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Failure analysis at deep drawing of low carbon steels

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ABSTRACT

This paper presents a comparison in behaviour of two Zn coated, low carbon steels during deep drawing of bearing housing. The failures occurred during deep drawing process only for one steel. The experimental work consisted of a visual inspection, microscopic examination and chemical analysis of both materials. Metallurgical tests revealed the difference in microstructure and in carbon content. The anisotropy in behaviour was observed during deep drawing process. Metallography confirmed formation of longitudinal micro and macrocracks and elongated chains of cementite particles in matrix of ferrite. This study highlights the detrimental effect of the interface cementite particle/ferrite matrix as the main reason for the microcracks formation and reduction of steel capacity for deep drawing.

1. Introduction

Thin steel sheet is important material for manufacture of numerous products with deep drawing and stamping. Cold rolled steel sheet combining uniformity of mechanical properties and low levels of surface contamination following the annealing process is desired to meet increasingly stringent product quality requirements [1].

Complex shapes of stamped and cold drawn components are required for today's automotive and various other industries. Such components are now developed with the aid of data obtained from laboratory experiments that enables the press and deep drawing formability of sheet metals to be reliably predicted [2]. Therefore, an understanding of the formability of sheet metals is essential for the successful production of quality stampings and deep drawn components [2].

Deep drawing is used to manufacture a variety of products from beverage cans to automotive panels with complex surfaces. The process involves forcing a blank or work piece into and/or through a die using a punch [3].

Demands on higher mechanical properties of components are reasons that deep drawing process is not limited only to application of low carbon steels (<0.02% C) but is applied also with medium and high carbon steels. Application of these steels is more critical because increased content of carbon drops the workability. In a medium carbon steels (0.36% C) the pearlite lamellar morphology has been found to lead to undesirable cold working mechanical properties in highly stressed components. While globular cementite morphology conduces to higher toughness, good cold workability and machinability [4]. In such steels cementite precipitates are located at the ferrite–ferrite grain boundaries and their distribution is homogeneously throughout the microstructure [5].

In deep drawing process behaviour of deep drawn material as well as of the punch [6] plays very important role. Higher hardness of deep drawn material worsen its workability, increases the wear of tools and decreases the service life of drawing

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tool. A difference in behaviour is often observed in longitudinal and transversal direction in cold rolled steels as a consequence of texture [7] and anisotropy of material.

The steel sheet is often coated with Zn for better corrosion resistance of deep drawn products. Zinc protects the base metal by providing a barrier to corrosive environment and also by the sacrificial nature of the coating [8].

At failure analysis of hot dip galvanized low carbon steel should not be neglected the possibility of strain-ageing embrittlement [9]. The principal cause of strain ageing in steels is pinning of dislocations by a diffusion interaction with small interstitial atoms, in particular nitrogen and carbon [10] and the high internal stresses, present after cold rolling, when steel is exposed to elevated temperatures (as is galvanizing, enameling or paint baking).

To prevent the effect of nitrogen a free aluminium must be available in steel to combine with nitrogen to AlN. In general the required content of aluminium should be greater than twice the nitrogen content, to ensure that there is available enough free aluminium to combine with the free nitrogen [11]. Strain-ageing can be prevented either by soft annealing after cold rolling or with steel deforming after galvanizing. The flaking and cracking of galvanized coating can occur in such case.

The differences were observed in behaviour of two low carbon aluminium killed, cold rolled, annealed and Zn coated steels for deep drawing. The aim of the study was to declare the reasons for the differences in behaviour of Zn coated steels with low carbon content during deep drawing process.

2. Experimental procedure

The two types of low carbon aluminium-killed and soft annealed steels were applied for production of bearing housing by deep drawing process. Workability of Steel 1 was without problems but at Steel 2 the cracks were observed at deep drawing. Chemical composition of both steels was determined by inductively coupled plasma ICP-AES spectroscopy. Carbon and sulphur were analysed by Leybold device and nitrogen with ELTRA ON 900 analyser. Chemical composition of both steels is presented in Table 1.

