Effect of Friction in the Punch-to-Specimen Contact Zone upon the Punching Behaviour of Synthetic Leathers

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Abstract

Upholstery materials during their performance experience biaxial deformations, which are effected by friction in the contact zones: material-to-human skin, material-to-material, and material-to-inner parts of the furniture. The aim of this research was to define the effect of friction in the punch-to-specimen contact zone upon the tearing character and strength of non-perforated and perforated synthetic leathers under biaxial punching. Tests were performed with three different punches. The variation of friction coefficients in the punch-to-leather contact zone was achieved by the application of four different lubricants. Leather samples were investigated on the face (vinyl) and reverse (textile) sides. The results of the investigations confirmed that the maximal punching force $P_{max}$ increases with an increase in the punch size. The same tendency is valid in cases where different levels of friction act in the punch-to-specimen contact zone or whether the specimens were punched from both sides. Dependencies exist between area $S$ of the punch-to-specimen contact zone during tearing and the average static $\mu_{s}$ and dynamic $\mu_{d}$ friction coefficients.

Key words: non-perforated leather, perforated synthetic leather, biaxial punching, friction, lubricants.

Introduction

The variety of materials used in upholstery production is extremely large. Among them are different leathers, which are applied in cars, boats and aircraft seats, etc. Many scientists have studied the physical, mechanical and thermal properties of natural [1-3] and artificial leathers [3-5]. Perforated leather has small equally spaced holes, which is advantageous for use in heated leather seats [6, 7]. Perforated leather is usually thinner than ordinary leathers, therefore it is softer and more comfortable. Perforated leathers also have good absorption, but are still out-performed by most cloth seat fabrics [8].

Upholstery materials during their performance experience biaxial deformations, which are effected by friction in the contact zones: material-to-human skin [9-12], material-to-material [13, 14], and material-to-inner parts of the furniture: polyurethane [15] or metal [14]. The majority of such investigations are related to the clothing industry with the aim to increase comfort in contact with human skin, e.g. in medicine – for injured or disabled patients who are chained to a wheelchair [9, 11, 12], and in sports – for athletes to reduce friction between clothing and weather conditions, e.g. snow [16].

New technologies are applied [17] in innovative textile material surface treatment, such as HeiQ’s Glider, which helps the wearer feel more comfortable during summer sport [18]. A realistic skin model in combination with an objective friction test method allows to develop new textiles for sport and medical applications with an improved skin adapted surface and frictional properties [10]. Different lubricants are also applied in friction studies [19, 20]. S. N. Jawale et al. applied lubricant to affect both yarn-to-metal and yarn-to-yarn friction [19]. Ujevic, D. et al. analysed the uniaxial strength, bursting strength and density of two artificial leathers designed for car seats: artificial leathers with woven and knitted fabrics on the reverse side [5].

It must be noted that a big part of textile materials during their exploitation are affected by forces perpendicular to their surfaces. As a result, the shell, i.e. spatial surface, with a biaxial state of deformation is formed. Up to now, two biaxial deformation test methods are well known and widely used for such investigations: the membrane and punch methods [21]. The deformational behaviour of textile materials during punching is investigated using a big variety of punches which can be different in shape and size. J. E. Rocher et al. presented the results of bias tension, bending and friction tests performed in order to characterise the formability of two 3D fabrics punched with a double-curved punch with a triple point (tetrahedral punch) [22]. B. Vanleeuw et al. used a double-dome shaped punch to measure full field displacements [23]. F. F. Wu et al. investigated the size dependant plastic deformation of metallic glass under biaxial loading using the small punch (SP) test [24]. X. Zhang et al. analysed the deformation and failure characteristics of four types (PE, three-layer, ceramic-coated, non-woven) of lithium-ion battery separators. Biaxial punching was performed with four punches of different size which were made of Teflon to reduce friction [25].

