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Influence of different zinc coatings on laser brazing of aluminum to steel

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Abstract

Joining of aluminum to steel is a common challenge in light-weight structures. In case the steel is zinc-coated, aluminum can be joined to steel using laser processes without the use of flux. However, this is not yet fully understood.
In this paper, the influence of type and thickness of the zinc coating on the wetting behavior of molten aluminum on steel sheets was investigated in bead-on-plate laser brazing. Two hot-dip and two electro galvanized zinc coatings with thicknesses between 6 µm and 10.5 µm were analyzed. Appropriate wetting was observed for all four coatings in the experiments. The results show that the solidification time, the spreading time and the final wetting length decrease with increasing coating thickness. Aluminum seams on hot-dip galvanized steel sheets appear smoother than seams on electro galvanized steel sheets.

Keywords: dissimilar materials, zinc coating, laser brazing

1. Introduction

Joining of dissimilar material combinations has a wide range of applications for light-weight constructions e.g. aluminum-ultra-high-strength-steel joints in the automotive industry, as shown by Mori et al., 2006 and aluminum-titanium joints in the aircraft industry, as pointed out by Kocik et al, 2006. The formation of brittle intermetallic phases and the different material properties are main challenges for thermal joining processes such as welding and brazing. In special, different melting temperatures, heat conductivities or thermal expansion coefficients as well as low solubilities need special joining solutions, as Möller and Thomy, 2013

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illustrated. Therefore, it is recommendable to not melt both materials. Hence, Radscheid, 1997 identified that possible joining techniques are soldering, brazing, diffusion bonding and welding processes where only one joining partner is molten while the other remains in solid state.

The low evaporating temperature of zinc (T_V = 907 °C, Brandes and Brook, 1998) requires an evaporation of zinc to avoid seam imperfections in laser deep penetration welding, as shown by Schmidt and Kägeler, 2008. A geometric approach to realize accurate laser welding of zinc coated steel sheets in lap configuration is given by Bley et al., 2007. In contrast, zinc coatings are helpful for aluminum-steel joints because zinc enables fluxless joining of aluminum-steel joints. The positive influence of zinc as an interlayer was observed for different joining processes and with different materials and material combinations. The influence of zinc as an interlayer in diffusion bonding of aluminum was observed by Livsey und Ridley, 1991. It was assumed that the molten zinc penetrates through the aluminum oxide layer, forming a low melting liquid which is displaced by the pressure. Chen and Nakata, 2009 described the beneficial effect of zinc for joining magnesium and steel by friction stir welding in a similar manner by forming a low melting Mg-Zn eutectic which, together with the broken oxides, is driven to the side of the propagating melt pool due to the pressure.

However, in both aforementioned processes, pressure is higher than in laser beam welding and laser beam brazing. Nevertheless, Wahba and Katayama, 2012 observed the formation of a low melting eutectic which dissolves the oxide film during laser welding of magnesium-steel joints and is pushed out of the fusion zone. Agudo et al., 2007 observed zinc-rich zones at the toe of the seam in joining of aluminum to zinc coated steel with the so-called CMT (cold-metal-transfer) arc welding process. This behavior was shown by Thomy and Vollertsen, 2012 for laser-MIG hybrid welding of aluminum to zinc coated steel. It is assumed by Agudo et al., 2007, that capillary effects are the driving forces for the zinc enrichments in this area. The effect of zinc coatings on the wetting length of aluminum on steel was shown by Thomy and Vollertsen, 2011.

The wetting behavior of aluminum droplets on electro galvanized and hot-dip coated steel was investigated by Gatzen et al., 2014. The results show that the wetting length on surfaces at elevated temperature of 400 °C tends to decrease with increasing coating thickness. In addition, the wetting angle increases and the solidification time decreases with increasing coating thickness.

For industrial application, flux-free processes have a lot of advantages. Flux-free processing shortens the process chain by avoiding steps like flux application and surface drying before joining as well as flux removal after the process. Additionally, flux-free techniques enable the joining of closed geometries. In this paper, the not fully understood influence of different zinc coatings on the thermal behavior of aluminum-steel joints is investigated by varying coating type and thickness.

