# DETERMINATION OF TECHNOLOGICAL CHARACTERISTICS OF PRESSABILITY

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**DOI: 10.17973/MMSJ.2024_11_2024021**

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This article deals with the results of technological tests of pressability (Erichsen's - IE index and capping - limit drawing ratio (LDR)). It also presents on which material parameter (ductility, strain hardening exponent, coefficient of normal anisotropy...) should be given more emphasis when choosing a steel sheet, if stretching stress (uniaxial tension, biaxial tension) dominates during the production of stampings, or if dominates the “pull-pressure” technique (pulling out from under the flange).

**KEYWORDS**

Erichsen test, technological parameters, cupping test, index according to Erichsen - IE, limit drawing ratio (LDR)

## 1 INTRODUCTION

Surface forming includes a whole range of technologies, in which the stress-strain state in individual areas on the pressings changes from a combination of tension and pressure, through uniaxial tension to biaxial tension. The complexity of the technological formability of steel sheets dependence on individual variables (state of tension, material properties, tool geometry, pressing conditions, etc.) on one hand, leads to the fact that it is not possible to formulate a simple indicator of technological formability for assessing the steel sheets pressability, and on the other hand, it indicates the range of indicators used [Sukhodub 2018]. Based on these assumptions, it can be concluded that during the production of pressings (deep drawing, bending, etc.) from sheet metals, it is not possible to determine all possible stress-deformation states with a tensile test. Therefore, the results obtained by the tensile test must be supplemented with the results of technological tests (cupping test, hole expansion test, bending, Erichsen test, etc.), which are carried out under similar stress conditions that occur during the real pressing process [Mielnik 1991, Hrivnak 2004, Evin 2016a].

## 2 STEEL SHEETS USED IN EXPERIMENTAL RESEARCH

- DC 01 - suitable for the production of various structural parts of specific products and for cold forming and medium deep drawing,
- DC 05 - extra deep drawing, suitable for complex large-scale stampings of car bodies and other stampings (it is marked as material A),
- DX 54D – hot-dip galvanized, extra deep drawing, suitable for complex large-scale stampings of car bodies and other stampiings (it is marked as material E),
- DC 04 EK – ductile steel sheet, designed for conventional enameling (it is marked as material C),
- DIN 1.4301 – chrome-nickel anti-corrosion steel suitable for cold forming (STN 17 241 - is marked as material D),
- DC 03 - hot-dip galvanized steel sheet is mainly used as equipment for storing and transporting materials and packaging tools.

## 3 DATA PROCESSING

Experimentallly-obtained data were processed in Matlab and Excel software. Matlab is an integrated environment for scientific and technical calculations, modeling, simulation, presentation and data analysis. Matlab provides powerful graphics, calculation tools and extensive libraries of functions [Mathworks R2014a]. The working environment of Excel consists of a large table with cells in which text, numbers, formulas and functions can be inserted. However, Excel is not limited to textual data and can supplement the necessary information with various images, graphs and tables.

## 4 RESULTS AND DISCUSSION

During the stretching production of stampings, biaxial tension occurs. This condition can be modeled by the Erichsen test. The degree of pressability in this test is the indentation depth, or index according to Erichsen IE at which a crack occurs. For the materials used for experimental research, in accordance with STN 420406, the indentation depth values IE were determined on the ERICHSEN type E-1 testing machine [Erichsen 2024], Tab. 1. An average value was calculated from five indentation depth measurements for each material.

**Table 1** Measured values of the index according to Erichsen IE

| Material | Thickness $a_0$ [mm] | Measured values of the index according to Erichsen IE | | | | | Average value $\overline{IE}$ [mm] |
|---|---|---|---|---|---|---|---|
| | | 1 [mm] | 2 [mm] | 3 [mm] | 4 [mm] | 5 [mm] | |
| E | 0.8 | 11.1 | 11.1 | 10.9 | 10.9 | 11.1 | 11.02 |
| DC 03 | 0.8 | 10.9 | 10.8 | 11.0 | 10.9 | 10.9 | 10.9 |
| DC 01 | 0.8 | 10.6 | 10.7 | 10.5 | 10.7 | 10.8 | 10.7 |
| A | 0.8 | 11.5 | 11.5 | 11.5 | 11.5 | 11.4 | 11.5 |
| C | 0.8 | 11.3 | 11.2 | 11.1 | 11.1 | 11.2 | 11.2 |
| D | 0.8 | 12.3 | 12.4 | 12.3 | 12.3 | 12.4 | 12.3 |

