DEFORMATION AND FRACTURE OF HOT DIP GALVANIZED STEEL SHEETS

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Two interstitial-free (IF), titanium added steels and one low carbon Al killed steel were subjected to the 0 deg bend test and to the low temperature impact loading and fracturing with aim to describe the deformation behavior and the failure modes of the steel-zinc coating interface. The system of steel sheet-intermetallic phases layer-pure zinc phase after the deformation was studied from both compression and strain sides of the sheet materials. It was shown that the failure has been initiated in the intermetallic phases region, meanwhile the uppermost pure zinc phase exhibited very high deformation potential. After the impact load at low temperatures, both IF steels with different zinc coating thicknesses fractured by intergranular decohesion mechanisms, while the low carbon steel exhibited transgranular fracture. The fracturing mechanism of basic steel material remarkably influenced the steel-zinc layer interface failure mode. The zinc layer in all cases fractured by complicated brittle mechanisms.

Key words: hot dip galvanizing, intermetallic phases, deformation, bend testing, compression, strain, low temperature fracture

DEFORMÁCIA A PORUŠOVANIE ŽIAROVO POZINKOVANÝCH OCEĽOVÝCH PLECHOV

Dve ocele bez interstícií (IF) obohatené Ti a jedna nízkouhlíková oceľ upokojená hliníkom boli podrobené ohybu do doľahnutia ramien a dynamickej skúške rázom pri nízkej teplote s cieľom opísať deformačné správanie a mechanizmy porušovania na rozhraní oceľ-zinkový povlak. Systém oceľový plech-vrstva intermetalických fáz-čistá zinková fáza bol po deformácii študovaný z tlakovej i ťahovej strany plechu. Ukázalo sa, že porušenie bolo iniciované v oblasti intermetalických fáz, zatiaľ čo vonkajšia čistá zinková fáza vykazovala veľký deformačný potenciál. Po rázovom zaťažení pri nízkej teplote sa obe IF ocele s rozdielnymi hrúbkami zinkových povlakov porušovali interkryštalickými dekohéznymi mechanizmami, zatiaľ čo nízkouhlíková oceľ vykazovala transkryštalický lom. Mechanizmy porušovania základného oceľového materiálu význačne ovplyvnili spôsob porušovania rozhrania oceľ-zinková vrstva. Zinková vrstva sa vo všetkých prípadoch porušovala komplikovanými krehkými mechanizmami.

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1. Introduction

Zinc coated steel sheets are recently very demanding in many industrial branches, in wide scale of their applications. According to their further processing and utilization the wide assortment is produced with different combination of special properties. For example in automobile industry, besides the excellent corrosive resistance, also high deformability, weldability, paintability, and stability of mechanical properties are required. The development in steelmaking technologies brought new modern steels, treated by vacuum degassing methods. The very high purity and controlled chemical composition allowed the production of steels with combination of excellent properties, e.g. for demanding deformations and deep drawings. To ensure the stability of properties and exclude the ageing, the content of carbon and nitrogen interstitial elements is depressed to extremely low values, the steels are commercially known as interstitial-free (IF) steels. IF steels being free of interstitial atoms do not overage, and so they can be treated at a rapid heating rate, which is necessarily applied for hot dip galvanizing [1]. It was shown also that such a chemical composition promotes the diffusion mobility of iron atoms, and in case of galvanizing, the intensity of intermetallic phases formation on steel-zinc coating interface significantly increases. The detailed study of the phenomenon showed that the grain boundaries enable even faster iron atoms diffusion to the steel surface and the local increase of intermetallic phase growth was documented in their vicinity. The addition of phosphorus to IF steels with the aim to increase the strength of material resulted also in the retarding effect of phosphorus on formation and growth of iron-zinc intermetallic phases [2]. Such steels became sensitive to the intergranular fracture at low temperatures or at high rates of deformation [3], due to the ultrathin phosphorous layers on the ferritic grain boundaries. When such materials are selected for industrial use, their characteristics should be considered in detail for proper utilization.