2. Experimental

2.1. Materials

In the experiments, low-carbon steels with different coating types and thicknesses were used. Two kinds of coating, electro galvanized (ZE) and hot-dip galvanized (Z), are investigated. The steel sheets were cut into specimens having a size of 140 mm x 30 mm. Table 1 gives an overview on the investigated material and the different coating thicknesses. AlSi12 filler wire with a diameter of 1.0 mm was applied as braze.

Table 1. Investigated zinc coatings by Gatzen et al., 2014

base material	specimen thickness [mm]	coating	mean coating thickness [µm]
DC04	0.7	ZE50/50	6.0
DC04	0.8	ZE75/75	6.0
DX56D	0.8	Z100	7.0
DX56D	0.81	Z140	10.5

2.2. Set-Up

The experiments were carried out by using a Trumpf optic containing 200 mm collimation lens and 200 mm focus lens. A Trumpf TruDisk 8002 Nd:YAG laser with 1030 nm wavelength was used having a spot diameter of 1.8 mm. Bead-on-plate brazing was carried out as depicted in figure 1. The brazing wire was leading with an angle of α = 39° to the surface and 20 l/min argon was supplied as shielding gas in order to protect the joining zone against surrounding oxygen.

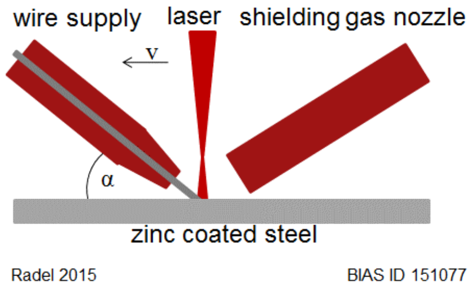


Figure 1: Experimental bead-on-plate laser brazing set-up

The temperature cycle of the molten aluminum was measured by a LumaSense Impac IGAR 12-LO two-color pyrometer operating at a frequency of 500 Hz in the range from 350 °C to 1300 °C. The pyrometer

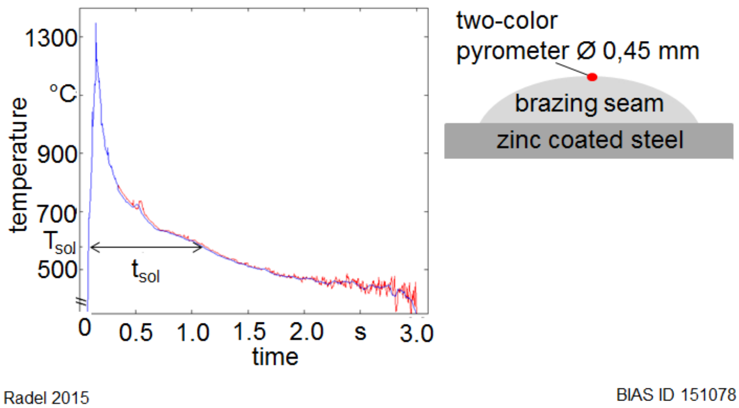
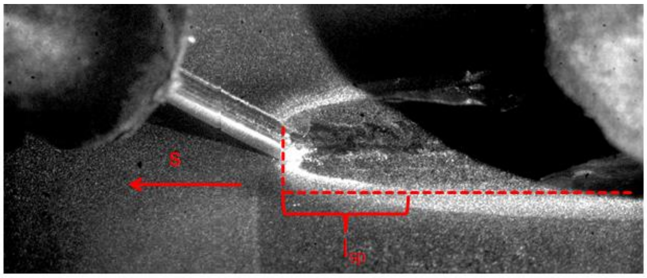


Figure 2: Principle of the solidification time determination based on pyrometer measurements (red: measured temperature cycle; blue: smoothed curve (moving average); T_{sol}: solidification temperature; t_{sol}: determined solidification time)

spot was adjusted to the middle of the seam at a stationary sheet position in order to measure the cooling cycle. The time interval where the seam temperature is higher than the solidification temperatur T_{sol} of 580 °C is determined as characteristic solidification time t_{sol}, shown exemplarily in figure 2.

