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EXPERIMENTAL AND NUMERICAL STUDY OF SPRINGBACK PROBLEMS IN SHEET METAL BENDING

EKSPERYMENTALNA I NUMERYCZNA ANALIZA ZJAWISKA SPRĘŻYNOWANIA PODCZAS GIĘCIA BLACH

Accurate prediction of springback is essential for the design of tools used in sheet metal stamping operation. This investigation aims to clarify the process conditions of three different bending operations of aluminium alloy brass and deep drawing quality steel sheets, by performing some experiments and finite-element simulation. The computer code MARC was used to simulate the *V*-die bending process under plane-strain condition. It provides a model, which predicts the precise final shape of products after unloading, in relation to the tensile properties of the material, especially instantaneous strain hardening parameters.

Dokładne określenie powrotnych odkształceń sprężystych jest bardzo istotne przy projektowaniu narzędzi do gięcia blach. Celem podjętych badań było określenie parametrów trzech różnych operacji gięcia blach ze stopu aluminium, mosiężnych i stalowych, na drodze eksperymentalnej oraz obliczeń numerycznych. Program komputerowy MARC został zastosowany do symulacji gięcia typu *V* w warunkach odkształcenia płaskiego. Zastosowany model pozwolił na dokładne określenie kształtu wyrobu po sprężynowaniu, przy uwzględnieniu właściwości materiału, zwłaszcza chwilowych wartości parametrów krzywej umocnienia odkształceniowego.

1. Introduction

Springback is a phenomenon in which the metal strip unbends itself after a forming operation. Control of springback for the bending processes applied in practice is difficult for a number of reasons, especially in mass production [1]. Sheet metal forming processes, such as bending, stretching and drawing are widely applied industrially, but design of tools and selection of sheet material remain almost invariably dependent on trial and error [2]. The main reason is that the shape of tools, characteristics of material, process variables and the

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geometric configuration of the workpiece all influence the manufacturing process: these characteristics are difficult to formulate into a precise mathematical model.

Bending is a frequently encountered process for sheet metal forming. In the field of sheet metal bending, one can find literature on pure bending, *V*-die bending, simple flanging and so on. Most materials can be bend to quite a small radius, but a problem is to control the shape of the bend workpiece. In general, a bend workpiece will recover elasticity i.e. springback on unloading, so that the bend quality is heavily dependent on the springback, which is a function of material properties and process parameters such as Young's modulus, yield stress, strain hardening abilities, plastic anisotropy, thickness and die geometry [3]. The most important die bending process is bending in a *V*-shaped die, so that deformed shape results from the sheet being pressed into the die by the punch until it is in contact with the sides of the die to the maximum extent possible.

The evaluation of elastic springback effects is a fundamental aspect in the practice of sheet forming operations. Springback, in fact, introduces deviations from the desired final shape – consequently, the stamped sheet does not conform to the design specifications and could result unsuitable for the application. Since almost all the sheet forming processes are characterised by a significant amount of deformation introduced by a bending mechanics, the distribution of strain along the sheet thickness is strongly inhomogeneous. Such a distribution, together with the elastic-plastic behaviour of the workpiece determines the occurrence of springback after removal of the forming tools [4]. It is well known from the tensile test that the elastic part of the total strain, which is recovered if the load is released, is equal to the ratio of the stress before unloading to the Young modulus. The tendency to elastic springback increases at increasing the strain hardening coefficient and at decreasing the elastic stiffness [5]. A complete knowledge of the springback phenomenon and its dependence on material and process variables is strongly required in order to develop effective real time process control systems.

Plane strain bending is a common mode of deformation. It is a difficult task to undertake numerical simulation of sheet bending process precisely. In the last two decades some mathematical models were proposed to predict springback effects for simple geometries. As far as bending is concerned, most analytical approaches were based on simple beam or plate bending theories, and have allowed to analyse the influence of material parameters on springback. More recently powerful numerical techniques based on the finite element method have been proposed to simulate sheet bending processes. They allow significant cost reductions in manufacturing process planning due to their predictive capabilities regarding material flow, strains, forming loads and so on [6]. Nevertheless, the application of numerical techniques to the prediction of the springback effect is far from that obtained for prediction of parameters such as strains, loads or material flow.

