The sliding speed of the specimen was 2 [mm/s]. The friction tests were carried out for four nominal pressures of 3, 6, 9, 12 [MPa] and in conditions of dry friction (in the as-received sheet-metal state) and the sheet surface lubricated with oil. Typical synthetic oils were used, which are generally available and relatively cheap compared to professional deep-drawing greases: Castrol Axle EPX SAE80W-90 gear oil and Castrol Edge SAE5W-30 engine oil with a kinematic viscosity of 134 [mm^2/s] and 70 [mm^2/s], respectively.

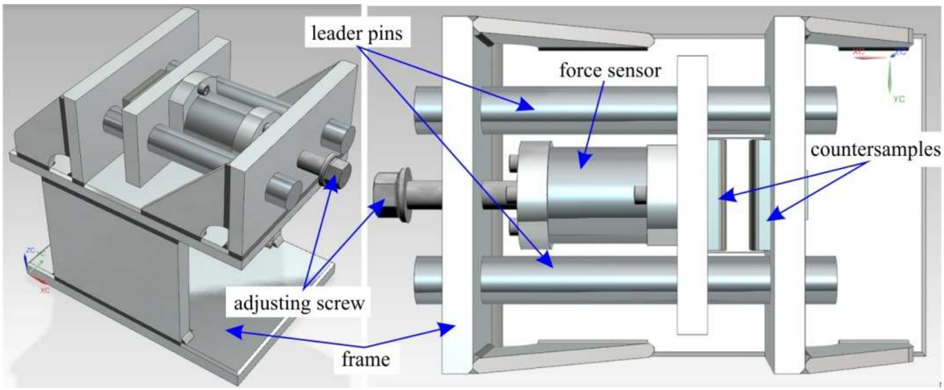

Fig. 2. Model of the friction tester

3. Results and discussion

The value of the COF for all friction conditions investigated decreases with increasing nominal pressure. This is related to the flattening of the roughness asperities and a reduction in the role of the mechanism of interlocking of the asperities in the total resistance to friction. This is a well-known phenomenon that has also been observed by Kirkhorn et al. (2012), Severo et al. (2009), Recklin et al. (2018), Vollertsen & Hu (2006). In the pressure range studied, the coefficient of friction is reduced by 11.5 [%], 15.4 [%], 6.8 [%] for dry friction, lubrication with engine oil and gear oil, respectively. The introduction of a lubricant between the rubbing surfaces changes the external friction into internal friction in this substance. Lubrication with engine oil reduced the coefficient of friction by an average of about 6.1 [%]. in relation to dry friction. The gear oil showed greater lubrication efficiency in reducing the coefficient of friction by an average of about 13.4 [%]. This oil was almost twice as viscous as engine oil.

Low-viscosity oils flow better, so that less energy is lost to overcome internal friction, surface activity and viscosity and this determines the maintenance of the lubricant on the surface under high unit pressures. Liquid lubricants separate the surfaces of the drawpiece and the tool to a to a greater or lesser extent. Due to high unit pressures, it is not always possible to maintain a continuous layer of lubricant, which results in the activation of the adhesion mechanism. The behaviour of the coefficient of friction in the case of lubrication is illustrated by the so-called Stribeck curve [8].

For the highest value of nominal pressure, the difference in the value of the coefficient of friction for both oils is blurred. The difference in the value of the coefficient of friction determined in the lubrication conditions for the pressure of 12 [MPa] was only 2.6 [%].

