Experimental research of the thermoplastic belt plasticizing process in the hot plate welding

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Abstract. Most of the industrial machines use belt transmission for power transfer. These mechanisms often use the round belts with a few millimeters in diameter, which are made of thermoplastic elastomers, especially polyurethane. Their production process requires the bonding step, which is often performed via butt welding, using the hot plate. One of the most important parameters which describe this bonding phenomenon is plasticized distance. Identifying its value is necessary to predict the length reduction ratio of the belt during welding, and in consequence to evaluate the joint quality. To predict the quantity of plasticized material, which depends on a lot of process parameters, the physical model of plasticizing process should be designated. The experimental research of this phenomenon is helpful to estimate value of force which is necessary to perform plasticizing, and show the typical problems during this process. The paper presents the results of the round drive belts plasticizing attempts, for different diameters of the belt, which were performed using the strength test station and heating device. In conclusion of the paper, there is the correlation between plasticizing force, velocity and distance.

1. Introduction

Drive belts, both employed in conveyors and drive systems, are commonly used in machine building. Transportation technology utilizes drive belts with full cross section as well as perforated strands in vacuum transportation of light objects [1–3]. Whereas in the category of drive belts, the most commonly used are: flat belts, toothed belts and shaped belts (e.g. V-shaped or round). Toothed belts are employed both in simple transmission units as well as in non-classical solutions, e.g. with variable ratios [4–8]. Shaped belts, in particular the round and V-shaped, are commonly used in drive system technology and are most commonly made of rubber [9, 10] or elastomers based on polyester or polyurethane [11, 12]. Their common usage in industrial machinery calls for an efficient manufacturing process which is usually carried out in two stages [13]. First, a long belt strand is manufactured, subsequently it is cut down to desired length and finally its ends are permanently joined together [11, 12]. In most cases the joining process utilizes the hot plate butt welding method. The process is relatively inexpensive and utilizes simple technological solutions [14].

The butt welding of polymers is commonly practiced in the automotive industry and civil engineering, e.g. in the process of joining: tanks for utility fluids, lamp enclosures, engine instrumentation [14, 15] and pipes [16, 17]. Studies were performed for the hot welding of different polymer materials, including: acrylonitrile butadiene styrene copolymer (ABS) [18], poly(methyl methacrylate) (PMMA) [19], polycarbon (PC) [20], as well as polypropylene (PP) [21].

The authors began design works on a device for automated butt-welding of drive belts utilizing the hot plate method [12], which is to improve the manufacturing efficiency of endless belts. In order to
verify the construction design assumptions, it was began to examine the process together with the study to identify the influence of hot-welding parameters on the quality of joint [22, 23]. It was assumed that the item to hot weld will be a polyurethane TPU C85A belt, commonly offered by belt manufacturers [24]. A review of available literature determines that information on joining thermoplastic elastomers utilizing this method is not readily available.

The hot plate butt-welding process, in general terms, can be divided into 5 stages [22, 25, 26]. One of the most important activities in the course of the process is heating which leads to the plasticization of the belt end, facilitating the chemical reactions and physical interactions between the macromolecules of the material during the second stage of actual joining [27]. The plasticization of the belt is performed during the first and second stage of the heating process (figure 1): during the matching of belt surfaces (A) and actual heating (B) [25].

![Figure 1](image.png)

**Figure 1.** The diagram of the heating phase of the belt end using hot plate: A – belt end matching stage, B – actual heating phase, 1 – belt, 2 – grip, 3 – hot plate, 4 – flash; p – thickness of plasticized layer, h – length of the section heated above ambient temperature, \( F_m \) – force applied during matching of surface, \( v_m \) – velocity during surface matching, \( F_h \) – pressing force during heating, \( T_p \) – hot plate temperature, \( T_w \) – welding temperature, \( T_0 \) – ambient temperature.

During process analysis and modeling of the butt welding of belts, it is very important to identify and describe the physical phenomena occurring during the heating and plasticization of the belt. This includes, among others: the thickness of the plasticized material \( p \) at the set value of forces used in the technological process \( F_m \) and \( F_h \), as well as the hot plate temperature \( T_p \), assuming that the welding temperature \( T_w \) is achieved in the required volume of material.