In this paper springback dependence on the mechanical properties has been examined experimentally in three different sheet metal forming tests: *V*-die air bending (*V*-type), flanging (*L*-type) and stretch-bending (*U*-type). The computer code MARC was used to simulate the *V*-die bending process under plane strain condition. Experimental results were used for comparing with the finite element simulations, to verify the efficiency of strain hardening models applied in calculations.

2. Materials tensile testing

Three types of commercial sheet metal with thickness in the range of 0.5 ÷ 1.2 mm were used in present investigation as test materials:

- AW5754 aluminium alloy sheet – temper 0. H14 and H24,
- 63-37 brass sheet – temper 0. H14, H22 and H24,
- 08FeP04 drawing quality steel sheet – five different drawing qualities.

When the mechanical testing is concerned, tensile specimens of 240 mm gauge length and 20 mm width were prepared from strips cut at 0°, 45° and 90° to the rolling direction of the strip. The experiments were carried out using a special device, which recorded simultaneously the tensile load, the current length and the current width of the specimens. The effective stress - effective strain relationship was described using the Hollomon model. The plastic anisotropy factor, r, has been determined on the basis of the relationship between the width strain and thickness strain in the whole range of specimen elongation using the least square method. The value of the tensile parameters (Table 1) has been averaged according to:

$$x_{mean} = (x_0 + 2x_{45} + x_{90})/4, \tag{1}$$

where the subscripts refer to specimen orientation.

For many years strain hardening laws such as those from Ludwik, Hollomon, Voce, Swift and Krupkowski has been used to describe the plastic behaviour of polycrystalline metals and alloys. The Hollomon law in the form of:

$$\sigma = C\varepsilon^n \tag{2}$$

has been used the most frequently. The parameters involved in this law, particularly n-value has been correlated to changes in the microstructure of a material and in some way represents processes, which occur during deformation. They have also been used extensively to characterise the formability of sheet material.

The value of strain hardening exponent, n, is usually determined from the double logarithmic plot of the true stress and true strain by linear regression. But the n-value is strain dependent what resulted from the changes in the crystallographic texture [7]. Because of this the mean n-value (which describe the strain hardening of the whole strain range – see Table 1) and differential n_t-value were determined on the base of the results of uniaxial tensile test.

Equation (2) assume a constant, average n-value determined for the whole range of straining from double logarithmic stress-strain data by a least squares approach. To examine the true strain hardening behaviours the instantaneous n_t-value should be determined. Taking the derivative from equation (2) yields

$$\frac{d\sigma}{d\varepsilon} = Cn\varepsilon^{n-1} = \frac{\sigma}{\varepsilon}n \tag{3}$$

which results in

$$n_1 = \frac{d\sigma}{d\varepsilon} \frac{\varepsilon}{\sigma}. \tag{4}$$

TABLE

Mechanical properties of sheet metal tested

Material	Material temper	Sheet thickness	Yield stress	Ultimate strength	Young modulus	Plastic anistropy factor	Strain hardening coefficient	Strain hardening exponent
		t, mm	R_e, MPa	R_m, MPa	E, GPa	r	C, MPa	n
AW5754 aluminium alloy	0	1.0	102	187	77	0.723	374	0.293
	H24	0.6	188	218	67	0.919	531	0.231
	H14	0.8	213	263	66	0.918	364	0.097
	H14	0.6	221	264	68	0.893	363	0.091
63–37 brass	0	1.0	120	282	90	0.956	517	0.304
	H22	1.0	213	394	87	0.855	590	0.202
	H24	0.7	317	382	105	0.787	565	0.142
	H14	0.5	473	503	103	1.050	608	0.042
08FPO4 diffrent drawing quality steel		0.5	262	368	195	1.210	551	0.127
		1.0	196	362	190	1.130	575	0.171
		1.0	196	330	180	1.432	544	0.184
		1.2	163	316	187	1.444	539	0.207
		0.8	153	287	187	1.638	487	0.211

The results presented in Fig. 1 show clearly that there is no unique constant strain hardening exponent, which may characterise strain hardening process of the sheets tested. The differential n_t-value varies continuously with strain – increases rapidly at small strains and at higher strains falls again somewhat less rapidly. Scatter of results in the case of aluminium alloy (Fig. 1a) resulted from the serrated flow curve of this material. It was established [7] that at large strains (above 0.10) stress is controlled by the cell size. This observation suggested that there is a change in the accommodation process from the grain level at low strains to the cell level at large strains – what resulted in a change in the strain hardening process. The changes in the n_t-value at first stage of straining should be taken into account in the analysis of sheet metal bending, since in the case such processes the effective strain very often amounts the value below 0.10.

