Precision Jetting of Solder Paste – A Versatile Tool for Small Volume Production

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Abstract

During the last years, jetting processes for higher viscosity materials have gained widespread interest in microelectronics manufacturing. Main reasons for this interest are high throughput/productivity of jetting, contactless material deposition, high volume precision and freely designable deposition patterns.

In previous studies [i,ii] we have demonstrated the jetability of different resin-based materials, being exemplary for unfilled adhesive, for low viscous Underfill resin and for higher viscosity Glob Top materials. The focus of our previous work was on the dosing of various encapsulants - Underfill material with low viscosity and near Newtonian behaviour and Glob Top resins, being non-Newtonian fluids due to higher matrix viscosity and higher filler content (up to 70 wt %) with resulting increased filer/filler and filler/matrix interaction. During the last years jetting has become widely used and has been applied to the dosing of much more complex materials, combining high viscosity matrix materials with odd shaped and compressive particles. Examples for these materials are conductive adhesives and also solder pastes, where the jetting system developed by Swedish company Mydata set's the current standard for solder paste jetting.

In a technological study solder paste jetting using different jetting systems has been investigated in comparison to solder paste dispensing and solder paste printing, especially material rheological behaviour and the correspondence to processability have been evaluated in detail. To illustrate the potential of solder paste jetting as a flexible and powerful tool for electronic system prototyping, a test vehicle has been designed, containing areas for SMD soldering and for process reproducibility. To determine process quality not only basic process data on droplet diameter, resulting material depot size and positioning accuracy have been evaluated, but also statistical means have been employed to determine process homogeneity and stability depending on the respective parameter set.

Summarized this paper gives an insight into solder jet process development and describes material rheology demands and limitations and thus allows the optimized use of advanced solder jetting technology for electronics assemblies.

Key words: , Contactless, Paste Jetting, Precision Material Deposition, Process Optimization, Solder

I. Introduction

Within microelectronics soldered interconnections account for the largest number of contacts formed. Most of these solder joints are formed using the SMT process flow of solder paste application, component placement and subsequent reflow. Materials used are lead free solder pastes, typically consisting of particles of SnAg3Cu0,5-alloy and an adapted flux. Melting temperature for this alloy is in the range of 217 °C to 221 °C. To dose these materials on the printed circuit boards basically three processes are available: printing, dispensing and since only a few years, jetting. For cost reasons solder paste printing is the process of choice for mass manufacturing as the productivity cannot be beaten by any other process as long as we are talking large volume processing on planar substrates. For niche markets as assembly on 3D substrates, e.g. MID [iii] or small scale production, the tool less, free programmable dosing by dispensing and jetting shows significant advantages, i.e. no need for a stencil saving time and reducing cost plus the ability to compensate for substrate topography.

To address these niche markets and additionally increase efficiency for small scale, high mix manufacturers, Mycronic AB from Sweden, formerly known as Mydata, has developed the MY500 solder paste system, that is free programmable, can handle PCBs up to 508 x 508 mm² and can apply solder paste depots with diameters down to 350 µm, allowing the assembly of smallest SMD components of 0201 form factor (see Figure 1 – right). The typical jet frequency is in the range of 800.000 Dots/h.

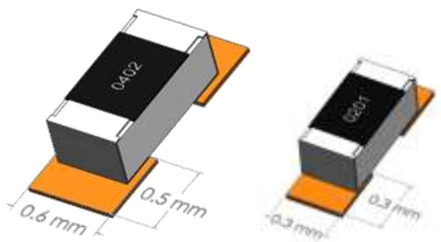

Figure 1: Typical geometries of solder pads for small SMD components; right 0402 and left 0201 form factor

Drawback of this system is that dedicated jettable solder pastes are needed; only these are supported by the machine supplier. Especially for prototyping with jetting targeting higher volume production with printing, this might be an obstacle, as the transfer of the results from for different solder pastes is not always possible.