The main difference in both steels was in the content of carbon. From Table 1 is evident that Steel 1 with lower content of carbon (0.01 wt.%) was stabilized with 0.04 wt.% of Ti. The aim of stabilization with Ti (the content of Ti should be around 5 times content of C in steel) is to bound the free carbon to TiC and to prevents the formation of cementite (Fe_3C) which is harmfull for cold workability of steel. Steel 2 has higher content of carbon (0.047 wt.%) and is not stabilized with Ti. The content of Al and N is similar in both steels.

The photographs of samples with failures were taken by Panasonic LUMIX DMC FZ1.

Samples for metallography were cut from the sheet and from the deep drawn components. Evaluation of the microstructure was done with metallography on light microscope Nikon Microphot FXA. For evaluation of microstructure the samples were prepared by well known method of metallography; cutting, grinding, polishing and etching in Nital.

The hardness HV1 was measured on cross section of sheet by Zwick hardness measurement device.

The EDS analyses were done by analytical electron microscope JSM-6500F FE SEM, equiped with energy dispersive spectroscopy (EDS), wave dispersive spectroscopy (WDS) and with system for electron back scattered diffraction (EBSD).

Technological tests of deep drawing of both steels sheets were performed with Erichsen device for testing of deep drawing (Fig. 1). For Erichsen test a sheet metal specimen is clamped between a blank holder and a die and then deep-drawn

Table 1
Chemical analyses of investigated steel sheets (wt.%).

Material	C	Si	Mn	P	S	Al	N	Ti
Steel 1	0.01	<0.01	0.16	0.021	0.010	0.041	0.0067	0.04
Steel 2	0.047	<0.01	0.19	0.017	0.010	0.046	0.0072	<0.002

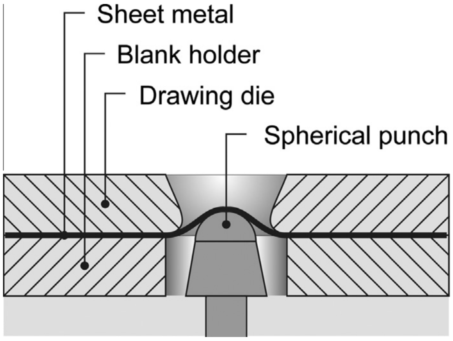

Fig. 1. Schematic presentation of Erichsen test of deep drawing [10].

with a hardened spherical punch. This procedure is continued at a prescribed speed until it results in a fine, continuous crack in the sheet metal. This fast, cost-effective testing method is just as suit-able for use in incoming inspection as for in-process controls – and that without any lengthy specimen preparation [12]. In Fig. 1 is schematic presented cross section of Erichsen device for test of deep drawing of steel sheet [12].

3. Results and discussion

In the presented study, the behaviour of two steels during deep drawn process are described. The cracks were observed during deep drawing process only at Steel 2. The cracks appeared in longitudinal direction of rolling of sheet. From the appearance of cracks is evident that fracture occurred because the material is anisotropic, had not enough workability and could not resist internal stresses during deep drawing process. Comparison of properties of Steel 1 and Steel 2 were performed.

From the chemical analyses of both steels (Table 1) is evident that Steel 1 and Steel 2 have different carbon content and Steel 1 with lower content of carbon is additionally stabilized with Ti. It is well known that for good deep drawing properties the content of carbon in steel should be below 0.02 wt.% which represents the maximal solubility of carbon in ferrite, according to Fe–C phase diagram. Such low quantity of carbon prevented the formation of cementite. Steels with carbon content above 0.02 wt.% have in general lower deformability due presence of harder cementite or perlite in the microstructure of sheet. In both steels the content of Al is high enough to bound free nitrogen and to prevent its influence on strain-age embrittlement.