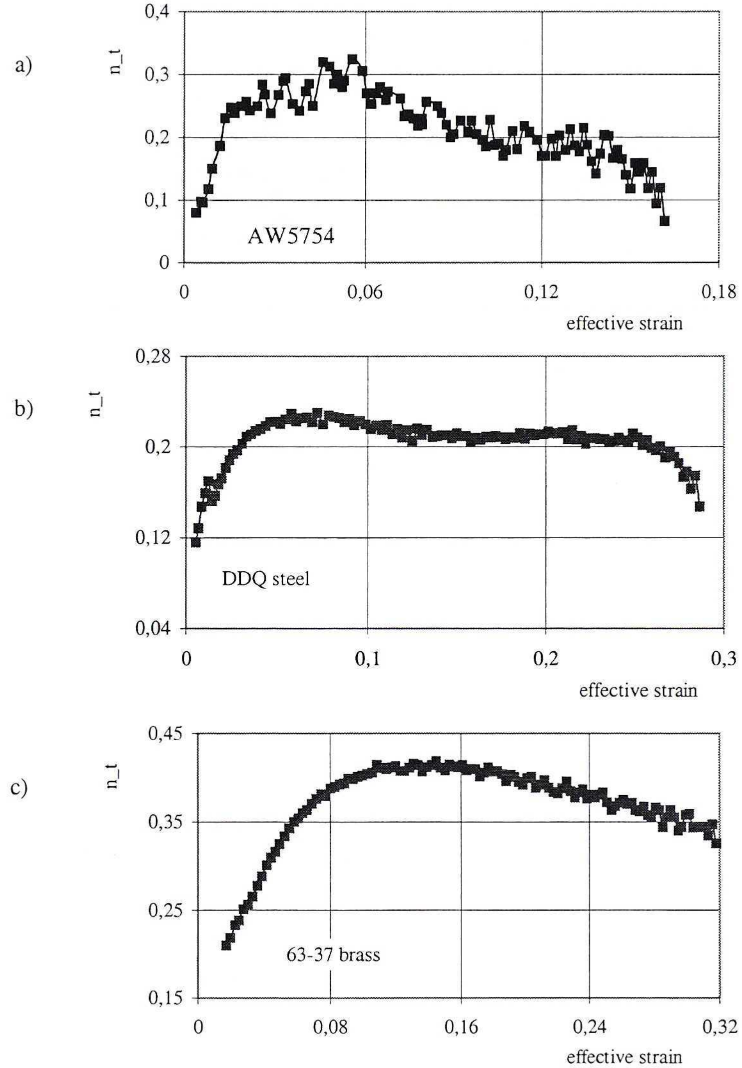

Fig. 1. Variation of differential n_t-value with strain for the (a) AW5754, (b) 63-37 brass and (c) DDQ steel sheet

3. Bending test

Three different *V*-type, *L*-type and *U*-type bending tests (Fig. 2) were used in experiment to determine the value of springback coefficient. Sheet specimens, prepared from the strips cut of in rolling direction and transverse to rolling direction, were deformed progressively – loaded and unloaded by suitable punch motion. The specimen shape at corresponding bending stage was recorded using the digital photo-camera and stored as a .jpg files. Using professional computer code GIMP, the .jpg files were elaborated in order to determine changes in a specimen shape, caused by springback phenomenon, and then the springback coefficient was calculated.