So major motivation for the work described in this paper was to understand what makes the difference between a printable, a dispensable and a jettable solder paste by using rheological tools and to eventually find a way to apply the jetting process to dispensable and printable pastes – by not or only slightly modify the materials.

II. Processing Implications

As the solder pastes are specifically developed with processability in mind, at first the rheological implications of the different dosing processes have been analyzed.

For printing the solder paste is delivered in a large cartridge or a pot, is applied to the stencil in front of the squeegee and is "rolled", driven by the squeegee, over the stencil, filling the openings in the stencil by a geometrically defined amount of solder paste, that is then released from the stencil and remains on the substrate.

Table 1: Calculated shear rates of a solder paste through pipes of different diameters

	0.5 mg/s	1 mg/s	5 mg/s	15 mg/s
Diameter mm	Shear rate 1/s	Shear rate 1/s	Shear rate 1/s	Shear rate 1/s
0.1	688	1376	6882	20650
0.5	5.5	11	55	165
1	0.69	1.4	6.9	21
2	0.09	0.17	0.86	2.6

Typical shear rates of the printing process are in the range of 1 s^{-1} to 10 s^{-1} [iv]. For dispensing and jetting the solder paste is delivered in syringes and is typically driven out of the syringe by air pressure, further material transport is then done either by air pressure or by an extruder screw into the dispense needle or by a spring or Piezo actuated tappet that is jetting the paste out of the nozzle. Characteristic shear rates of dispensing and jetting processes strongly depend on the diameter of the nozzle as well as the flow rate of the material. Table 1 shows shear rates of a solder paste of a density of 7.4 g/cm³ through pipes of low (nozzle) and high (hose pipe) diameters. Values were calculated according to Hagen-Poiseuilles law of flow in a pipe [v]. Very high shear rates larger than 10^3 s^{-1} arise in thin nozzles at high material flow rates as applied by the jetting process. Medium shear rates of 10 s^{-1} to several 100 s^{-1} are typical for dispensing and very low shear rates less than 1 s^{-1} are found in the hose pipe from the cartridge to the valve. These shear rates will be used as the boundary conditions for rheological characterization of the pastes.

Additionally the composition of the materials will be taken into account, i.e. the size and shape of the solder particles and the amount of flux in the paste. Especially the size of the particles plays a major role – for printing and dispensing the rule of thumb is, that the smallest diameter in the flow path must be ~6 times larger than that of the largest particle [vi]. For jetting no such rule exists, but due to the high impact of the tappet on the paste, with particles too large, there is a chance of mechanical alloying particles together, leading to a clogged valve.

III. Material Analysis

Six materials were selected among the large number of solder pastes according to the technical data sheet: three of them certified as jettable (J1-J3), two dispensable (D1, D2) and two printable (P1, P2). None of the dispensable or jettable pastes are rheologically suited for jetting. All of them contain Sn/Ag/Cu-solder spheres with 96.5/3.0/0.5 wt.-% of the three metals. The content of solder and flux and characteristic diameters of the spheres as published in the data sheets are summarized in Table 2.

Table 2: Characteristics of the solder pastes investigated

Name	Solder wt.-%	Flux vol.-%	Diameter & Type µm	$\varnothing_{max}$ µm
J1	87	55	10-25 (90%) T5	30
J2	86	57	10-25 (90%) T5	30
J3	85	59	10-25 (90%) T5	30
D1	83.3	62	10-25 (90%) T5	30
D2	85	59	25-50 (80%) T3	50
P1	88.5	52	25-50 (80%) T3	50
P2	88.3	52	20-38 (80%) T4	40

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Here printing pastes contain much coarser particles of type 3 and 4, while dispensable pastes are type 3 and 5, all jettable pastes are type 5 with particles smaller 30 µm. Particle size comparison of paste depots is depicted in Figure 2. All pastes contain more than 50 vol.-% of flux to guarantee an appropriate flow behavior during the application processes. It should be noted that printable pastes contain the lowest content of flux attributed to the robustness of the printing process. On the other hand, higher lubrication content seems to be needed to reach a constant flow through channels of different sizes during dispensing and jetting.