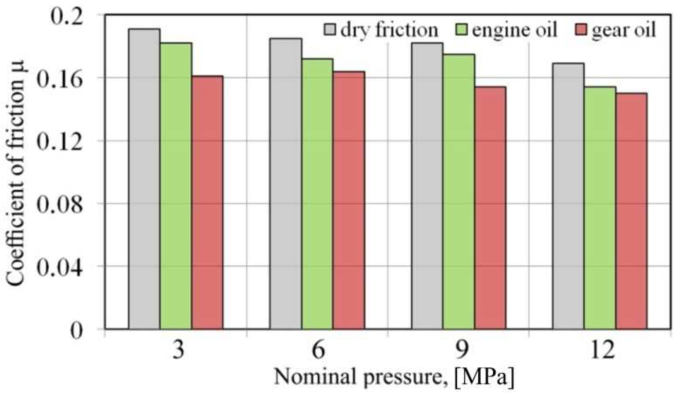

Fig. 3. Effect of nominal pressure on the value of coefficient of friction

Under dry friction conditions, a tendency was observed to decrease the values of the maximum height Sz, maximum profile valley depth Sv and maximum profile peak height Sp (Fig. 4a). The value of the main amplitude parameters (Sa and Sq) determined for the entire surface measured decreases only slightly with increasing nominal pressure. Different behaviour of the friction surface was observed under lubricated conditions (Figs. 4b and 4c). The value of the parameters Sz, Sv and Sp increased only to a certain pressure value of 3-6 [MPa], and then there is a downward trend. In the range of low pressures, the pressure of the lubricant is insufficient to create a “lubricant cushion” completely separating the rubbing surfaces. Thus, there is a significant role of the mechanism of mechanical cooperation of asperities and their flattening. In this way, the values of the parameters Sv and Sz only decrease from a certain pressure value (9 MPa in Figs. 4b and 4c).