The main aim of this research was to define the effect of friction in the punch-to-material contact zone upon the tearing character and strength of non-perforated and perforated synthetic leathers under biaxial punching. Tests were performed with three punches different in size. The variation of friction coefficients in the punch-to-leather contact zone was achieved by the application of four different lubricants. Leather samples were investigated from both sides – the vinyl face and the back textile.

Materials and methods

For the investigations, two types of commercial synthetic leathers were selected: non-perforated L1 and perforated L2. They were vinyl coated on the face side and had a plain jersey background, the composition of which was cotton and polyester. Such man-made vinyl leathers are treated and dyed to resemble real leather and are used in upholstery, clothing, fabrics and for other uses where a leather-like finish is required. Both of the vinyl leathers investigated, L1 and...
L2, are commonly used for car interior installations – seats, front and lateral panels, etc. Perforated leather is often paired with other fabrics for adjustable temperature controlled car seats. The perforation diameter of L2 leather is 1.32 mm, density – 4 holes in cm², and the distance between the holes in the longitudinal and transverse directions – 7.25 mm (Figure 1). The characteristics of synthetic leathers L1 and L2 are presented in Table 1.

Biaxial punching was performed with a special test unit attached to a standard tensile testing machine – Tinius Olsen (load cell – 500 N) (Figure 2). The tensile velocity of the upper clamp was 100 mm/min. For the investigations, ten specimens (180 x 180 mm) were cut from each sample of synthetic leather. The radius of the clamped specimens was R = 60 mm. Punching was performed from both sides of the specimens using punches of three different sizes: r₁ = 9.0 mm (r₁/R = 0.15), r₂ = 23.5 mm (r₂/R = 0.39) and r₃ = 31.0 mm (r₃/R = 0.52). Typical punching curves P/H until complete cracking were registered during the experiment. The variation coefficient of biaxial punching reached 6.73% when punched with the smallest punch r₁, and did not exceed 5% when punched with the others, r₂ and r₃. The variation coefficient was 4.17% and 3.08%, respectively.

Friction testing was performed in accordance with the requirements of Standard DIN EN ISO 8295 [26]. Static Fₛ and dynamic Fₜ friction forces as well as static μₛ and dynamic μₜ friction coefficients were defined. The variation coefficient of the results obtained did not exceed 5%. For investigation of the friction phenomenon, four different types of lubricants were applied: A – pure water, B – commercial cleaner Arexons, which is developed for car seats and upholstery cleaning, polishing and protection, and is enriched with glycerine and natural waxes, C – industrial silicone, D – commercial leather cleaner and Turtle Wax conditioner, the ingredients of which are water, silicone, emulsifiers and additives.

All four types of lubricants were used not only to determine friction parameters but also to define and analyse the effect of friction between the punch and specimen upon the deformation behaviour of the synthetic leathers chosen. In all cases, lubricant was spread over metal surfaces with the help of a rubber brush. After each test, the surfaces were cleaned and an appropriate lubricant was re-applied.

The area S of the punch-to-specimen contact zone during tearing was defined according to the scheme presented in Figure 1 and was calculated according to the equation S = pb², where: S – area of tearing zone, mm²; b – radius of tearing zone, mm.

### Results and discussion

During the investigations, punching was performed from both sides of the specimens taking into consideration the fact that products from synthetic leather, e.g. soft furniture, car seats, etc. experience external normal loading from both sides during production and, especially, during their performance and utilisation. Figure 3 presents typical punching curves P/H (punching force/punching height) of synthetic leathers L1 and L2 when punched from both sides with r₁, r₂ and r₃ punches without the application of any lubricant. It was obtained that the maximal punching force Pₘₐₓ depends upon the punch radius r₁, r₂, r₃ (Figure 5).
These results confirm the tendencies obtained by other researches [25], the investigations of which were performed with PE, three-layer, ceramic-coated and non-woven materials. Also they confirm the same relationships obtained for knitted materials [21], which showed that punching strength characteristics were dependent upon the size of the punch, i.e. the punching force \( P_{\text{max}} \) increased and the punching height \( H_{\text{max}} \) decreased with an increase in ratio \( r/R \). In [21], the decision was made to apply the universal ratio \( r/R \) for comparative analysis of the effect of the punch-to-material’s contact area. From this standpoint all three investigations (including the current research) confirm the same tendency of relationship obtained for knitted and non-woven materials. Also they confirm the tendencies obtained by other researches [25], the investigations of which were performed with similar tendencies existed for punching strengths \( P_{\text{max}} \) of non-perforated L1 and perforated L2 leathers.