The formation of intermetallic phases in expense of pure zinc on the galvanized steel sheets in some cases can be advantageous, they improve the weldability, paintability and cosmetic corrosion resistance [4]. On the other hand, intermetallic phases may significantly impair the deformability due to their brittleness and powdering. The alloyed coating can fracture during deformation process such as stamping and deep drawing, resulting in the exfoliation of the coating [5]. Some producers of galvanized sheet materials involve the annealing process immediately after hot dip galvanizing (so called galvannealing), which allows the control of intermetallic layers formation for different and very specific use.

The paper deals with selected galvanized steel sheet materials heavily deformed at room temperature and fractured at low temperatures with the aim to describe and explain the deformation and fracture micromechanisms of the steel substrate--intermetallic phases-pure zinc phase system.

2. Materials and experiments

Three types of industrially produced steels were used for experiments, which involved the 0 deg bend test and low temperature impact loading and fracturing. The data about the sheet specifications and their geometrical characteristics are in Table 1, the chemical composition is listed in Table 2. Two IF steels marked IF1 and IF2 are interstitial-free steels with addition of titanium and the AK steel is a low carbon Al killed steel. IF1 steel was manufactured for current utilization in various branches of industry meanwhile IF2 and AK steels were produced predominantly for demanding automobile applications. Metallographic analyses were used for investigation of characteristics of present intermetallic phases and for measurements of coating thicknesses. Scanning electron microscopy equipped with EDX microanalytical unit was used for detailed observation, analyses and identification of individual intermetallic phases.

Table 1. Coated sheet thicknesses of used steels and their applications

	Thickness of the sheet [mm]	Thickness of the coating [μm]	Application
IF1	0.98	18.5	consumer industry
IF2	0.65	8.4	automobile industry
AK	0.96	13.1	automobile industry

Table 2. Chemical composition of used steels

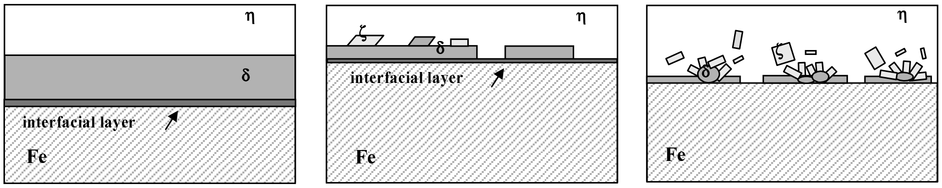
	Chemical composition [%]							
	C	Mn	S	P	N	Si	Al	Ti
IF1	0.005	0.18	0.010	0.007	0.004	0.02	0.053	0.090
IF2	0.002	0.14	0.004	0.007	0.003	–	0.049	0.090
AK	0.04	0.17	0.011	0.007	0.005	0.01	0.055	–

The 0 deg bending test was carried out at room temperature and samples for detailed observation were prepared as cross-sections allowing to observe the iron zinc coating interface behavior on both compression and strain sides of bend loading.

The impact loading and fracturing were carried out after the samples cooling down in liquid nitrogen. SEM investigations were used for fracture micromechanisms study with semiquantitative measurements of fractographic features along the interface fracture line.

3. Results and discussion

The zinc coating on the IF1 interstitial-free steel was 18.5 μm thick and consisted of a continuous Γ phase intermetallic layer, well developed compact δ phase layer, which formed about half of the entire coating, and upper η zinc phase layer. The coating on the IF2 steel was thinner, 8.4 μm thick, and was formed by a thin noncontinuous layer of Γ phase, covered by a noncontinuous layer of δ phase with scattered crystals of ζ phase in the upper η zinc phase layer. Aluminum killed low carbon steel was covered by a noncontinuous δ phase layer with the clusters of differently oriented crystals of ζ phase in the upper η zinc phase. The Γ phase on the steel zinc layer interface was not observed in this material. The individual phases and layers for investigated steels are schematically drawn in Fig. 1.



a) IF1 b) IF2 c) AK

Fig. 1. Schematic figure of composition and morphology of layers for individual types of materials a) IF1, b) IF2 and c) AK.