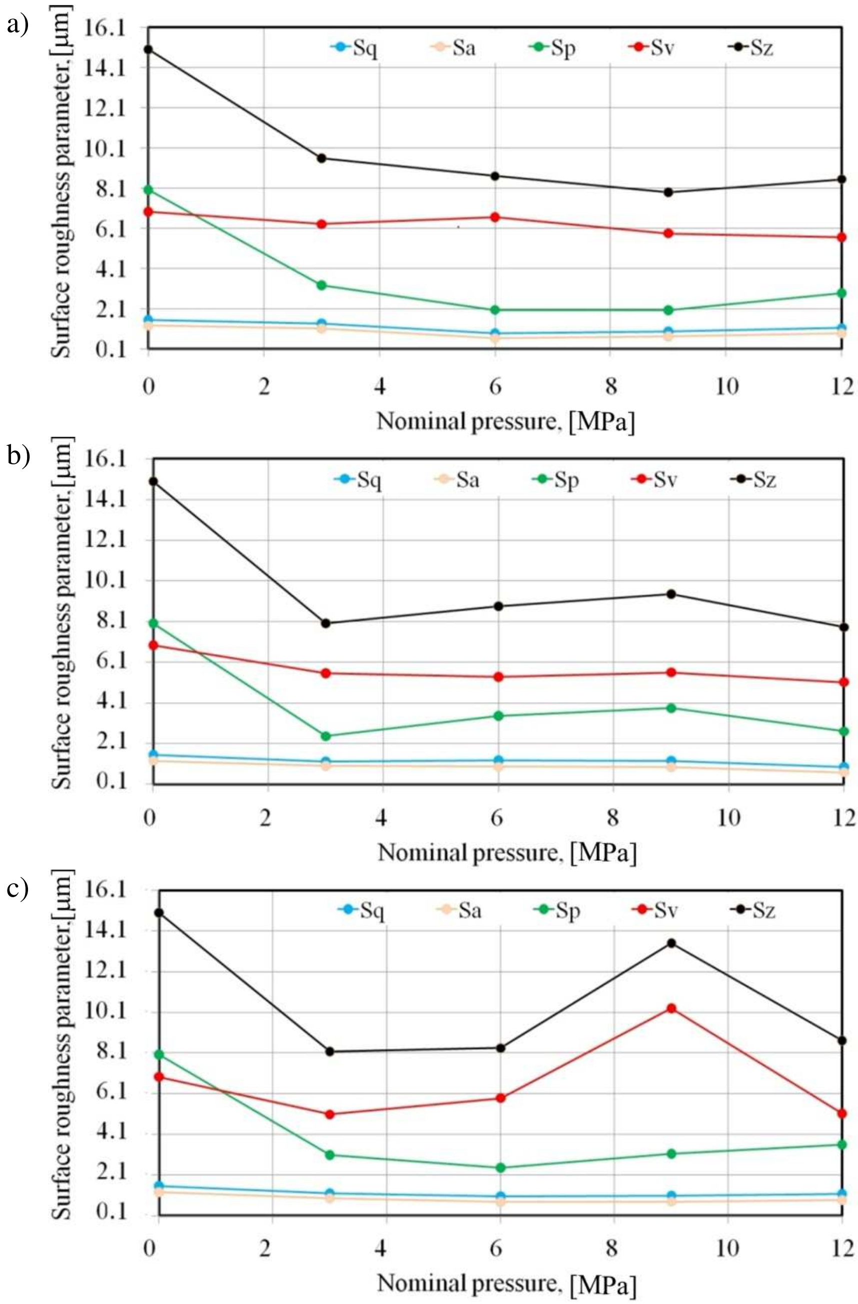

Fig. 4. Influence of nominal pressure on the surface roughness parameters after a) dry friction and lubrication of sheet metal surfaces with b) engine oil and c) gear oil

Due to the large contact area in the flat strip drawing test, the test surface of the sheet is subject to an intensive flattening process, which is visible for all friction conditions investigated (Figs. 5a-5c). It should also be noted that the sheet material is characterised by a much lower yield stress value than the tool material. This distinguishes the friction conditions in metal forming processes from the friction occurring in kinematic pairs, i.e., bearings.

a) b) c)

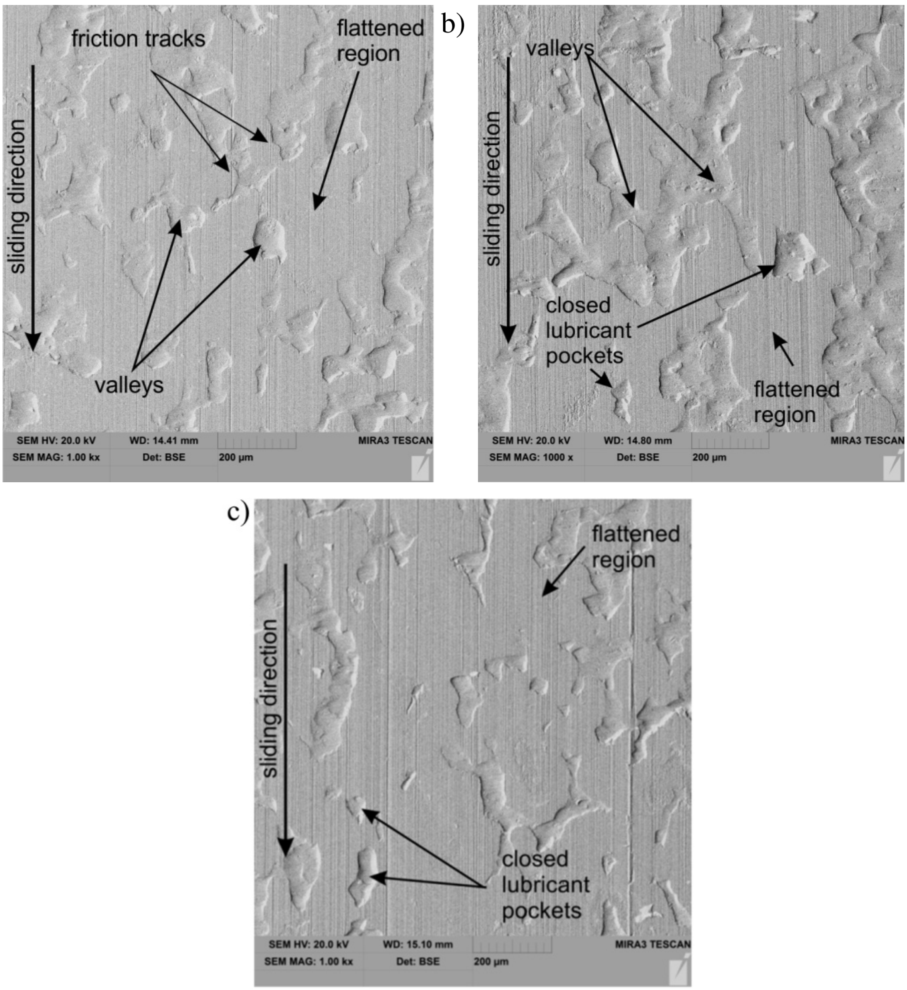

Fig. 5. SEM micrographs of sheet metal surfaces tested under a load of 9 [MPa] in conditions of: a) dry friction, b) lubrication with machine oil and c) lubrication with gear oil