Research about this process is difficult because welded material has non-classical properties. Similarly, like other such materials i.e.: crystallized carbon-dioxide [28–30], natural shredded materials [31–34] or other mechanical connections [35, 36], it is hard to predict their behavior under mechanical and thermal load. Considering this fact, the precise examinations are needed to recognize behavior of round drive belts during welding. Therefore, actions were undertaken in order to estimate the influence of the velocity of pressing the belt end to the hot plate on the forces employed in the process and changes in temperature for two different belt diameters.

### 2. Study methodology

The study of the plasticized belt end on the hot plate was performed, assuming constant motion velocity of the belt in relation to the heating device in the entire scope of plasticization time. Therefore, both heating stages were merged (A and B at figure 1) as a singular technological operation. The purpose of the above is to simplify the control algorithm. The simplification entails only controlling the
displacement of the belt end towards the hot plate, rather than the commonly employed control of the belt pressing force.

The examination was performed using MTS Insight 50 kN durometer (figure 2), with jaws (1) and grips of the author’s design (2) which presses the belt end (3) towards the heater plate (4) of the electrical hot welding device for Multi-TC drive belts by BEHABelt, with rated power 70 W, adjacent to a thermal insulation pad (5) made of ceramic material.

Figure 2. Testing station view during the examination: 1 – MTS durometer jaw, 2 – grip for sample designed by the author, 3 – sample, 4 – heater with hot plate, 5 – thermal insulation pad.

The construction design for the testing station, for both states of performed examination is provided at figure 3.

Figure 3. Construction design of the testing station for pressing the belt end to the hot plate: I – calibration stage, II – actual examination stage; 1 – belt sample, 2 – grip, 3 – hot plate, 4 – thermal insulation pad, 5 – thermal insulation spacer, \( v_i \) – initial calibration speed, \( v_t \) – testing speed.

At each time before the measurement, calibration (I) is performed (figure 3). At this stage, the belt sample (1) with height \( h \) (with loose end moved out of the grip at the distance \( h_1 \)) and diameter \( d \), fastened in the grip (2), is moved at constant velocity \( v_i \) towards the thermal insulation spacer (5) with constant thickness \( t = 0.5 \text{ mm} \), until physical contact is achieved (detected by the force measurement system of the durometer). The spacer adheres to the hot plate (3), on the ceramic pad (4). Next, the traverse motion is stopped, and the spacer is removed. Afterwards, the actual examination (II) begins, during which the belt is pressed to the hot plate with working velocity \( v_t \) and measurement is taken for the following parameters: durometer traverse displacement \( s \), pressing force \( F_h \) as well as the temperature value of the hot plate \( T_p \). 50 tests were carried out for: 5 pressing velocities of the belt towards the plate \( v_t \) and two sample diameters \( d \). The plasticization was carried out to the degree significantly exceeding the actual deformation during welding – up to 50 % of the total length of the loose end \( h_1 \). The parameters for the performed tests are provided in table 1.
Table 1. Assumed testing parameters.

| Parameter                              | Designation | Value                  |
|----------------------------------------|-------------|------------------------|
| Belt diameter                          | $d$ (mm)    | 12 and 18              |
| Velocity during testing                | $v_t$ (mm min$^{-1}$) | 2, 4, 8, 12 and 16  |
| Velocity during calibration            | $v_i$ (mm min$^{-1}$) | 2                   |
| Hot plate temperature                  | $T_p$ (°C) | 300±1                  |
| Sample height                          | $h$ (mm)    | 25±0.1                 |
| Sample length moved out of the grips   | $h_1$ (mm) | 10±0.1                 |
| Maximum sample displacement            | $s$ (mm)    | 5.5                    |

The introduction of the calibration stage allows to compensate for the inaccuracy in the measurement of sample height $h$. The use of thermal insulation spacer limits convection heating of the sample during calibration, before the actual examination begins.

3. Result analysis

The set of sample characteristics of force dependence during the pressing of the belt to hot plate $F_h$ and belt end displacement $s$ for the two pressing velocities are indicated in table 2. The belt with higher diameter $d$ requires plasticization force $F_h$ with higher value at constant pressing velocity $v_t$. Such a correlation is trivial, because the larger volume of material (the difference in diameter $d$), at the same material parameters requires a longer heating time at the same plasticization temperature $T_p$. At the same velocity $v_t$ the belt with larger diameter $d$ exhibits lower temperature at the cross-section and therefore a larger stiffness [22].