Stages of deep drawing process of components from Zn coated Steel 2 are presented in (Figs. 2–4). Light microscopy (Figs. 5–7) revealed in Steel 2 presence of particles oriented in rolling direction (Figs. 6 and 7) and presence of cracks at the interface particle/ferrite matrix (Figs. 7b and 8). Further investigations with SEM and EDS analysing on Steel 2 confirmed that particles are cementite particles (Fig. 9), oriented in longitudinal direction of cold rolling process. Observed microcracks follow direction of cementite particles (Figs. 7b and 8). In general the cementite particles are often observed in steels with carbon content above 0.02%, which is the upper limit of solubility of carbon in solid solution of ferrite.

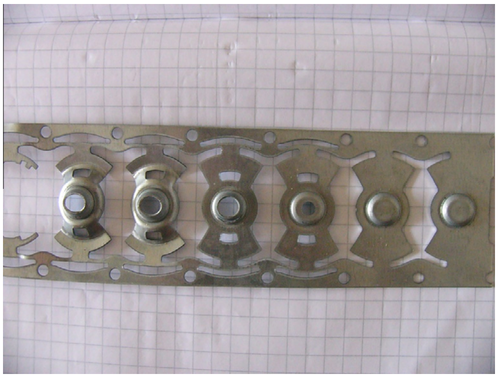

Fig. 2. Steps during deep drawing process of steel bearing housing. The ovality of openings confirmed worse workability of steel in transverse direction, Steel 2: The grid is 1 × 1 cm.

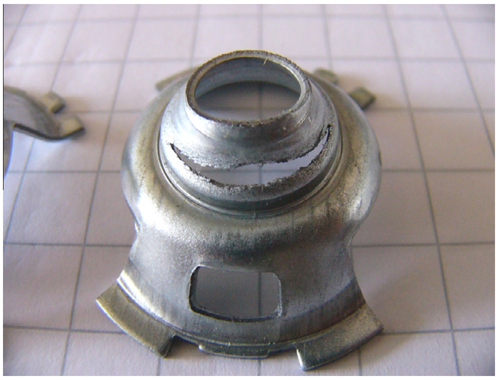

Fig. 3. Fracture of the wall. The fracture in direction of rolling of material shows worse workability of sheet in transversal direction, Steel 2: The grid is 1 × 1 cm.

Fig. 4. Internal part of the housing with fracture, Steel 2: The grid is 1 × 1 cm.

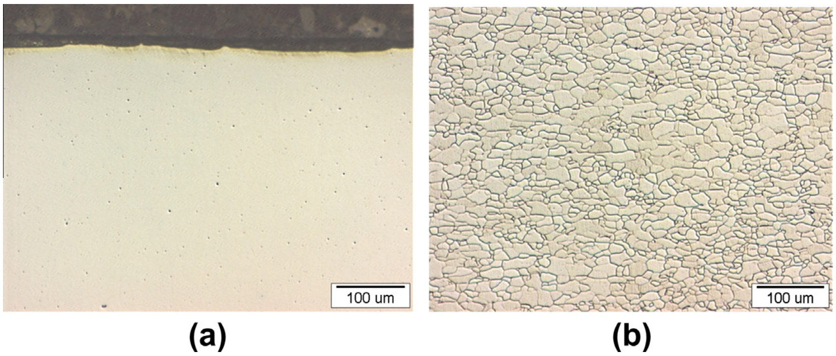

Fig. 5. Microstructure of cross section of Zn coated Steel 1 sheet (good capability for deep drawing). (a) Not etched and (b) etched with Nital.