The valleys in the as-received sheet-metal state do not, however, undergo a complete flattening process. However, most of the valleys are connected to each other, which makes it difficult for a "lubricant cushion", consisting of the formation of hydrostatic pressure of the lubricant in closed lubricant pockets (Figs. 5b, 5c), to occur. The lack of deep grooves on the surface of the sheet indicates that the sheet material does not stick to the surface of the tool. Under unfavourable conditions, hard forms build up on the surface of the tools, associated with the phenomenon of adhesive sticking, which forms ridges on the surface of the sheet. The surface of the sheet is subjected to the work hardening phenomenon in places where surface asperities are flattened, which is related to the increase of yield stress of material caused by plastic deformation.

4. Conclusions

In this article, the specially designed flat strip drawing tester was used to investigate friction mechanisms and the change in surface topography of DC04 steel sheets. The values of the COFs of the test material were evaluated in dry friction conditions and with the presence of two commonly available synthetic oils. The experimental tests revealed that, in the range of pressures investigated between 3 and 12 [MPa], 80W-90 gear oil provided a greater reduction in the value of the COF than 5W-30 engine oil. In general, a trend to a decrease of COF with nominal pressure was observed. Lubrication efficiency decreased with increasing pressure. For the highest pressure value (12 [MPa]), the difference in the efficiency of reduction of the COF by both lubricants was equal to about 2.6 [%]. SEM analysis has shown that the friction process causes intensive flattening of the surface asperities, even under lubrication conditions. This can be explained by the cooperation of relatively hard countersamples with the sheet material, characterised by a lower yield stress. Under these conditions, the volumes of the valleys are reduced and, consequently, the lubricant is not able to build up sufficient lubricant pressure.

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ANALIZA MECHANIZMÓW TARCIA BLACH STALOWYCH DC04 ZA POMOCĄ TESTU PRZECIĄGANIA PASA BLACHY

S t r e s z c z e n i e

W artykule przedstawiono wyniki oceny zmian topografii powierzchni blach stalowych DC04 za pomocą specjalnie zaprojektowanego testera do realizacji testu przeciągania pasa blachy. Test ten symuluje warunki tarcia na styku blachy z dociskaczem w procesach głębokiego wytłaczania. Badania eksperymentalne przeprowadzono przy różnych naciskach nominalnych oraz w warunkach tarcia suchego i smarowania. Do badań wykorzystano dwa powszechnie dostępne oleje przekładniowe i silnikowe. W zakresie analizowanych nacisków 3-12 [MPa], olej przekładniowy SAE80W-90 zapewnił większe obniżenie wartości współczynnika tarcia w porównaniu do oleju silnikowego SAE5W-30. Olej przekładniowy zredukował wartość współczynnika tarcia średnio o około 13.4 [%]. Efektywność smarowania zależy od wartości nacisków. Im większy nacisk tym efektywność smarowania była mniejsza. Zauważono zmniejszenie wartości głównych parametrów amplitudowych chropowatości powierzchni Sa oraz Sq. Na podstawie mikrofotografii SEM zaobserwowano, że nawet w warunkach smarowania dochodziło do intensywnego wyrównywania wierzchołków nierówności blachy.

Słowa kluczowe: współczynik tarcia, tarcie, kształtowanie blach, topografia powierzchni

DOI: 10.7862/rm.2022.4

Submitted//Tekst złożono w redakcji: July 2022
Accepted/Przyjęto do druku: October 2022
Published//Tekst opublikowano: December 2022