The process was observed by a high-speed camera operating at 2000 Hz in order to investigate the wetting behavior. The distance in brazing direction between the front tip of the melt pool and the position where the melt pool reaches its maximum width is defined as spreading length l_{sp}, see figure 3. The characteristic spreading time t_{sp} quantifies the spreading process. It is calculated by dividing the spreading length l_{sp} by the brazing speed s.



$$t_{sp} = \frac{l_{sp}}{s}$$

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Figure 3: Determination of the spreading length and the charateristic speading time t_{SP} based on high speed camera observations (spreading length l_{sp} and brazing speed s)

3. Results

Figure 4 shows the influence of the coating thickness on the measured characteristic solidification time for a brazing speed of 3 m/min. The longest characteristic solidification time of 1.24 s was observed for the thinnest coating. The characteristic solidification times of 1.243 s and 1.239 s for 6.0 µm and 6.5 µm coating thickness are comparable. For the thickest coating, the shortest solidification time of 0.50 s was measured. The solidification time decreases with increasing coating thickness.

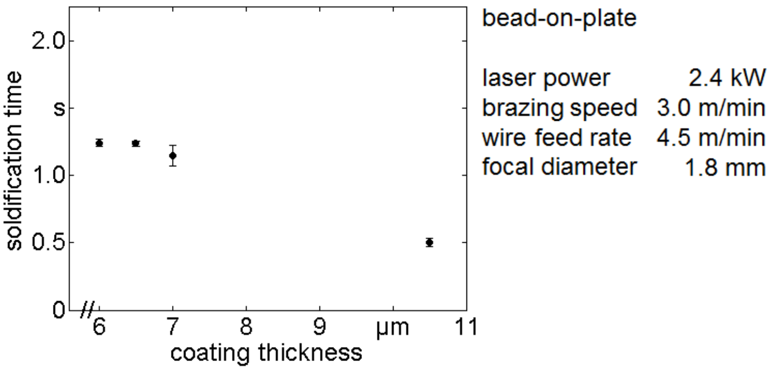

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Figure 4: Measured solidification time of a bead-on-plate brazing seams on zinc coated steel sheets

The determined spreading times for different coating thicknesses are given in figure 5 for a brazing speed of 1 m/min. The results show that the longest spreading time of 0.19 s has been measured in case of the 6 µm thick zinc coating. The average spreading time decreases with increasing coating thickness and has a value of 0.13 s at the thickest investigated coating having an average thickness of 10.5 µm.

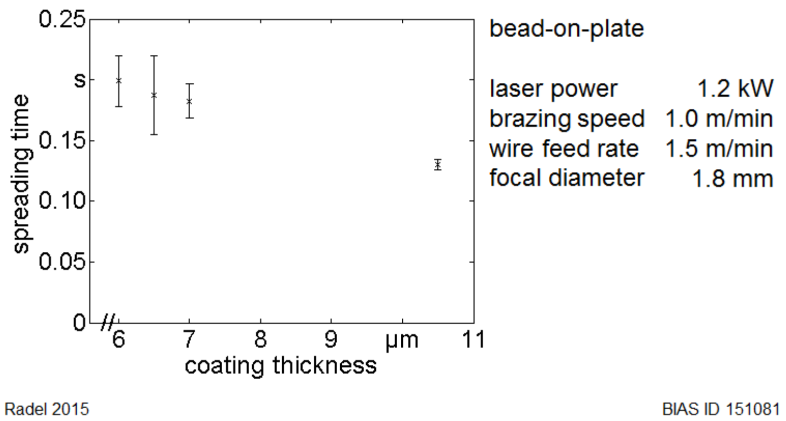

Figure 5: Measured spreading time of bead-on-plate brazing seams on zinc coated steel sheets

The seam surface appearances show a dependency on the coating type and coating thickness. Figure 6 shows typical brazing seam surfaces for the four investigated zinc coatings. In case of hot-dip galvanized sheets less fume residue are visible next to the seam compared to electro galvanized specimens. Furthermore, these seams show a smoother surface, especially in case Z140 coatings. Cross sections of the braze seams and a detailed views of the outer toe are shown in figure 7. Noticeable is the high seam height of the hot-dip coating Z140 specimens, which is caused by the shorter wetting length. All seams show typical enrichments of zinc at the toes whereas no zinc was observed in the middle of the seams. Nearly no pores due to zinc evaporation are detectable.