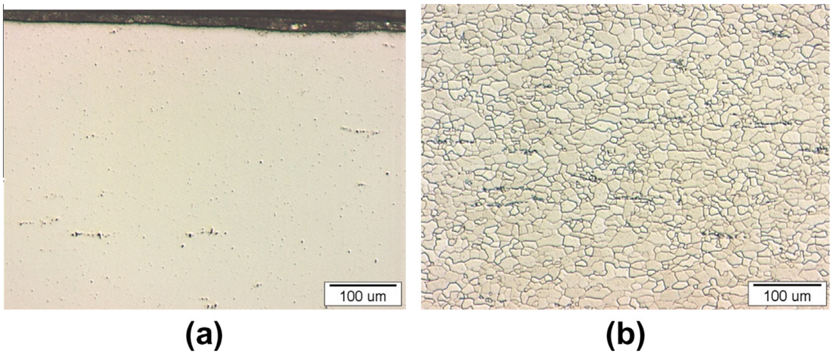

Fig. 6. Microstructure of cross section of Zn coated Steel 2 sheet (bad capability for deep drawing). Cementite particles and elongated cracks in the rolling direction. (a) Not etched and (b) etched in Nital.

In the microstructure of Steel 1 were present only a few inclusions (oxides and TiCN). Due their low number their influence on deep drawing properties was neglectable. There was no cementite particles because of low carbon content in steel.

Investigation of microstructure of sample cut from deep drawn component of Steel 2 revealed the cracks in cross section, Cracks confirmed that stresses during deep drawn process exceeded the tensile strength of the Steel 2. The thinning of the wall (Fig. 10) and presence of surface cracks initials (Fig. 11) were observed in the most deformed regions. Increased number of internal microcracks was observed in outer region, close to the surface. The position of microcracks confirm the strings of cementite particles are the initiation points of micro cracks formation. The growth and merging of microcracks caused the final fracture. One possible reason for the formation of cracks is also the strain-age embrittlement phenomena. But in this case it can be neglected as the content of Al in both steels is satisfactory to bound free nitrogen and to prevent strain-age embrittlement phenomena due nitrogen.

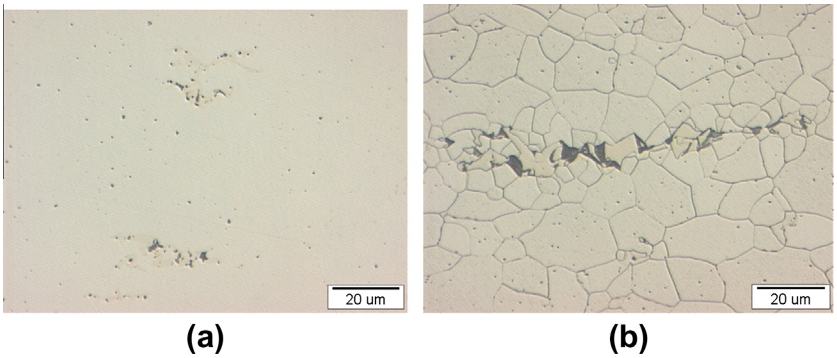

Fig. 7. Microstructure of Steel 2 sheet. Cementite particles in ferrite and small cracks at the interface ferrite–cementite. (a) Not etched and (b) etched in nital.

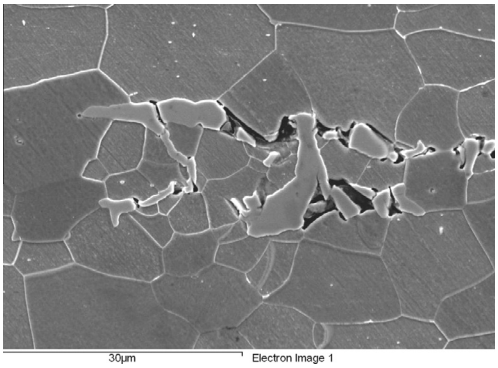

Fig. 8. Cementite particles and microcracks in Steel 2 sheet (SEM).