In order to analyse the effect of friction in the contact zone of punch-to-leather upon the punching strength characteristics, four different lubricants A, B, C and D were applied. Punching results after their application are presented in Figures 7 and 8, confirming the same linear dependencies between the maximal punching strength \( P_{\text{max}} \) and radius \( r/R \). For lubricant A – \( R^2 = 0.996-1.000 \), for lubricant B – \( R^2 = 0.981-1.000 \), for lubricant C – \( R^2 = 0.977-0.999 \), and for lubricant D – \( R^2 = 0.979-1.000 \). For all four types of lubricants non-perforated leather L1 was nearly twice stronger when compared to perforated leather L2, and \( P_{\text{max}} \) was higher when punched from the back textile side on average by 8.4% – 36.3% compared to the face vinyl side (Figure 6).

It must be noted that for all four lubricants A, B, C and D, similar tendencies existed in respect to the maximal punching height \( H_{\text{max}} \), unlike in the case where no lubricant was applied. Average values of maximal deformation \( H_{\text{max}} \) are higher for perforated leather L2 compared to L1 by 6.3% – 20.65%, increasing with an increase in the

Figure 3. Punching curves of synthetic leathers L1 and L2 when punched with \( r_1 \), \( r_2 \) and \( r_3 \) punches without the application of lubricants on the face vinyl side a) and back textile side b).

Figure 4. Dependencies of maximal punching forces \( P_{\text{max}} \) upon ratio \( r/R \) for knitted materials [21], ceramic coated materials [25] and non-perforated and perforated synthetic leathers (current research).

Figure 5. Effect of the punch size upon the maximal punching force \( P_{\text{max}} \) for synthetic leathers L1 and L2 when punched from the face (vinyl) side and reverse (textile) side without the application of lubricants.
punch size. Especially a linear dependency between $H_{\text{max}}$ and ratio $r/R$ ($R^2 = 0.883-0.935$ for L2) is evident when leather samples are punched from the back textile side and almost in all cases $H_{\text{max}}$ was higher by 4.6% on average, and 17.7% when punched from the reverse side than from the face side (Figure 7).

Comprehensive analysis of the effect of the lubricants applied in respect to the punching characteristics of samples without lubricants revealed that lubricant A (pure water) did not have any effect on the maximal punching force $P_{\text{max}}$ of non-perforated leather L1 when punched from the face side (Figures 8 and 9), varying within the limits of standard error, whilst it increased by 23% when punched from the reverse side, i.e. the textile background. The maximal punching force $P_{\text{max}}$ of perforated leather L2 after the application of lubricant A slightly increased: from the face side – by 6% on average, and from the reverse side – by 17% on average.