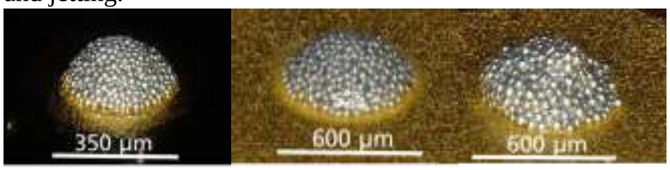

Figure 2: Depots of materials J1 (left), D1 (middle) and P1 (right).

Rheology

The aim of viscosity measurements was to look for characteristic rheological behavior and eventually differences of the three types of pastes. The shear rate dependencies of the viscosities of the selected solder pastes are plotted in Figure 3.

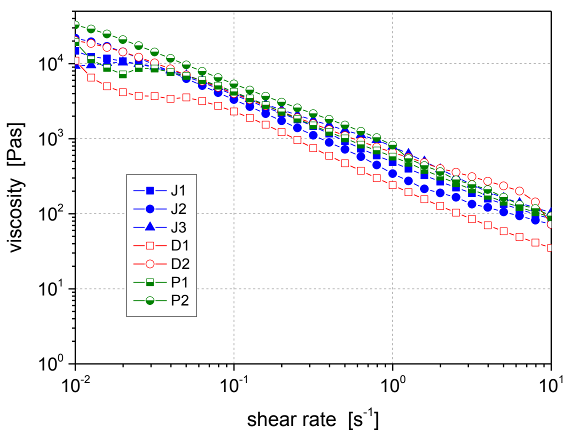

Figure 3: Shear rate dependent viscosities at 25 °C of solder pastes (see Table 2).

All pastes show a similar shear thinning behavior over the whole range of shear rates from 10^{-2} s^{-1} to 10 s^{-1}. The slopes of the curves only somewhat differ and the values of the viscosity at a fixed shear rate lie in the range of half a magnitude.

At higher shear rates above 10 s^{-1} the cohesion of the pastes breaks down and particles were driven out of the gap between the plates of the rheometer. This effect was also studied using a capillary breakup extensional rheometer, where the filament evolution after rapid extension of the pastes was measured. Differences in the filament breakup behavior of the pastes were expected, which hopefully could be related to their viscosity of flux content. However, critical breakup lengths of filaments of the pastes at certain extension rates gave no easy correlation to other characteristics of the materials.

Looking at the viscosity data in more detail, pronounced differences can be identified (see Figure 4).

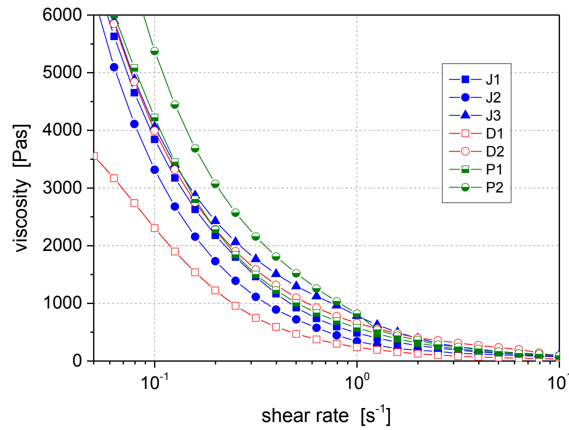

Figure 4: Semi-logarithmic plot of viscosities at 25 °C versus shear rate of solder pastes (see Table 2).

Shear thinning at higher shear rates as typical for dispensing or jetting through narrow nozzles leads to low viscosities for all materials but combined with the tendency of demixing. On the other hand, large differences become evident in the range of low shear rates, which are found in the relatively thick hose pipes. Here, jettable and dispensable pastes show much lower viscosities due to their higher amount of low-viscous flux.

A long-term measurement of the viscosity of jettable paste J3 was performed at two different temperatures to look for changes during a continuous production process.