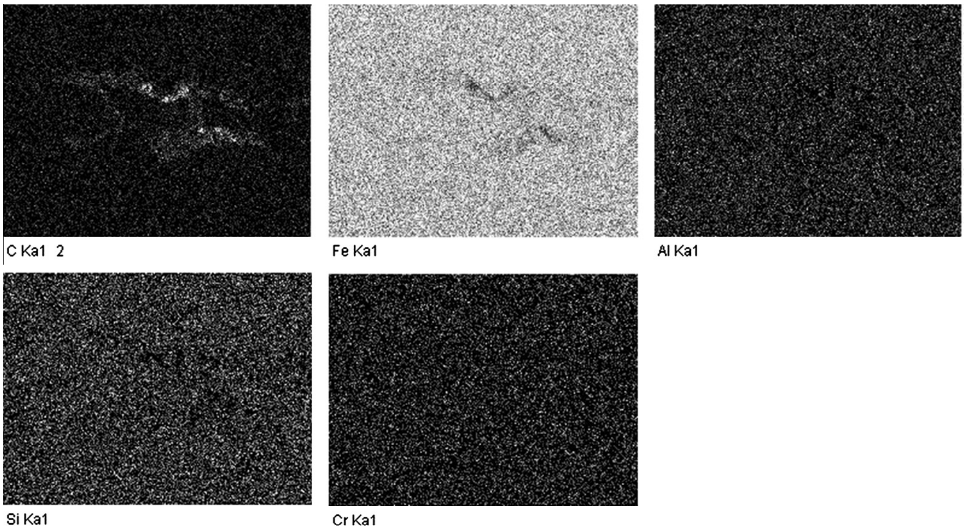

Fig. 9. EDS mapping confirmed cementite particles in Steel 2 sheet.

The results of hardness measurements of sheet before deep drawing are presented in Table 2. From the hardness of sheets is evident the sheets were in soft annealed condition and no internal stresses were present in steels before hot dip Zn-coating. For that reason the strain-age embrittlement was prevented.

As expected form the observation of microstructure the hardness of Steel 1 was lower, around 106 HV1, due the absence of cementite particles and with low scattering of hardness measurements. The Steel 2 is harder, about 120 HV1 but the

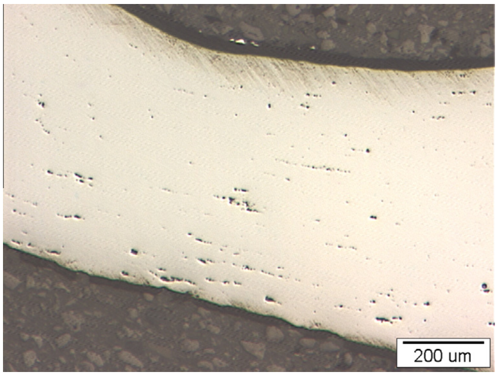

Fig. 10. Cross section of deep drawn part, Steel 2: Thinning of the wall at the point of maximum deflection and the internal cracks.

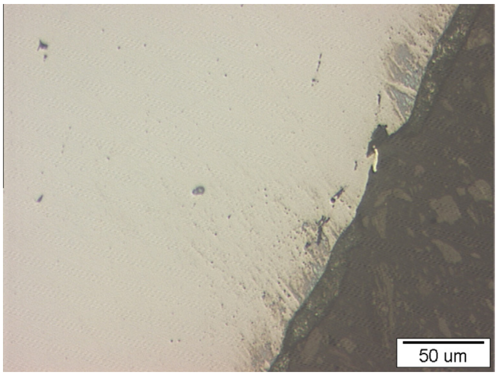

Fig. 11. Cross section of deep drawn part from Steel 2. Initials of crack on the surface and interrupted layer of Zn coating.

Table 2
Hardness HV1.