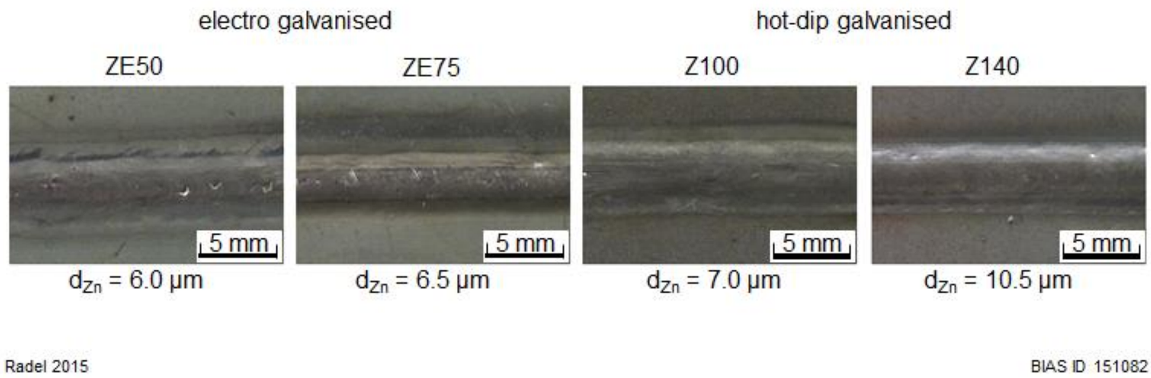

Figure 6: Resulting bead-on-plate brazing seams on sheets having different coatings

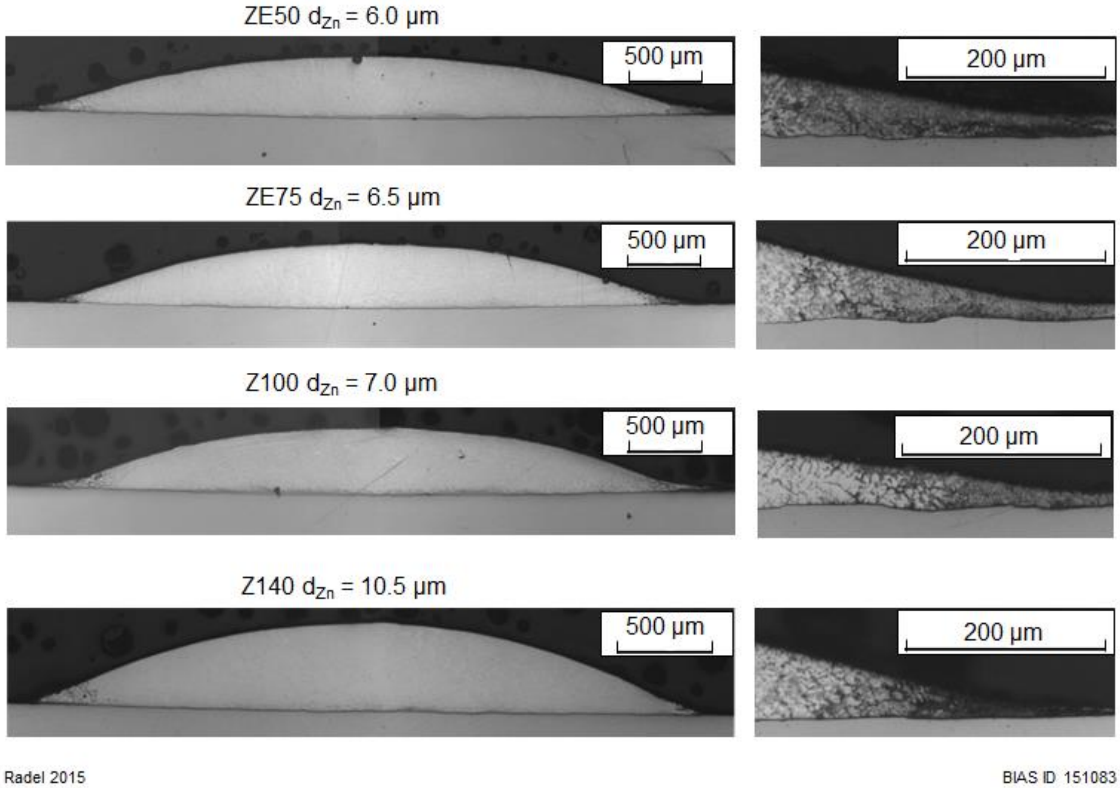

Figure 7: Seam cross sections in case of different zinc coatings (left: complete brazing seam cross section, right: zinc enrichments of the outer toe)