IF1 galvanized steel sheet on the internal side of bended sample, i.e. in the locations with maximal compression load, showed a significant deformation of steel substrate, the surface of which was wrinkled. The steel deformation caused the brittle Γ and δ intermetallic phases transversal cracking followed by a massive mass movement – an intensive material displacement. Cracked fragments relocated each over others and were pressed into the soft zinc upper layer, forming new internal cavities and surfaces (Fig. 2). During this huge deformation under the favorable compression conditions the mutual splitting of Γ and δ intermetallic phases was observable on certain locations, longitudinal cracks along the fragmented layers of intermetallic phases are documented on Fig. 3. The upper η zinc phase layer exhibited a sufficient plasticity reserve and during the bending process it was deformed intensively but without failure; the steel surface was not revealed, remaining covered.

In IF2 and AK materials the steel substrate surface also wrinkled intensively, the intermetallic phases were not enough developed and compact to exhibit similar crackings and fragment displacements as in the previous case (Figs. 4, 5). It is

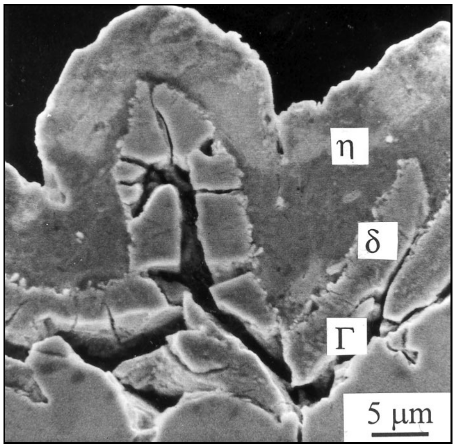


Fig. 2. Deformation and layer failure on the compression side of IF1 material.

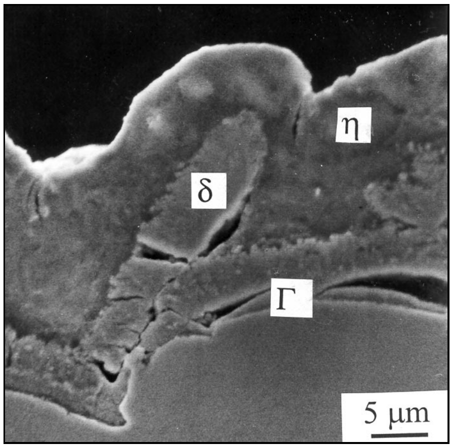


Fig. 3. Deformation and the mutual splitting of δ and Γ phases on the compression side of IF1 material.

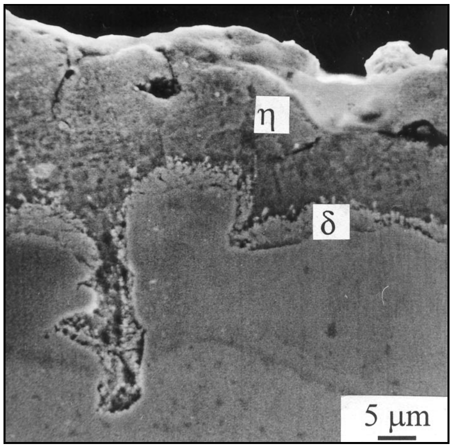


Fig. 4. Layer deformation on the compression side of IF2 material.

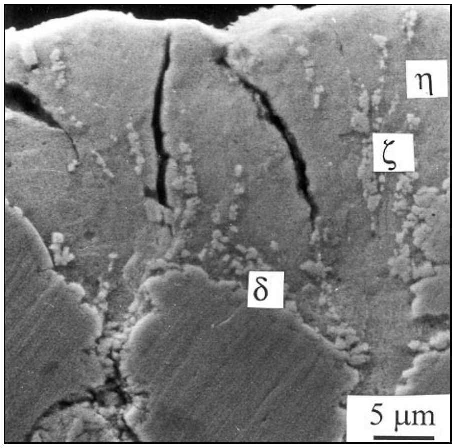


Fig. 5. Layer deformation on the compression side of AK material.

obvious, that for certain stresses and material geometry a critical thickness of intermetallic phases exists, which evokes the formation of internal cavities and new surfaces.