In cases where, during the production of the stamping, the material pulling out is dominant, not from the thickness of the stamping wall, but from under the blankholder, it is appropriate to use the cupping test. The criterion of deep drawing in this test is the limit drawing ratio (LDR)

$$K_{\max} = \frac{D_{0\max}}{d} \tag{1}$$

$D_{0\max}$ - the maximum diameter of the blank, from which it is possible to pull the yield without breaking with a punch, $d$ – the diameter of the punch. Experimentally, the values of the limit drawing ratio were determined on the hydraulic device RM – 501 [Evin 2016b, Labellarte 2000].

In the RM – 501 device, flat-bottomed cylindrical products were drawn from the diameters of the blanks of $\phi$ 55, $\phi$ 65, $\phi$ 75, $\phi$ 80 mm, see Tab. 2. From each type of experimental materials used, five samples were used for each diameter. At each measurement, the pulling force was recorded. Its average values are listed in Tab. 2.

**Table. 2** Calculated values of maximum diameters of blanks and limit drawing ratios.

| Material | Blank diameter $D_0$ [mm] | Pulling force [kN] | $D_{o\max} = \frac{F_{od} - y_0}{p}$ [mm] |
|---|---|---|---|
| A | 55 | 20.00 | =(35,3+21,863/0,76)=78<br>$K_{max}$=78/34,5=2,261 |
| | 65 | 27.62 | |
| | 75 | 35.23 | |
| | 80 | 35.3 | Broken product |
| Material | Blank diameter $D_0$ [mm] | Pulling force [kN] | $D_{o\max} = \frac{F_{od} - y_0}{p}$ [mm] |
| B | 55 | 16.19 | =(31,19+32,73/0,892)=71<br>$K_{max}$=71/34.5=2.05 |
| | 65 | 26.19 | |
| | 75 | 29.34 | |
| | 80 | 31.19 | Broken product |
| Material | Blank diameter $D_0$ [mm] | Pulling force [kN] | $D_{o\max} = \frac{F_{od} - y_0}{p}$ [mm] |
| D | 55 | 34.66 | =(60.67+74.056/1.98)=68<br>$K_{max}$=68/34.5=1.97 |
| | 65 | 54.43 | |
| | 75 | 60.81 | |
| | 80 | 60.67 | Broken product |
| Material | Blank diameter $D_0$ [mm] | Pulling force [kN] | $D_{o\max} = \frac{F_{od} - y_0}{p}$ [mm] |
| E | 55 | 16.19 | =(35.5+21.308/0.74)=77<br>$K_{max}$=77/34.5=2.232 |
| | 65 | 26.19 | |
| | 75 | 29.34 | |
| | 80 | 35.5 | Broken product |

When determining the limit drawing ratio, it is based on the assumption that the tensile force grows linearly depending on the diameter of the blank - Figures 1 and 2. The point at which the pulling force intersects the force required to break the wall determines the limiting diameter of the blank, then

$$D_{o\max} = \frac{F_{od} - y_0}{p}, \qquad (2)$$

where $F_{od}$ is the force required to tear off the bottom, $y_0$ - displacement, $p$ - slope of the straight line.