Table 2. Results of compression test for different velocities and diameters: $d$ – belt diameter, $v_t$ – pressing velocity to hot plate, $F_h$ – pressing force, $s$ – displacement.

|                |                |                |                |
|----------------|----------------|----------------|----------------|
| $d$ = 12 mm, $v_t$ = 4 mm min$^{-1}$ | $d$ = 18 mm, $v_t$ = 4 mm min$^{-1}$ | $d$ = 12 mm, $v_t$ = 12 mm min$^{-1}$ | $d$ = 18 mm, $v_t$ = 12 mm min$^{-1}$ |
Analyzing the averaged relationships between the force $F_h$ and displacement value $s$ for belt with diameter $d = 12$ mm and different velocities $v_t$ (Table 3), one can determine 3 characteristic stages of the plasticization process:

- I – the constant force $F_h$ with value close to 0, during which the reduction of clearance between the hot plate and the sample, after removing the thermal insulation spacer,
- II – determined plasticization of the material with proportional increase in force $F_h$,
- III – undetermined plasticization of the material with different course of force $F_h$.

**Table 3.** The average characteristics of pressing force $F_h$ for belt with diameter $d = 12$ mm: $F_h$ – pressing force, $s$ – displacement, $a$ – proportionality coefficient, $b_{1...5}$ – constant, I – clearance elimination stage, II – set plasticization stage, III – undetermined plasticization stage.

| $v_t$ | $F_h$ | $s$ | $a$ | $b_{1...5}$ | $R^2$ |
|------|-------|-----|-----|-------------|-------|
| 2 mm min$^{-1}$ | $F_h = 23.839 \cdot s - b_1$ | | | $R^2 = 0.9559$ | |
| 4 mm min$^{-1}$ | $F_h = 51.952 \cdot s - b_2$ | | | $R^2 = 0.9846$ | |
| 8 mm min$^{-1}$ | $F_h = 133.39 \cdot s - b_3$ | | | $R^2 = 0.993$ | |
Table 3 – continue

d) \( v_t = 12 \text{ mm min}^{-1} \)

![Graph for \( v_t = 12 \text{ mm min}^{-1} \)]

\[ F_h = 199.92 \cdot s - b_4 \]
\[ R^2 = 0.997 \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \\
0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \]
\( F_h \quad [N] \)
\( s \quad [\text{mm}] \)

\[ s \quad [\text{mm}] \quad I \quad II \quad III \]

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4 \quad 4.5 \]

\[ 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \quad 450 \]
\( F_h \quad [N] \)
\( s \quad [\text{mm}] \)

\[ s \quad [\text{mm}] \quad I \quad II \quad III \]


e) \( v_t = 16 \text{ mm min}^{-1} \)

![Graph for \( v_t = 16 \text{ mm min}^{-1} \)]

\[ F_h = 245.45 \cdot s - b_5 \]
\[ R^2 = 0.999 \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \]
\( F_h \quad [N] \)
\( s \quad [\text{mm}] \)

\[ s \quad [\text{mm}] \quad I \quad II \quad III \]

Analyzing the determined values for belt diameter \( d = 12 \text{ mm} \) one needs to point out the following:

- the key stage of the analysis is stage II, in which the plasticization force exhibits a linear relationship with the displacement, whereas the coefficient \( a \) derived from a linear equation:
  \[ F_h = a \cdot s + b, \tag{1} \]
  is proportional to the quotient of the pressing velocity and temperature change velocity:
  \[ a \sim v_t \cdot \left( \frac{\partial T}{\partial t} \right)^{-1}. \tag{2} \]

It can be defined as the stiffness of the pitted belt during compression in elevated temperature. The increase in this value demonstrates that together with the increase in pressing velocity \( v_t \), the material doesn’t have sufficient time to plasticize, whereby it is compressed in its solid form where the plastic material is characterized by higher stiffness,

- during the undetermined plasticization stage (area III) the features of the graph curve change depending on the pressing velocity \( v_t \). For lower values of the velocity \( v_t \) (2 and 4 mm min\(^{-1}\)) the curve decreases exponentially, which indicates the flow of the material. For velocity of 8 mm min\(^{-1}\), a balance is achieved between the plasticization speed and pressing velocity \( v_t \). In the case of higher pressing velocities \( v_t \), the plasticization force \( F_h \) increases during this stage, which indicates that the material is compressed in its solid state.