On the strain load side of IF1 material with well developed intermetallic phases, the joined Γ and δ phase layer failed by brittle transversal cracks, and

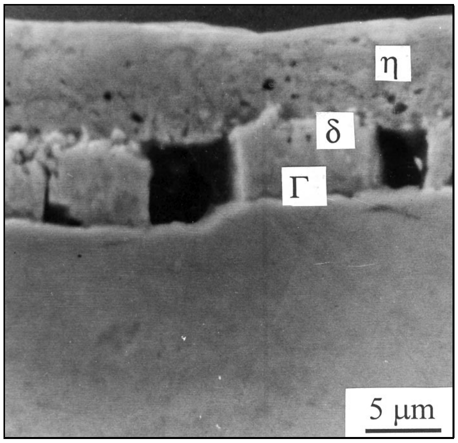


Fig. 6. Deformation and layer failure on the strain side of IF1 material.

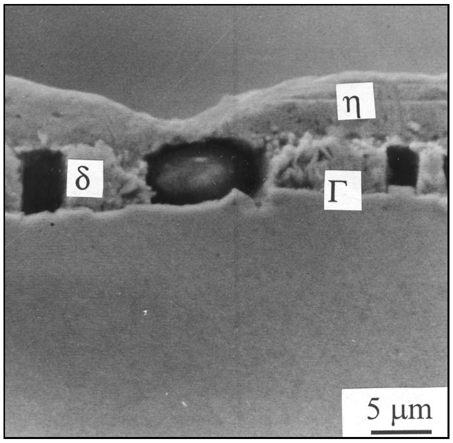


Fig. 7. Deformation, layer failure and local necking on the strain side of IF1 material.

by further deformation the cracked intermetallic fragments were separated while in particular fragments new transversal cracks were formed (Fig. 6). The internal cavities and new surfaces were also created, and they grew during the bending process. The mutual splitting of Γ and δ intermetallic phases was not observed as it was documented on the compression load side. The uppermost η zinc phase layer was deformed by strain and became thinner. At favorable locations above the large internal cavities during the final part of deformation necking occurred (Fig. 7) but the complete failure of upper zinc layer was not observed.

Thinner galvanized layers of the IF2 and AK materials were gradually deformed during the bending test and became thinner. At the locations with developed intermetallic phases IF2 steel cracked transversally at higher degrees of deformation and the formation of internal cavities and new surfaces was significantly lower than in the previous case. No locations with failure in η upper zinc phase layer were observed, Fig. 8. In the case of AK steel the continuity of zinc layer was not destroyed. In the literature, the limit of 4 % Fe content in the zinc layer is considered to be necessary to prevent the total cohesion failure of the coating [6].

The impact loading of deeply cooled samples led to the brittle fracture of all galvanized steel sheet samples. Steel sheet of IF2 material with 8.4 μm zinc layer cracked mainly by intergranular decohesion mechanism of ferrite grains (Fig. 9). About 15 to 20 % of steel fracture surface planar fraction was the transgranular brittle cleavage with typical river pattern facets. The iron zinc coating interface failed continuously by the proceeding fracture front and caused on certain part of interface splitting separation of the galvanized layer from the steel substrate. By

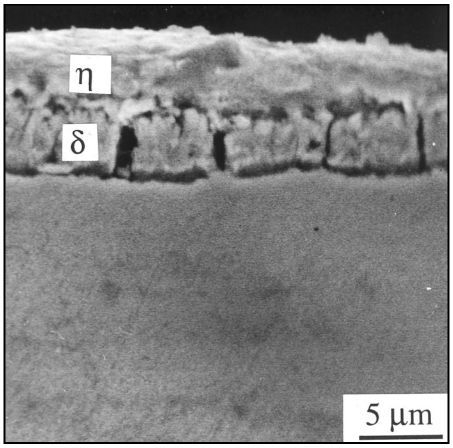


Fig. 8. Deformation and layer failure on the strain side of IF2 material.