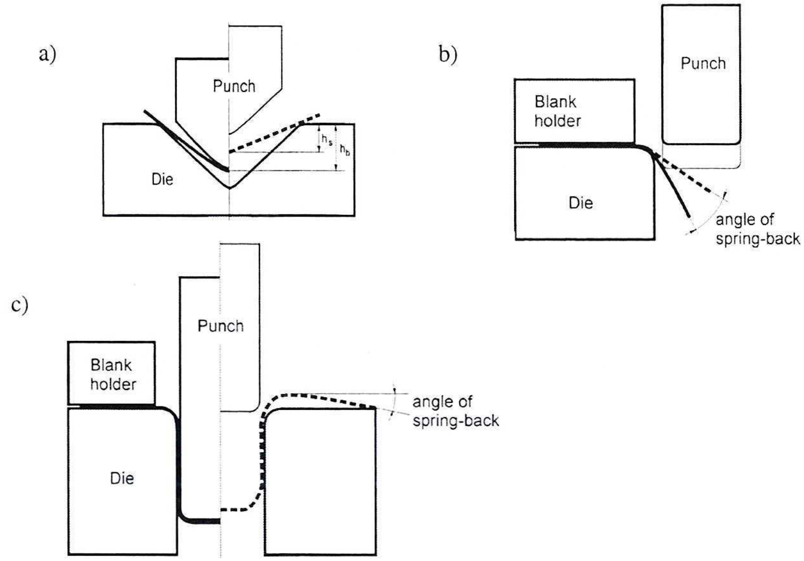

Fig. 2. Scheme of; (a) *V*-type, (b) *L*-type and (c) *U*-type sheet metal bending tests

When the *V*-type test (Fig. 2a) is concerned, the value of springback coefficient was calculated as:

$$K = h_s / h_b \tag{5}$$

where: h_b – bend depth under loading,
h_s – bend depth after unloading.

The results of springback coefficient calculation were plotted as a function of a relative bending depth defined as:

$$h_r = w / h_b \tag{6}$$

where: w is the bending length of a specimen.

When the *L*-type test (Fig. 1b) is concerned, the value of spring-back coefficient was calculated as:

$$K = \alpha_s / \alpha_b \tag{7}$$

where: α_b – bend angle under loading,
α_s – bend angle after unloading.

The most complicated shape of unloaded workpiece is observed in the case of stretch bending process [8]. Because of that the angle of flange spring-back (Fig. 2c) was assumed as a measure of this phenomenon.

The results of spring-back coefficient calculation were plotted as a function of a curvature defined, in the case of the *V*-type test, as relative bending depth h_r - eq. (6). Some examples of spring-back characteristics are presented in Fig. 3. Similar characteristics were obtained in the case of the *L*-type test. From this presentation it is visible that the value of spring-back coefficient increase with bending process proceeding, what is a result of elastic zone decreasing in the centre of sheet thickness.

Spring-back phenomenon depends on the value of plastic anisotropy of a material tested. The values of r-factor of materials presented in Fig. 3 are as follow:

- $r = 1.63$ –for DDQ steel sheet, rolling direction,
- $r = 2.03$ – for DDQ steel sheet, transverse rolling direction,
- $r = 0.79$ – for AW5754 aluminium alloy sheet, rolling direction,
- $r = 0.97$ – for AW5754 aluminium alloy sheet, transverse rolling direction.

It means that the spring-back phenomenon is more visible when plastic anisotropy factor more differs from the value of $r = 1.0$ (isotropic material).