The resulting graph of pressing force is different from the one given in subject literature [25]. This is caused by the employment of a different control system of the plasticization process, i.e. the use of controlled, constant velocity \( v_{ct} \) instead of constant force \( F_m \) and \( F_h \).
The average characteristics of force $F_h$ in displacement $s$, for different velocities of a 18 mm diameter belt are provided in Table 4. In analyzing these characteristics, one needs to point out that the general function graph of pressing force $F_h$ in stages I and II are similar to the 12 mm diameter belt, but higher values of the coefficient $a$ are observed. The graph lines for force $F_h$ during stage III are also similar, apart from the velocity $v_t = 8$ mm min$^{-1}$, which is similar to the graph line for force $F_h$ at higher velocities $v_t$. This is due to the fact that the heating time for the belt with diameter $d = 18$ mm up to the plasticization temperature $T_p$ is longer due to larger material volume.

**Table 4.** Averaged characteristics of the pressing force $F_h$ for belt with diameter $d = 18$ mm: $F_h$ – pressing force, $s$ – displacement, $a$ – coefficient of proportionality, $b_{6...10}$ – constant, I – clearance elimination stage, II – determined plasticization stage, III – undetermined plasticization stage.

| $v_t$ | $F_h$ | $s$ | $R^2$ |
|-------|-------|-----|--------|
| 2 mm min$^{-1}$ | $F_h = 90.79s - b_6$ | 0-5 | 0.9803 |
| 4 mm min$^{-1}$ | $F_h = 258.15s - b_7$ | 0-10 | 0.9974 |
| 8 mm min$^{-1}$ | $F_h = 429.06s - b_8$ | 0-15 | 0.9984 |
Table 4 – continue

d) \( v_t = 12 \text{ mm min}^{-1} \)

\[
\begin{align*}
\text{I} & : F_h = 528.89 \cdot s - b_9 \\
\text{R}^2 & = 0.999 \\
\text{II} & : F_h = 619.45 \cdot s - b_{10} \\
\text{R}^2 & = 0.9983 \\
\text{III} & : 
\end{align*}
\]

Comparing the obtained graph lines in pairs for the same velocity values \( v_t \) and both belt diameters \( d \), the following is observed:

- for the testing velocity \( v_t = 2 \text{ mm min}^{-1} \) and \( v_t = 4 \text{ mm min}^{-1} \) (a-b in table 3 and a-b in table 4), for both diameters of the belt \( d \), the curves are similar with linear increase followed by an exponential decrease. It is therefore possible to assume that in this case after exceeding a certain initial heating time, the material becomes fully plasticized and begins to flow,

- for testing velocity \( v_t = 12 \text{ mm min}^{-1} \) and \( v_t = 16 \text{ mm min}^{-1} \) (d-e in table 3 and d-e in table 4), the graph line for pressing force \( F_h \) increases along the whole range of displacement \( s \), as well as in stage III. This shows that the material at such pressing velocity did not fully plasticize, which means during stage III we observe the compression of a solid.

- for testing velocity \( v_t = 8 \text{ mm min}^{-1} \) (c in table 3 and c in table 4), the curves are different depending on the diameter \( d \) of the sample. For sample diameter \( d = 12 \text{ mm} \) at stage III of the plasticization process, an approximately constant value of plasticization force \( F_h \) was obtained as a function of displacement \( s \). This indicates that a balance was achieved between the material plasticization speed and velocity of pressing the belt towards the hot plate \( v_t \). This state is very advantageous as in this case the necessary plasticization of the material (the \( F_h \) force value does not increase), is achieved without unnecessary loss of energy for excessive, needless melting of the material (the \( F_h \) force value does not decrease).