Lubricant B (cleaner Smash leather treatment – Arexons) had more evident effect compared to pure water. It must be noted that $P_{\text{max}}$ after the application of lubricant B on non-perforated leather L1’s face (vinyl) side decreased on average by 13%, but increases on average by 19% when the same lubricant was applied on the textile (back) side. Furthermore these tendencies of increasing and decreasing become more significant with an increase in the punch radius. In the case of perforated leather L2, $P_{\text{max}}$ increased on both the face (4%) and reverse (14%) sides (Figures 8 and 9). Pure silicone – lubricant C decreased the strength of non-perforated leather L1 by 6% when punched from the face side, but had almost no effect when punched from the reverse side. It also decreased the strength of perforated leather L2 by 11% when punched from the face side, and it is the only lubricant which decreased (by 10.8%) the strength of perforated leather L2 from the reverse side. The most significant effect can be observed with lubricant D (commercial leather cleaner and conditioner Turtle Wax Professional). The maximal punching force $P_{\text{max}}$ of non-perforated leather L1 when punched from the face side decreased by 20% and increased by 31% when punched from the textile (reverse) side. In the case of perforated L2 leather, it decreased by 3% and increased by 21%, respectively. Thus it is evident that lubricants A, B and D have a more significant effect upon $P_{\text{max}}$ when they are applied from the textile (reverse) side in respect to the case where no lubricant was applied, i.e. $P_{\text{max}}$ decreases when samples are punched from the vinyl side and increases when they are punched from the textile side. The punching behaviour of samples is different when pure silicone is applied – $P_{\text{max}}$ slightly decreased in all cases.

It can be seen that all four lubricants show a different effect upon the punching behaviour of investigated leathers L1 and L2 from the face vinyl side, as well as from the reverse textile side. Thus the effect of friction in the punch-to-specimen contact

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**Figure 6.** Maximal punching force $P_{\text{max}}$ of synthetic leathers L1 a) and L2 b) when punched from the face and reverse sides with punches $r$, $r$, and $r$, after the application of lubricants: A – pure water, B – commercial cleaner Arexons, C – industrial silicone, D – commercial leather cleaner and Turtle Wax Professional.

**Figure 7.** Maximal punching height $H_{\text{max}}$ of synthetic leathers L1 a) and L2 b) when punched from the face and reverse sides with the punches $r$, $r$, and $r$, after the application of lubricants: A – pure water, B – commercial cleaner Arexons, C – industrial silicone, D – commercial leather cleaner and Turtle Wax Professional.
zone was investigated during the next research stage. The results of static \( F_S \) and dynamic \( F_D \) friction forces, as well as static \( \mu_s \) and dynamic \( \mu_d \) friction coefficients are presented in Table 2. It can be seen that static friction parameters compared to dynamic are evidently higher on the face (vinyl) side. In certain case this difference reaches even 68.6%. However, on the reverse (textile) side the friction process is smoother, and this difference does not exist or varies in the limits of standard error.

The differences in friction parameters between leathers L1 and L2 were analysed from two standpoints: (1) in respect to longitudinal and transverse directions, and (2) in respect to the face and reverse sides. In all cases of lubricants applied, friction characteristics on the face side of non-perforated leather L1 were higher compared to perforated leather L2. Here the case without a lubricant can be exceptional, because the difference in the longitudinal direction was very significant, i.e. 44.7%-58.5% compared to the rest. Meanwhile the difference in the transverse direction became opposite as the friction parameters of perforated leather L2 became higher by 1.5%-6.3% on average. Friction characteristics from the reverse side maintain the same tendencies for all lubricants, although the difference between leathers L1 and L2 is a bit lower, except the cases where no lubricant or industrial silicone – lubricant C – was applied. Friction characteristics of leather L2’s reverse side, in contrast to the face side in the longitudinal direction, were higher by even 41.0% and 46.2%, respectively. The assumption can be made that the four lubricants applied – A, B, C and D, make the values of static \( \mu_s \) and dynamic \( \mu_d \) friction coefficients lower (from face side), e.g. by 27.6-53.85% in leather L1’s longitudinal direction and by 15.69-59.42% in leather L2’s transverse direction.