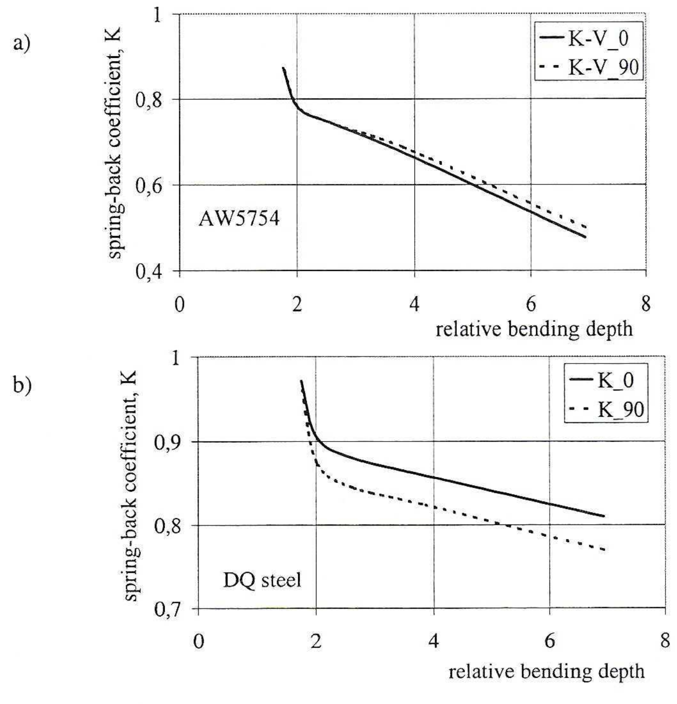

Fig. 3. The spring-back characteristic for different specimen orientation znder *V*-type test of 0.8 mm thick (a) aluminium alloy and (b) DDQ steel sheet

Statistical elaboration of the experimental results enabled to find nearly linear relationship between the value of strain hardening exponent and spring-back coefficient, *K*, in the case of the *V*-type test (Fig.4) and the *L*-type test (Fig. 5), as well as spring-back angle of flange in the case of the *U*-type test (Fig. 6).

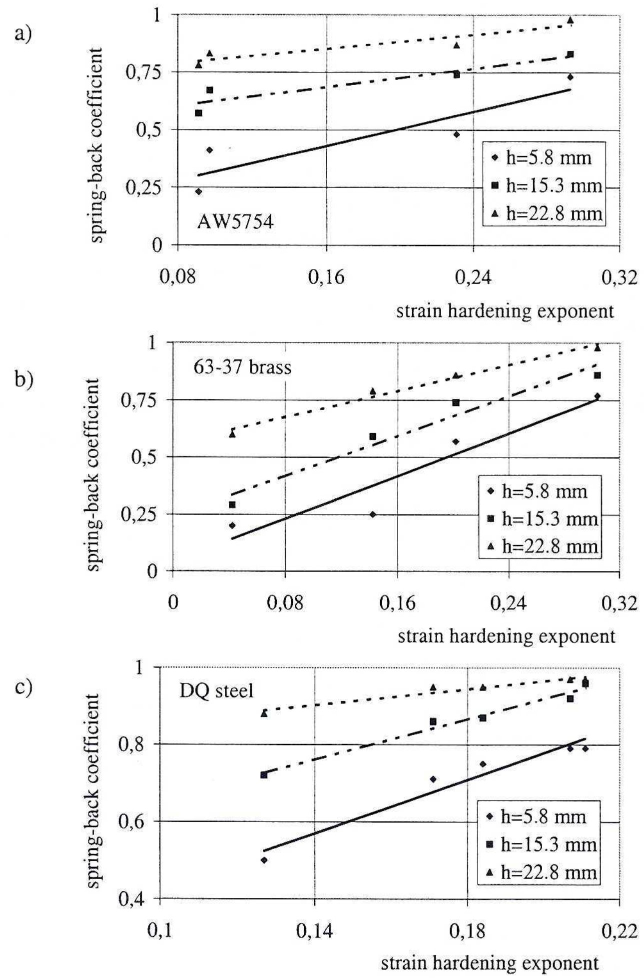

Fig. 4. The spring-back coefficient as a function of strain hardening exponent for aluminium alloy (a), brass (b) and steel (c) sheet metal used in *V*-type bending test