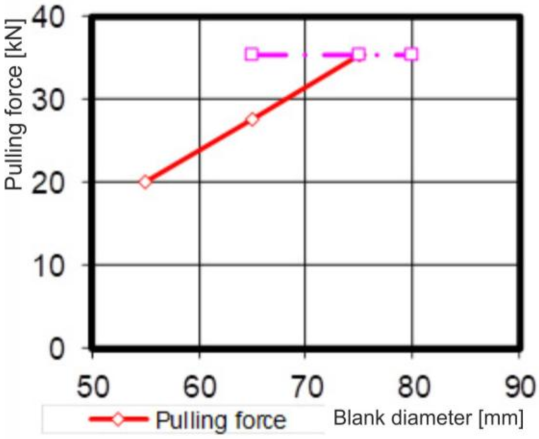

**Figure 1.** Dependence of the pulling force on the blank diameter for material A

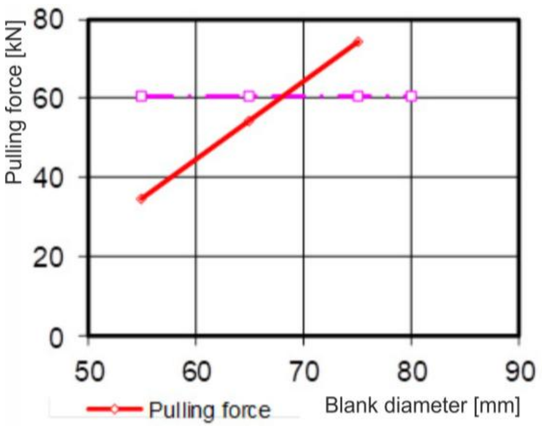

**Figure 2.** Dependence of the pulling force on the blank diameter for material D

Low-alloy steels have a greater resistance to thinning (high r values) than austenitic stainless steels. It means that if a greater reduction in the wall thickness of the stamping is permissible from a functional point of view, then from a material with a greater value of the strain hardening exponent, independently on the normal anisotropy coefficient, it is possible to produce a stamping with a greater height. However, it is true only in those cases when, during the production of stampings, the material is pulled from the thickness and not from under the blankholder. This assumption was confirmed by the results of the Erichsen test (Fig. 3 to Fig. 6).

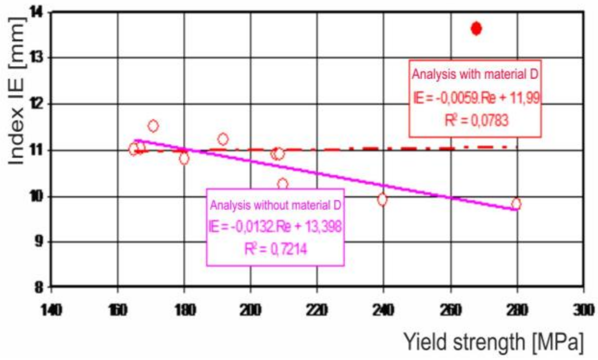

**Figure 3.** Dependence of the index according to Erichsen IE on the yield strength

In the dependences of the IE index on the yield strength and normal anisotropy coefficients, large differences in the slopes were noted in the analyzes with material D, and the values of the correlation coefficients were low. In the dependences of the IE index on the ductility and the strain hardening exponent [Domanski 2016], a good agreement of the slope lines was noted in the analyzes with material D, and the values of the correlation coefficients were 0.9 and 0.92, respectively. Austenitic stainless steel is characterized by a high strain hardening exponent and sensitivity index, while the anisotropy coefficient is small compared to carbon steel. The high strain hardening values of stainless steel are due to a suitable combination of strength and formability [Kopas 2017].

In the production of stampings by deep drawing (pulling out the material from under the holder), the pull-pressure combination is predominant. This combination of material stress can be modeled by a cupping test, during which the material is pulled out from under the holder.