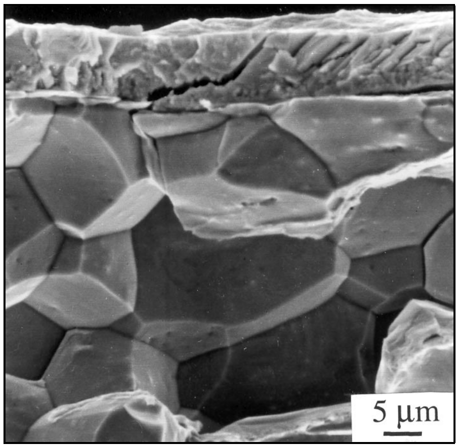


Fig. 9. Intergranular fracture of IF2 material and failure of steel-zinc coating interface.

the detailed measurement of interface line on the fracture surface, 59 % of steel-zinc coating interface failure length was combined by splitting decohesion separation of galvanized layer. At some locations even the double splitting mechanism was observable – the simultaneous decohesion of intermetallic phase from both the steel substrate and from the δ phase part of coating (Fig. 10). According to the location and the thickness, the compound detached from both sides was determined as the interfacial Γ phase. The η phase zinc layer fractured also by brittle mechanism of hexagonal crystals containing numerous twins [7], and, due to its very small thickness in the range of microns, large brittle cleavage facets could not develop. The fracture surface was intricate as the crack trajectory passed the complicated structure of the layer with numerous deflections and reinitiations. In the zinc coating the transverse cascades like lateral cracks profile were observable too (Fig. 9).

The IF1 steel was covered by coating thickness more than twice as in the previously described fractured sample. About one half of the coating close to the iron substrate was the compact layer of Γ and δ intermetallic phases formed during the galvanizing. The fracture of IF1 steel substrate is similar to IF2 material with intergranular brittle decohesion and small portion of transgranular cleavage (Fig. 11). The failure continues transversely through the interface and zinc layer and also is accompanied by decohesion of galvanized layer, which was measured on 76 % of interface fracture line length. The intermetallic δ phase and the zinc layers failed by brittle mechanism without mutual splitting. Fracture facets for δ phase and the zinc layers exhibited different looks as the mechanical properties of both phases are different, as well (Fig. 12).

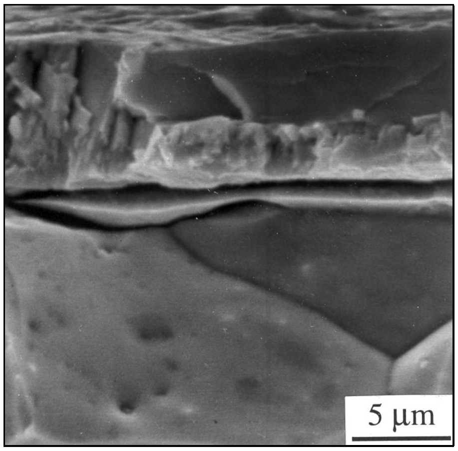


Fig. 10. Fracture surface and double splitting decohesion of IF2 material.

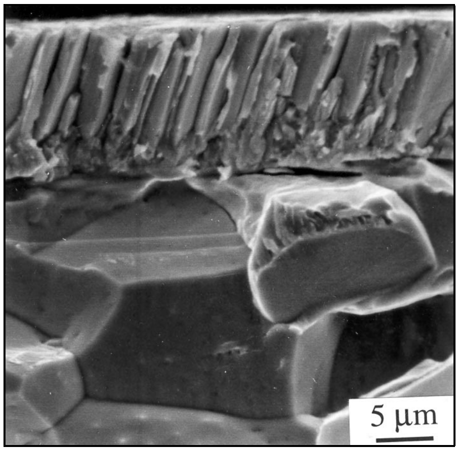


Fig. 11. Intergranular fracture of IF1 material and failure of steel-zinc coating interface.

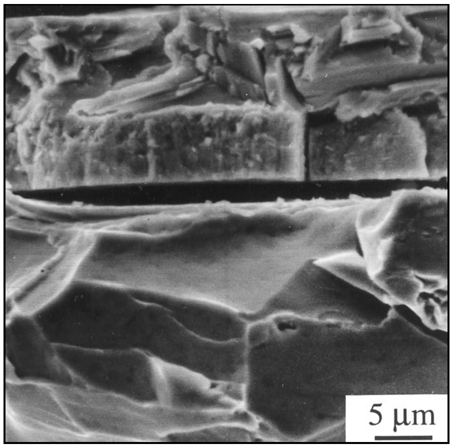


Fig. 12. Fracture surface of IF1 material, different fracture facets in the galvanized layer.