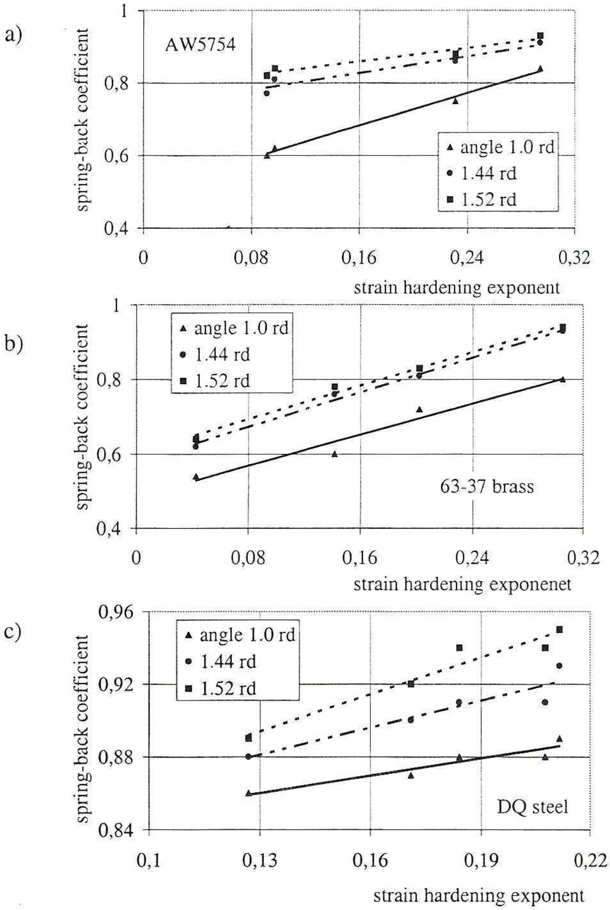

Fig. 5. The spring-back coefficient as a function of strain hardening exponent for aluminium alloy (a), brass (b) and steel (c) sheet metal used in *L*-type bending test

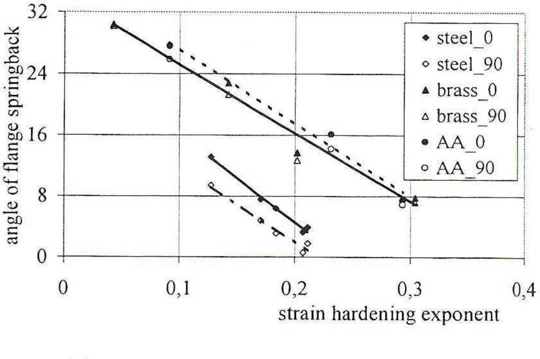

Fig. 6. The spring-back angle of flange as a function of strain hardening exponent for different orientation of specimens used in *U*-type bending test

The value of spring-back coefficient increase with n-value increasing and, what was expected, with bending depth (*V*-type test, Fig. 4) or bending angle (*L*-type test, Fig. 5) increasing. Intensity of these relationships was on the material type dependent the least changes in *K*-value were observed in the case of DQ steel sheets (Fig. 4c and Fig. 5c).

The value of flange spring-back angle (Fig. 6) decrease with the value of strain hardening exponent increasing. Additionally, in the case of DQ steel sheets, the spring-back phenomenon was visibly affected by the plastic anisotropy of material.

Relationships between other mechanical parameters of the sheet metal tested and the spring-back coefficient were weak or less visible.

4. Numerical procedure

Analysis of bending process is based on consideration of the plane strain condition. The finite-element computer code MARC was used to simulate strain distribution across the sheet thickness and springback coefficient calculation. Because of the symmetry of plate, only one half portion of the tools and workpiece was modelled. An automatic mesh program was applied in this work to generate the finite-element mesh grid, which is a bilinear quadrilateral element with the selective reduced integration, efficient for sheet metal forming. A modified Coulomb's friction law was employed to treat the discontinuous alternation of the sliding-sticking state of friction at the contact interface. To realize satisfactory lubrication between the tool and the sheet, friction coefficient $\mu = 0.01$ was assumed in the calculation.

Fig. 7 shows the sheet deformation geometry and strain distribution across sheet thickness at a particular stage of *V*-die bending process. From this presentation (Fig. 7a) it is visible that in the punch-sheet contact region the neutral plane (zero strain plane) is moved to punch surface, what could be treated as a result of friction. The geometry of specimen at loading and after unloading (Fig. 7b) demonstrate springback phenomenon.