The resulting wetting lengths and wetting angles for a brazing speed of 3 m/min are plotted in figure 8. The values of wetting length vary between 3.6 mm and 4.5 mm. The shortest wetting length is observed in case of the thickest coating Z140 and the longest wetting length in case of the thinnest coating. The wetting angle analysis shows a contrary behavior. The smallest angle of 16° appears at the electro galvanized coating ZE50 at a coating thickness of 6 µm. The largest observed angle of 22° at hot-dip coating Z140 is 6° larger.

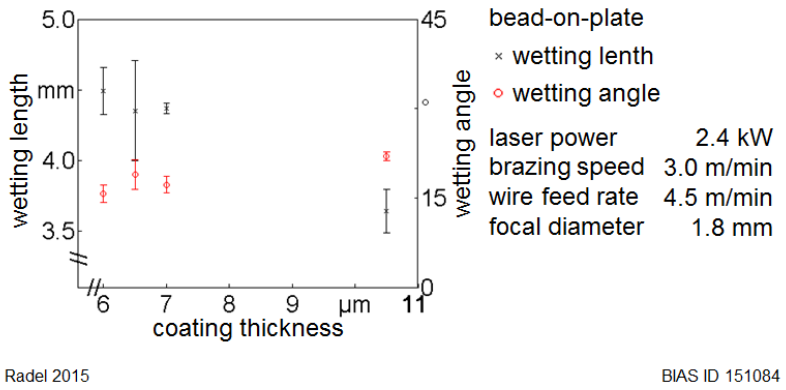

Figure 8: Measured wetting length and wetting angle values of bead-on-plate seams

4. Discussion

The experiments show that the solidification time and the spreading time are directly influenced by the coating thickness. It is assumed that the absorption of laser power primary depends on the molten aluminum due to the comparable values of spot diameter and wire diameter in the given experimental set-up. Further the spreading of the braze metal, causing the melt pool to cover the zinc coated surface from direct laser irradiation. Thus, the base material area for directly absorbed laser energy is small. Hence, the zinc coating has a minor effect on the absorption. Therefore, the decrease of solidification time with increasing coating thickness is casued by two different effects: (1) a change in the heat conduction along the interface between aluminum and base material or (2) additional heat losses, e.g. by evaporating zinc.

1. The heat conduction coefficient of zinc is higher compared to steel, but the mass of the zinc coating is probably too low to have a distinct influence on the thermal behavior of the system.
2. The cross sections show an agglomeration of zinc in the toe of the seam whereas at the aluminum-steel interface in the middle of the seam no zinc could be observed, which is in line with the observations of Gatzen et al., 2014. The amount of zinc in the toe seems to be small compared to the amount of the zinc coating material before brazing. This leads to the assumption that a high amount of zinc is evaporating during the process. These observations are in good agreement with the results of Zhou and Lin, 2014. As shown exemplarily in figure 2, the seam temperature is higher than the evaporation temperature of zinc. The enthalpy of evaporation (114.8 kJ/mol according to Graf, 2000) is removed irreversibly from the fusion zone.

Overall, it is assumed that the enthalpy of evaporation is the main influencing factor of the zinc coating to the thermal behavior. Therefore, the amount of evaporating zinc increases with increasing coating thickness and results in increasing heat losses due to evaporation. This probably causes the shorter characteristic solidification and characteristic spreading time in case of thicker coatings. As result, the wetting length decreases for thicker coatings.

5. Conclusions

The results of this study on the effect of coating type and thickness in bead-on-plate laser brazing of aluminum wire on zinc-coated steel substrates may be concluded as follows:

- The zinc coating thickness has an influence on the thermal behavior of the laser brazing process. An increasing zinc coating thickness results in a shorter characteristic spreading time and a shorter characteristic solidification time. Thus, the wetting length decreases with increasing coating thickness. Nevertheless, appropriate wetting is observed for all four coatings in the experiments.