The coefficient of proportionality \( a \) at the determined stage of plasticization is, in the authors’ opinion, a significant parameter describing material plasticization during heating because it is easy to determine and exhibits the properties of a characteristic indicator, allowing to determine the efficiency of the plasticization process.
Figure 4 provides the function of the modulus of proportionality $a$ during compression at stage II of the process and the compression velocity $v_t$ for the two examined sample diameters $d$.

![Graph showing the function of proportionality coefficient $a$ and belt pressing velocity $v_t$.]

**Figure 4.** The function of the coefficient of proportionality $a$ and belt pressing velocity $v_t$.

During the examination, the hot plate temperature $T_p$ was also measured after 10 seconds since the beginning of the plasticization process, depending on the belt diameter $d$ and displacement velocity during the pressing $v_t$ (figure 5).

![Graph showing the function of hot plate temperature $T_p$ and pressing velocity $v_t$.]

**Figure 5.** The function of hot plate temperature $T_p$ and pressing velocity $v_t$.

The hot plate temperature decreases with the increase in velocity. This means that the thermal energy required for heating the belt end as it is displaced at higher velocity was high enough that the capacity of the heating unit did not fully cover this demand, especially at higher pressing velocity values.

One needs to point out that both in the case of belt diameters $d = 12$ mm and $d = 18$ mm, the change in the coefficient of proportionality $a$ and the hot plate temperature $T_p$ as a function of pressing velocity to the hot plate $v_t$, have similar characteristics. It is highly interesting that for the belt diameter $d = 12$ mm the function is approximately linear, whereas for belts with higher diameter, the function is non-linear. This is probably due to the non-linear characteristic of the material during compression [22] as well as the non-linear characteristic of temperature distribution along the belt axis during heating [23]. In particular, one needs to consider that for the belt diameter $d = 18$ mm the heating efficiency was not sufficient, and therefore the compression was applied to a solid body.

Based on the obtained characteristics of the variance in force value as a function of pressing velocity, threshold force values were determined for the belt $F_h$ (figure 6) at the end of stage II of the plasticization process. It was decided that in the ideal case, the belt pressing force to the hot plate after stage II should not increase. Taking into account that in particular for the belt with diameter $d = 18$ mm and higher, at
the pressing velocity values $v_t$, heater efficiency was insufficient, and compression of solid body did occur, therefore the established values should be treated as informational. Therefore, at this state of the research they should not be used as a model. However, in both circumstances, the function is increasing together with the increase in velocity in an approximately linear fashion.

![Graph](image)

**Figure 6.** Function of the maximum pressing force $F_h$ and the pressing velocity of the belt towards the plate $v_t$.

### 4. Conclusions

The performed examination allows to check a rarely employed method to control the process plasticization during butt welding in practice, the method entailed controlling the displacement velocity of the welded material in relation to the hot plate, instead of the classic solution of controlling the pressing force. Research works on this issue are relevant as it is planned to use such method of process control in the designed equipment.

The carried out examination did not arrive at an exact answer in regards the maximum force during the plasticization of the drive belt. However, they allowed to characterize the material plasticization process. Based on the obtained results one can state what follows:

- correct plasticization of the material carried out with the above described method is possible under condition that correct pressing velocity of belt ends to the hot plate is determined,
- it is possible to select the parameters of the plasticization process in a manner which achieves balance between the plasticization speed and pressing velocity to the hot plate in order to achieve sufficient plasticization of the material,
- in the course of the material plasticization process, one needs to pay particular attention to the output of the heater,
- it is possible to describe the plasticization process with one parameter i.e. the coefficient of proportionality $a$ during stage II of the process. Based on this value, the further course of the plasticization process can be predicted, particularly the function of the process force $F_h$ and displacement $s$ of the belt end in relation to the hot plate. Identifying this dependence allows to determine if the plasticization process is sufficiently efficient at the set displacement velocity of the belt $v_t$ and if an excessive, unnecessary melting of the material is occurring.

The selection of value of the coefficient of proportionality $a$ is going to be the critical factor in determining the key parameter settings for the control system in the designed machine. The described procedure calls for further examination, in particular to carry out a further study for a higher number of pressing velocities.

The results of the performed and planned examinations will be used as a reference for the mathematical modeling of the plasticization process on the hot plate, which is necessary to fully analyze the hot plate butt welding process of drive belts.
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