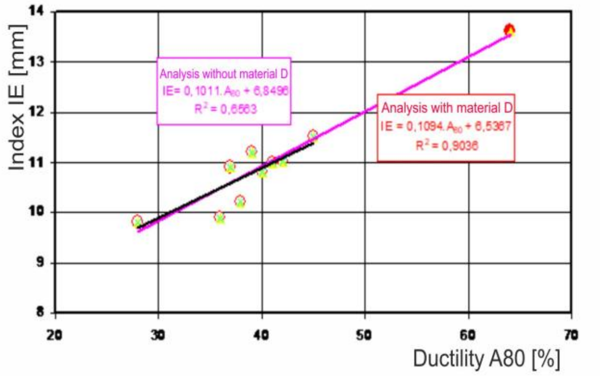

**Figure 4.** Dependence of the index according to Erichsen IE on the ductility

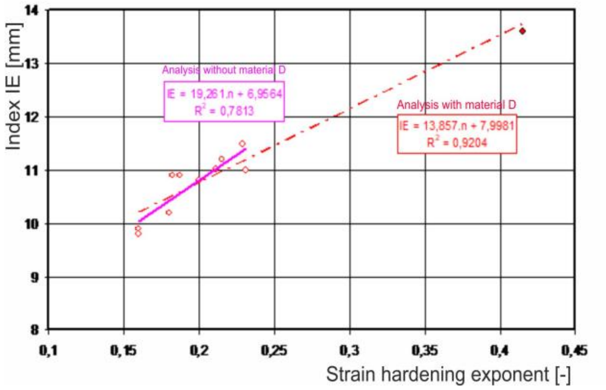

**Figure 5**. Dependence of the index according to Erichsen IE on the strain hardening exponent

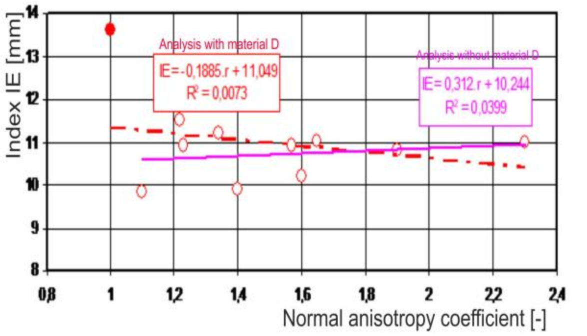

**Figure 6.** Dependence of the index according to Erichsen IE on the normal anisotropy coefficient .

As it is illustrated in Fig. 7 to Fig. 10, in the dependences between the limit drawing ratio and the coefficient of normal anisotropy and the yield stress in the analyzes with material D and without material D, there is a good agreement of the slopes of the straight lines, and the correlation values are relatively good, reaching the value of 0.47 and 0.66. In the analyzes with material D and without material D, a good agreement of the slopes was not noted in the dependences of the limit drawing ratio on the exponent of strain hardening and ductility. If we compare the values of limit drawing ratios of low-carbon steels and the limit drawing ratio of stainless steel, it is clear, that higher limit drawing ratio values can be obtained from low-carbon steels intended for forming than from austenitic stainless steel. As already mentioned, austenitic corrosion-resistant steels gradually strengthen during cold deformation, while in case of low-carbon steel sheets intended for cold forming, the strengthening reaches a certain value at a certain deformation and no further gradual strengthening occurs. This effect is accentuated by the partial transformation of the austenitic phase to martensite during the deformation of austenitic materials.