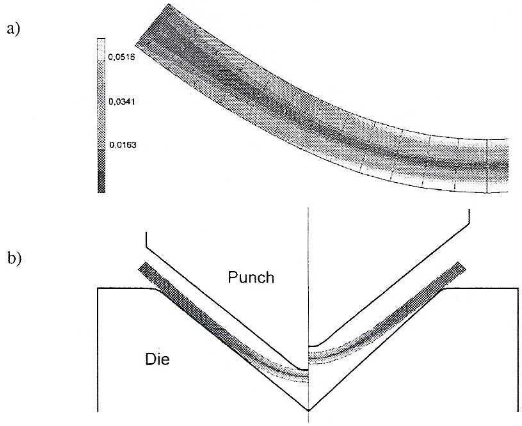

Fig. 7. Strain distribution across sheet thickness (a) and specimen geometry of the specimen under load and after unloading (b) at a particular stage of *V*-die bending process

Two different strain hardening modes have been used for the calculation of the springback coefficient:

- the mean values of strain hardening coefficient, C, and strain hardening exponent, n,
- the differential strain hardening parameters – C_t and n_t.

Fig. 8 shows the springback characteristics of the materials tested – AW5754 aluminium alloy, 63-37 brass and DQ steel sheet: experimental data (*K*_exp.) and results of finite-element simulation using mean (*K*_mean) as well as differential (*K*_t) strain hardening parameters. The best agreement between experimental results and calculations using both, mean and instantaneous strain hardening parameters was obtained in the case of AW5754 aluminium alloy sheet (Fig. 8a). When the 63-37 brass and DQ steel sheet are concerned, applying of differential strain hardening parameters resulted in better *V*-die bending simulation (Fig. 8b and Fig. 8c). Simulation of *V*-die bending process was performed under assumption of sheet metal isotropy, what resulted in weak agreement between experimental and calculated results of the springback coefficient determination in the case of DQ steel sheet (Fig. 8c), which is strongly anisotropic (see Table 1).

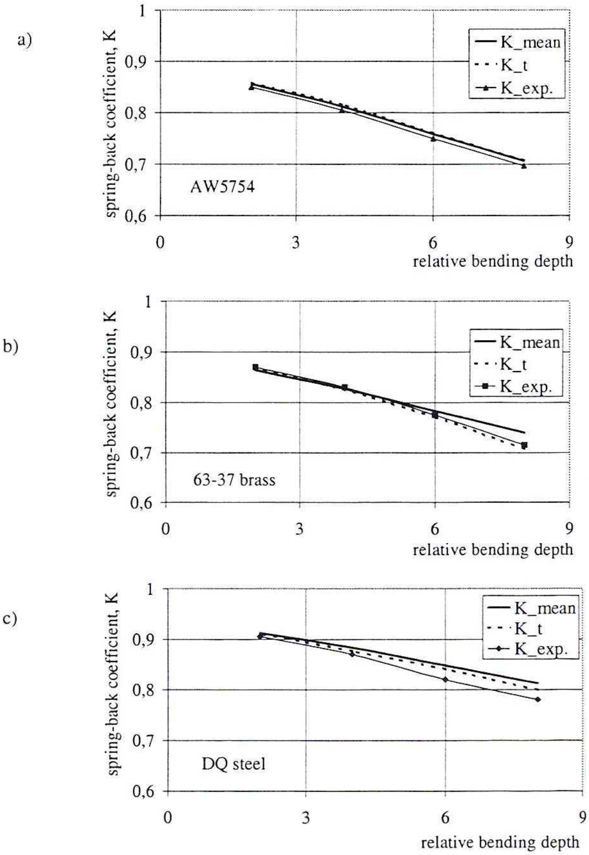

Fig. 8. Springback characteristics of (a) AW5754 aluminium alloy, (b) 80-20 brass and (c) DQ steel sheet

5. Conclusions

The experimental investigation of the aluminium alloy, brass and drawing quality steel sheet metal bending under both the *V*-die air bending, flanging and stretch-bending tests have shown, that the value of spring-back coefficient is in linear relationship with the value of strain hardening exponent. Significant anisotropy in the sheet materials led to different spring-back behaviours for different sheet orientation.

An attempt, based on the experiment and the simulation, was made to explore the effects of material variables on springback phenomenon in *V*-die bending process. Satisfactory agreement between the calculation and the experiment was obtained, what clearly demonstrates the efficiency of the computer code MARC. The enclaves of the plastic region, deformed geometry of specimen and springback characteristics were well predicted according to fine-element model. Better agreement between experimentally determined and calculated results of springback coefficient was obtained taking into account instantaneous strain hardening parameters of sheet metal.

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