- For laser brazing of steel-aluminum joints thin coatings should be preferred because longer wetting lengths and lower wetting angles result compared to thicker coatings.

- The enthalpy of evaporation is the main influencing factor of the zinc coating on the thermal behavior.

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References

Mori, K., Kato, T., Abe, Y., Ravshanbek, Y.:. Plastic joining of ultra high strength steel and aluminium alloy sheets by self piercing rivet. CIRP Annals-Manufacturing Technology, 55,1,2006; p. 283-286.

Kocik, R.; Vugrin, T.; Seefeld, T.: Laserstrahlschweißen im Flugzeugbau. 5. Laseranwenderforum (LAF'06), eds.: F. Vollertsen, T. Seefeld. BIAS-Verlag: p. 15-26.

Möller, F., Thomy, C.: Laser welding and brazing of dissimilar materials. In: Handbook of laser welding technologies. Ed. Katayama, S., Woodhead Publishing Cambridge (2013) p.255 – 279

Radscheit, C. R.: Laserstrahlfügen von Aluminium mit Stahl. Strahltechnik Band 4, Hrsg. Sepold, G.; Jüptner, W., BIAS Verlag Bremen (1997)

Brandes, E.A., Brook, G.B.: Smithells Metals Reference Book. Butterworth-Heinemann Oxford (1998)

Schmidt, M.; Kägeler, C.: Prozessuntersuchungen zum Laserstrahlschweißen verzinkter Karosseriebleche. 6. Laseranwenderforum (LAF'08), eds.: F. Vollertsen, T. Seefeld. BIAS-Verlag: p. 165-180.

Bley, H.; Weyand, L.; Luft, A.: An Alternative Approach for the Cost-efficient Laser Welding of Zinc-coated Sheet Metal, CIRP Annals - Manufacturing Technology, 56, 1, 2007, p. 17-20

Tzeng, Y. F.: Pulsed Nd:YAG laser seam welding of zinc-coated steel. Welding Journal 78, 7 (1999) p. 238 – 244

Livsey, D. W., Ridley, N.: Diffusion Bonding of Superplastic Aluminium Alloys Using a Transient Liquid Phase Interlayer (Zinc). In: Diffusion Bonding 2. Ed. Stephenson, D. J., Elsevier Science Publishers London and New York (1991) p. 83 – 100

Chen, Y. C., Nakata, K.: Effect of tool geometry on microstructure and mechanical properties of friction stir lap welded magnesium alloy and steel. Materials & Design 30.9 (2009): p. 3913-3919.

Wahba, M., Katayama, S.: Laser welding of AZ31B magnesium alloy to Zn-coated steel. Materials & Design 35, (2012) p. 701 – 706

Agudo, L., Eyidi, D.; Schmaranzer, C. H.; Arenholz, E.; Jank, N.; Bruckner, J.; Pyzalla, A. R.: Intermetallic Fe x Al y-phases in a steel/Alalloy fusion weld. Journal of materials science 42, 12 (2007) p. 4205 – 4214

Thomy, C.; Vollertsen, F.: Laser-MIG Hybrid Welding of Aluminium to Steel—Effect of Process Parameters on Joint Properties. Welding in the World, 2012, 56(5-6), p. 124-132.

Thomy, C.; Vollertsen, F.: Laser-Mig Hybrid Welding of aluminium to steel—A straightforward analytical model for wetting length. Welding in the World, 2011, 55(1-2), p. 58-66.

Gatzen, M., Radel, T., Thomy, C., Vollertsen, F.: Wetting behavior of eutectic Al–Si droplets on zinc coated steel substrates. Journal of Materials Processing Technology 214, 1 (2014) p. 123 – 131

Graf, G. G: Zinc. In: Ullmann's Encyclopedia of Industrial Chemistry. Ed.: Wiley-VCH, Wiley-VCH Verlag Weinheim (2000) S. 717 - 739

Zhou, Y.; Lin, Q.: Wetting of galvanized steel by Al 4043 alloys in the first cycle of CMT process. Journal of Alloys and Compounds, 2014 589, p. 307-313.