Material	Hardness HV1	Average hardness HV1
Steel 1	106, 109, 107, 103, 102	106
Steel 2	118, 139, 104, 127, 114	120

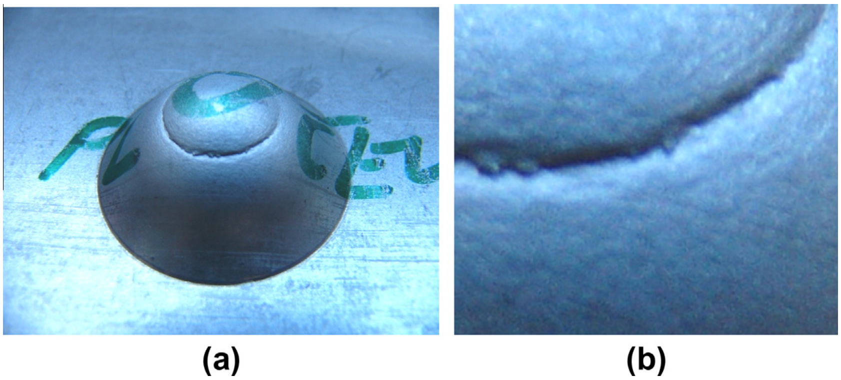

Fig. 12. (a) Erichsens deep drawing test of Steel 1 sheet. Zn layer was compact. (b) Detail of contraction at crack confirms good workability of Steel 1.

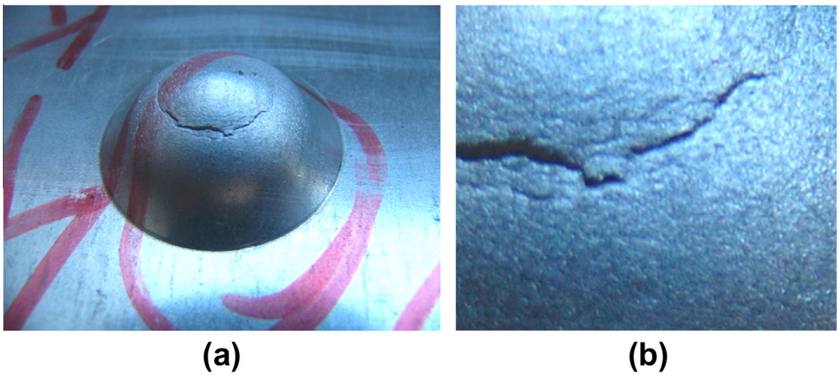

Fig. 13. (a) Erichsens deep drawing test of Steel 2 sheet. Zn coating is cracked and the layer is peeled off the surface. (b) Detail of crack without contraction confirms worse workability of Steel 2.

measured values show larger scattering. Cementite particles in Steel 2 influenced higher hardness of sheet that reflects also in poor workability and formation of cracks during deep drawing process.

Both materials were tested also by Erichsen deep drawing test. The strong contraction and no fracture in Steel 1 is a sign of good workability/ductility of steel. Also zinc layer was more resistant and did not crack in the region of contraction (Fig. 12).

By contrast in the Steel 2 the fracture was without contraction and also the zinc layer started to crack and flake off (Fig. 13). Lower ductility of Steel 2 was confirmed also with Erichsen test.

4. Conclusions

Based on performed investigations and tests the following conclusions can be drawn.

Two steels with carbon content below and above 0.02 wt.% revealed the difference in behaviour of steels at deep drawing process. Deep drawing of Steel 1, with lower content of carbon, was without failures. Lower content of carbon enabled better workability and showed contraction of sheet thickness in regions with higher rate of deformation.

The content of Al and N and soft annealing of sheets before hot dip galvanizing prevent the formation of strain age embrittlement.

The carbon content in Steel 2 was above 0.02 wt.%. For that reason the strings of cementite particles were present in cold rolled steel. The cementite particles in Steel 2 caused higher hardness and lower workability in transverse direction, compared with Steel 1.

The cementite particles are accompanied by microcracks originating from the cold rolling of Steel 2. Steel 2, with higher content of carbon was without contraction near the fracture, which confirms worse workability of steel.

The differences in ability for deep drawing between two steels were confirmed with Erichsens technological tests.

The presence of cementite particles is the main reason for worse deep drawing capability of Steel 2 in longitudinal and transverse direction.

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