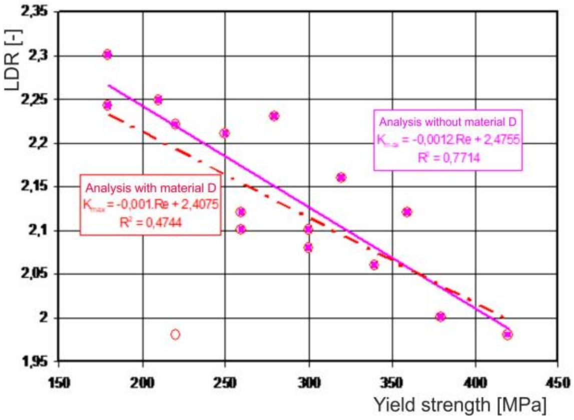

**Figure 7.** Dependence of the limit drawing ratio (LDR) on the yield strength

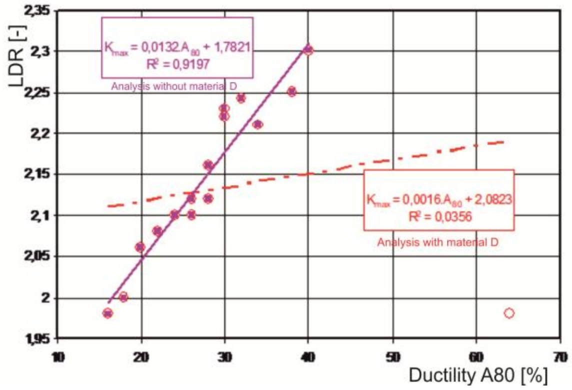

**Figure 8**. Dependence of the limit drawing ratio (LDR) on the ductility

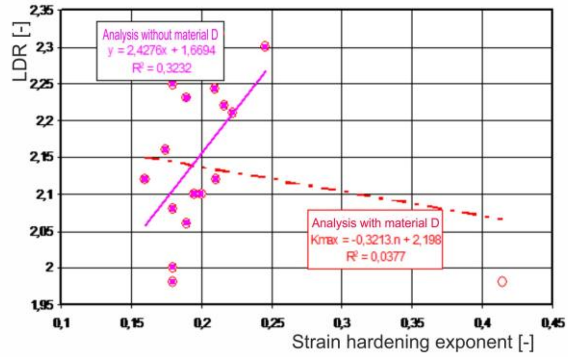

**Figure 9**. Dependence of the limit drawing ratio (LDR) on the strain hardening exponent

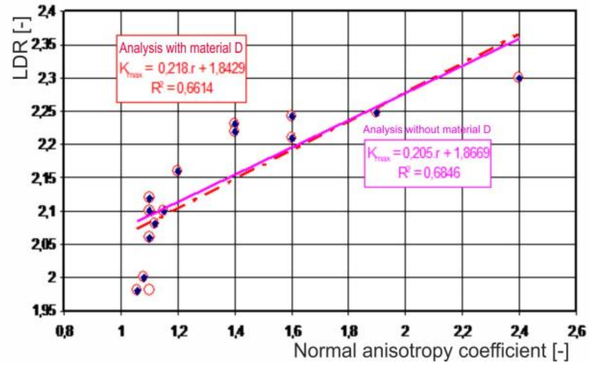

**Figure 10.** Dependence of the limit drawing ratio (LDR) on the coefficient notmal anisotropy

The stability of austenite decreases with decreasing content of alloying elements, then during cold forming more martensite is formed, which can cause deterioration of pressability [Krenicky 2022]. The martensitic transformation has a negative effect on pressability during deep drawing and especially during multiple drawing [Wen 2013].

The formation of martensite can be suppressed by a higher intensity of deformation, as a result of which the temperature of the material increases during pressing. Martensite can be removed by annealing. As can be seen from the obtained results, lower values of limit drawing ratios were achieved during deep drawing of cylindrical extracts from austenitic steels than when drawing cylindrical extracts from low carbon steels. On the contrary, better pressability was achieved with austenitic steel than with sheets made of low carbon steels.

When assessing the suitability of steel sheets for the production of stampings, it is necessary to take into account which stress-deformation schemes prevail during the pressing of a particular stamping. Based on the dependence of technological indicators of pressability on material properties, it is possible to determine the order of significance of the influence of individual material properties. When pulling out material from the flange area, the coefficient of normal anisotropy and the yield strength have the greatest significance.

For the reasons mentioned above, for the assessment of pressability (manufacturability of the stamping by stretching), the dependences of the index according to Erichsen on the ductility and the strain hardening exponent were analyzed. In order to assess the pressability (the manufacturability of the stamping by pulling out the material of the flange), the dependences of the limit drawing ratio on the coefficient of normal anisotropy and yield strenght were analyzed. In the analysis, it is necessary to divide the material characteristics expressing the improvement of pressability into those tendencies of which are increasing, and those tendencies of which are decreasing. If the trend is increasing, the change index $I_{ij}$ with respect to the reference value is calculated as follows:

$$I_{ij} = \frac{H_{ij}}{H_{iref}} > 1' \tag{3}$$

if the tendency of the parameter with respect to the reference value is decreasing, the change index $I_{ij}$ is calculated as follows:

$$I_{ij} = \frac{H_{iref}}{H_{ij}} > 1 \tag{4}$$

The significance of the influence of individual parameters is determined by weighted indices of change:

$$I_{ij}^{\prime\acute{}} = I_{ij} . q_i \tag{5}$$

The relative technical level of the i-th variant of the j-th type is determined using the sum of the weighted indices

$$^{\circ}F = S_j = \sum_{i=1}^{n} I_{ij}{}' , \tag{6}$$

where $H_{ij}$ - the value of the i-th pressability indicator of the j-th material, $H_{iref}$ - the value of the i-th pressability indicator of the reference material, $q_i$ - the weight of the significance of the considered parameter (the analyzes were based on the assumption that $q_i$=0.5).

Based on the dependence of the limit drawing ratio, index IE (Fig. 3 to 10) on the material properties, the dependencies of the limit drawing ratio, index IE were described on the weighted sum of indices $S_{ij}$ (parameter of the technical level of material properties) - Fig. 11 to Fig. 12.