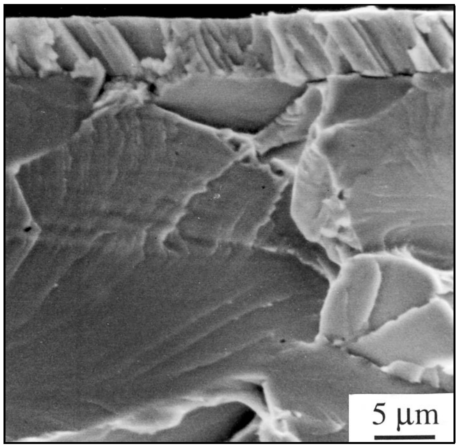


Fig. 13. Transgranular brittle cracking of AK material and failure of steel-zinc coating interface.

Low carbon aluminum killed steel was covered by 13.1 μm thick zinc layer with nonhomogeneously developed intermetallic phases consisting of clusters of differently oriented crystals of δ and ζ phase and pure zinc η phase. Steel substrate failed by typical transgranular brittle mechanism with facets of river morphology, rarely tongue-like features of local crack deflection into the twinning {112} planes were observable. The dominant mechanism of the steel-zinc interface failure was the continuous brittle fracture. The accompanying decohesion splitting of zinc layer was measured on 35 % of fractured interface length (Fig. 13). The intermetallic layer and the zinc coating failed in same way as in the previous case.

The intergranular cracking mechanisms of IF steel substrate evoked significant increase of zinc layer decohesion splitting on the steel-coating interface. During the fracturing of the steel by transgranular mechanism, as in case of classical low carbon steel, the materials geometry plays an important role at the formation of deformation stresses. In case of thin sheet the crack trajectory proceeds through the material in the shortest possible way, normal to the sheet thickness. The cleavage facets in individual grains of brittle fracture are oriented in normal direction or in certain angle close to the normal direction to the sheet thickness and hence to the steel-coating interface. Deflection of crack front to the weak interface and subsequent coating splitting is easier when the front crosses the interface under the lower angle. In case of intergranular decohesion failure the crack trajectory is defined by the geometry of the grain boundaries and not by the selective mechanism of the cleavage planes. The grain angle to the steel-coating interface is statistically random, and the lower angles of grain boundaries are significantly more frequent than the lower angles of cleavage plains in the grains. The crack front in the case of intergranular mechanism interacts with the interface under the larger angle on longer interface length and the possibility of the crack deflection causing the splitting is much probable. In case of identical failure micromechanisms of steel substrate, the coating splitting length is controlled by the thickness of the layer of zinc or intermetallic phases. The thicker layers shift the angles of the crack front and interface to greater values when the coating splitting is employed.

4. Conclusions

On the basis of the described investigations, the following conclusions can be formulated:

1. The deformation of the well-developed intermetallic phases caused their cracking and formation of internal cavities and new surfaces. On the compression side of galvanized sheets a huge displacement of material of intermetallic phases occurred and on the strain side a separation of cracked fragments was observed.

2. Non-continuous and not compact intermetallic phases adopted the deformation processes without remarkable formation of internal cavities.

3. The uppermost zinc layer accommodated the deformation, covered the deformed and fractured intermetallic fragments, and the steel substrate revelation was not recorded even at highest degree of bending deformation.

4. Low carbon steel fractured by transgranular mechanism and the crack front

passing the steel-zinc interface caused the coating splitting on 35 % of crack interface length.

5. IF steels fractured at low temperature by intergranular decohesion and significantly increased the splitting mechanism of zinc coating to the 76 % of interface fracture length.

6. Intergranular fracture mechanism of steel employs lower angle interactions of the crack front with the interface and the subsequent coating splitting increases if compared with the transgranular mechanism. The interactive angle is defined by the interface boundary geometry of the adjacent grains in the case of intergranular mechanism and by cleavage planes slope in the case of transgranular mechanism.

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