During punching, the part of the specimen which is in contact with the punch obtains its shape (Figure 2). The rest part of the specimen from the point where it loses contact with the punch up to the clamp obtains the shape of a concaved curve. Earlier investigations proved that the specimen tearing line is always located below the top of the shell formed, i.e. in the place where the specimen loses contact with the punch [21], and that it can extend along the whole perimeter (Figure 10.a) or be localised in one place (Figure 10.b). The results obtained during the testing performed with non-perforated and perforated synthetic leathers L1 & L2 did not contradict these findings (Figure 10). On one hand the position of the tearing line depends on whether the sample was punched from the face (vinyl) or reverse (textile) side. On the other hand, it depends on the size of the punch, i.e. the bigger the punch used, the further from the centre the tearing line was located and the bigger the area S (mm²) of the punch-to-leather’s contact zone during tearing. In most of the cases, the tearing line is perpendicular to the transverse direction of the specimens tested [21].
The areas $S$ of the punch-to-leather contact during tearing were defined according to the scheme presented in Figure 2. The results of the calculations are presented in Figure 11, from which it can be seen that bigger contact areas $S$ during tearing are characteristic for perforated leather L2 for all types of lubricants when punched from both the face and reverse sides. A comparison of the face and reverse sides show that bigger areas belong to the reverse (textile) side, especially evident in the case of perforated leather L2. The effect of lubricants A, B, C and D is more evident when they were applied from the face (vinyl) side (Figure 11.a). After their application, the areas $S$ of the punch-to-leather contact zones during the tearing of leathers L1 and L2 decrease by 25.9-61.2% in the case of lubricants A and B and by 24.1-96.5% in the case of lubricants C and D. The same tendency is not valid when the leather samples were punched from the reverse (textile) side as the area $S$ became bigger compared to that when no lubricant was applied (Figure 11.b).

The main aim of this research was to define the effect of friction in the punch-to-material contact zone upon the tearing character and strength of non-perforated and perforated synthetic leathers under biaxial punching. Thus it was defined that for both non-perforated and perforated leathers L1 & L2 there is no difference in the dependencies between areas $S$ and static $\mu_s$ and dynamic $\mu_D$ friction coefficients in the longitudinal and transverse directions (Table 3). Meanwhile a clear difference exists between coefficients $\mu_{sa}$ and $\mu_{DA}$. The determination coefficient $R^2$ of $\mu_{DA}$ dependency is higher and for non-perforated leather L1 varies in the limits of 0.65 ± 0.98, and for perforated leather L2 in the limits of 0.29 ± 0.87.

It must be noted that punching is a biaxial process during which friction acts simultaneously in both the longitudinal and transverse directions. Taking this into account together with the research results of other investigators [27, 28], the decision was made to use the average values of these coefficients in two main directions. The results of the dependencies (determination coefficients $R^2$) between the area $S$ of the punch-to-leather contact during tearing and average values of static $\mu_{sa}$ and dynamic $\mu_{DA}$ friction coefficients are presented in Table 4. These results confirm an obvious difference in the effect of static $\mu_{sa}$ and dynamic $\mu_{DA}$ friction coefficients. The determination coefficient $R^2$ of the $\mu_{DA}$ dependency is significantly higher (Figure 12). For non-perforated leather L1 it varies in the limits of 0.79 ± 0.98, and for perforated leather L2 – in the wider limits of 0.25 ± 0.94. It is important to mention that these dependencies are valid for individual punches $r_1$, $r_2$ and $r_3$. The same dependency for the research results of all three punches is weaker: determination coefficient $R^2$ does not reach 0.5.

Further investigations revealed that linear dependencies exist between the maximal punching force $P_{\text{max}}$ and punch-to-leather contact areas $S$ during tearing (Figure 13). In the case of non-perforated leather L1 for all three punch sizes and both the face and reverse sides, they are as follows: without lubricant $R^2 = 0.615$, for lubricant A – $R^2 = 0.869$, for lubricant B – $R^2 = 0.772$, for lubricant C – $R^2 = 0.737$ and for lubricant D – $R^2 = 0.753$. In the case of perforated leather L2 these dependencies are even stronger: without lubricant $R^2 = 0.919$, for lubricant A – $R^2 = 0.923$, for lubricant B – $R^2 = 0.891$.