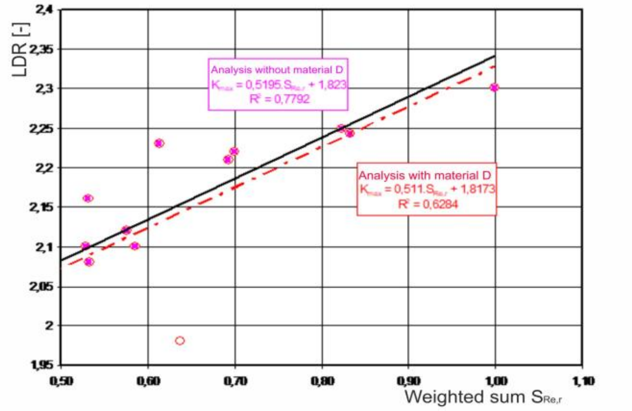

**Figure 11.** Dependence of the limit drawing ratio (LDR) on the weighted sum of indices of change of material properties $S_{Re,r}$

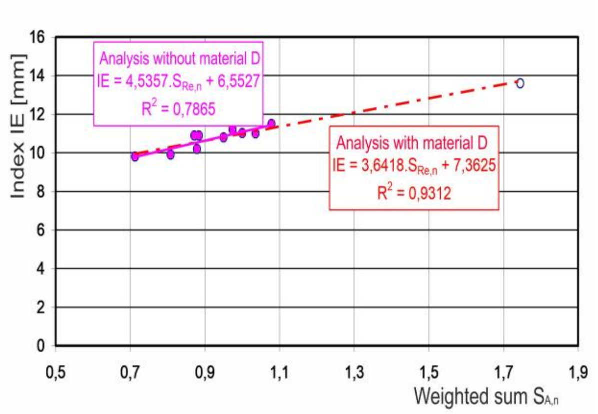

**Figure 12.** Dependence of the index IE on the weighted sum of indices of change of material properties $S_{A,n}$

Similarly, the dependences of the limit degree of drawing on the coefficient of normal anisotropy and yield strength were described

$$K_{max} = 0.511 \cdot S_{Re,r} + 1.82 = 0.511 \cdot \left(\frac{0.5 \cdot Re_{ref}}{Re} + \frac{0.5 \cdot r}{r_{ref}}\right) + 1.82 \tag{7}$$

and ductility index and strain hardening exponent

$$IE = 3.64 \cdot S_{A,n} + 7.36 = 3.64 \cdot \left(\frac{0.5 \cdot A_{80}}{A_{80,ref}} + \frac{0.5 \cdot n}{n_{ref}}\right) + 7.36 \tag{8}$$

where $Re_{ref}$, $r_{ref}$, $n_{ref}$, $A_{80,ref}$ are the values of yield strength, normal anisotropy coefficient, ductility and strain hardening exponent of the reference material [Murcinkova 2021] (in our case, the reference material was the sheet of DC 05 - material A).

## CONCLUSIONS

a) Based dependences on the results of technological tests of pressability (Erichsen's - IE index and cupping - limit drawing ratio) it follows that the largest values of the IE index were recorded for sheet metal from austenitic steel and smaller for materials A, B, C, E. While in the cupping test, it was found that the smallest value of the limit drawing ratio was achieved with the austenitic steel sheet D and larger values with the materials A, B, E. From the regression analysis of the dependence of technological indicators of pressability on material properties, it follows that between the index IE - ductility and IE - strain hardening exponent, a greater value of the correlation coefficient was recorded than in the dependences between IE - coefficient of normal anisotropy, IE - yield strength. In the dependences between $K_{max}$ – normal anisotropy coefficient, $K_{max}$ – yield strength, a greater value of the correlation coefficient was recorded than in the dependences between $K_{max}$ – strain hardening exponent, $K_{max}$ – ductility. On the basis of the above, it can be concluded that if the stretching tension (uniaxial or biaxial stretching) is dominant during the production of stampings, more emphasis should be placed on ductility and strain hardening exponent when choosing a suitable type of steel sheet. In the event that tension-compression stress is dominant during the production of stampings, it is necessary to focus more attention to the coefficient of normal anisotropy and yield strength when choosing a suitable type of steel sheet [Vlk 2003].

b) On the basis of the obtained results of technological tests (Erichsen and cupping), relations for predicting the pressability of sheets during tensioning operations (manufacturability of the stamping by stretching) were described:

$$IE = 3.64 \cdot S_{A,n} + 7.36 = 3.64 \cdot \left( \frac{0.5 \cdot A_{80}}{A_{80,ref}} + \frac{0.5 \cdot n}{n_{ref}} \right) + 7.36$$

and during deep drawing:

$$K_{max} = 0.511 \cdot S_{Re,r} + 1.82 = 0.511 \cdot \left( \frac{0.5 \cdot Re_{ref}}{Re} + \frac{0.5 \cdot r}{r_{ref}} \right) + 1.82$$

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