![Figure 10. Examples of synthetic leather L1's tearing lines when punched from the face side with punches r1 a), r2 b) and r3 c).](image-url)
Table 4. Dependencies (determination coefficients $R^2$) between the area $S$, mm$^2$ of punch-to-leather contact during tearing and average values of static $\mu_{SA}$ and dynamic $\mu_{DA}$ friction coefficients.

| Material code | Punch radius | Longitudinal face side | Longitudinal reverse side | Transverse face side | Transverse reverse side |
|---------------|--------------|------------------------|--------------------------|----------------------|------------------------|
| L1            | $r_1$        | 0.25                   | 0.32                     | 0.25                 | 0.32                   |
|               | $r_2$        | 0.45                   | 0.56                     | 0.45                 | 0.56                   |
|               | $r_3$        | 0.45                   | 0.55                     | 0.45                 | 0.55                   |

Table 3. Dependencies (determination coefficients $R^2$) between the area $S$, mm$^2$ of punch-to-leather contact during tearing and the static $\mu_{S}$ and dynamic $\mu_{D}$ friction coefficients in the longitudinal and transverse directions.

| Material code | Punch size | Face side | Reverse side | Face side | Reverse side |
|---------------|------------|-----------|--------------|-----------|--------------|
| L1            | $r_1$      | 0.00      | 0.02         | 0.00      | 0.02         |
|               | $r_2$      | 0.03      | 0.05         | 0.03      | 0.05         |
|               | $r_3$      | 0.05      | 0.07         | 0.05      | 0.07         |

Figure 11. Areas $S$ of punch-to-leather contact zones during the tearing of non-perforated and perforated leathers L1 & L2 when punched with punches $r_1$, $r_2$ and $r_3$ without any lubricant (0) and with all lubricants (A-D) from the face a) and reverse b) sides.

Figure 12. Dependencies between the area $S$ of the punch-to-leather contact zone during tearing and the average a) static $\mu_{SA}$ and b) dynamic $\mu_{DA}$ friction coefficients of non-perforated and perforated synthetic leathers L1 & L2 when they were punched with punch $r_1$.

for lubricant C – $R^2 = 0.819$ and for lubricant D – $R^2 = 0.807$.

**Conclusion**

The results of the current investigations have confirmed the dependency between the maximal punching force $P_{max}$ and the radius $r$ of the punch for non-perforated and perforated synthetic leathers. $P_{max}$ increased on average 2.72 times for non-perforated leather L1 and on average 2.90 times for perforated leather L2 when the punch radius increased from $r_1 = 9.0$ mm ($r_1/R = 0.15$) to $r_3 = 31.0$ mm ($r_3/R = 0.52$). The same tendency is valid in cases where different levels of friction act in the punch-to-specimen contact zone or whether the specimens were punched from the face (vinyl) or reverse (textiles) side. Comparative analysis has shown that non-perforated leather is nearly twice stronger, but less deformable.
ble compared to perforated leather due to increased stress concentration around perforated holes. The surfaces of synthetic leathers on the face and on the reverse sides differ because it has a textile background coated with a vinyl layer. Thus punching characteristics from both sides are different not only taking into account the size of the punch but also in respect to the contact friction.

It was also obtained that for non-perforated and perforated synthetic leathers dependencies exist between the area $S$ of the punch-to-leather contact zone during tearing and the average static friction coefficients, i.e. the tearing area increases with an increase in friction. An especially strong relationship was obtained in the case of dynamic friction $\mu_{\text{dyn}}$. It must be noted that static friction parameters compared to dynamic are evidently higher from the face vinyl side. In certain cases this difference reaches even 68.6%. But from the reverse textile side the friction process is smoother, and this difference does not exist or varies in the limits of standard error.

![Figure 13. Dependencies between the area $S$ of the punch-to-leather contact zone during tearing and $P_{\text{max}}$ when no lubricant was applied from the face and reverse sides of non-perforated and perforated synthetic leathers L1 & L2.](image)

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