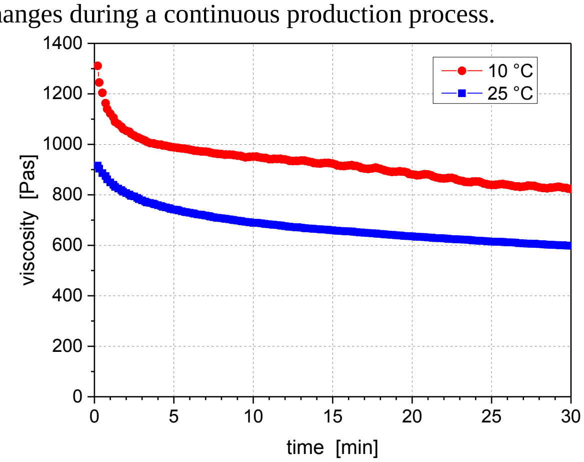

Figure 5: Viscosity of J3 at 10 °C and 25 °C at a shear rate of 1 s^{-1} over a period of 30 minutes.

It was found that after a short initial phase of shear thinning

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of the paste a slow continuous decrease of viscosity could be measured. This thixotropic effect is caused by interactions within the flux and between flux and solder and was also found and modelled by Pietrikova et al. [vii].
On the other hand, shorter moderate shearing of the pastes over about 45 minutes (up-down-up from 0.01 s^{-1} to 10 s^{-1}) has nearly no influence on the viscosity.

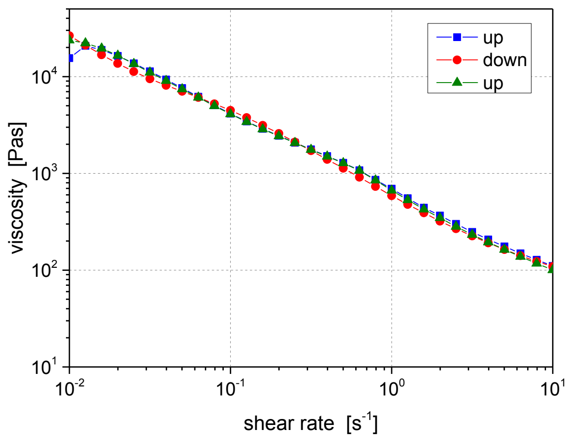

Figure 6: Shear rate dependent viscosity of J3 at 25 °C in an up-down-up cycle of varying shear rate.

In most cases, printable solder pastes can't be applied by dispensing through thin nozzles to get small solder bumps. One reason for that is the low amount of flux and therefore low lubricating properties of the solder particles. Thus, by higher flux content the dispensing and jetting behavior of a paste should be significantly enhanced. In order to test this approach, we modified the printable solder paste P1 by adding flux of the same type. Viscosity measurements of P1, its modifications and D1, the same paste but certified as dispensable have been performed to compare the flow behavior of the different materials; the results are plotted in Figure 7.

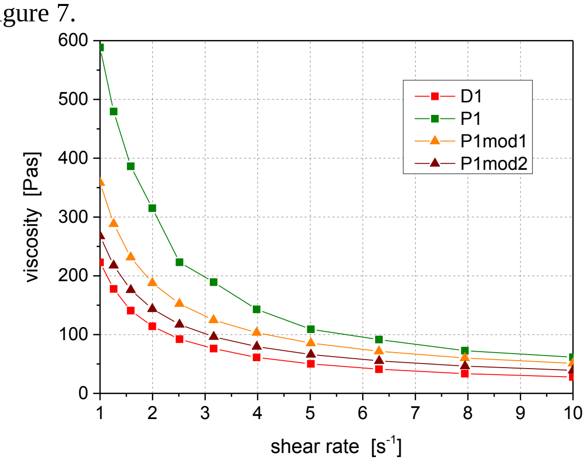

Figure 7: Viscosities of pastes P1, D1 and its modifications with flux P1mod 1 and P1mod2 at 25 °C at shear rates 1 s^{-1} to 10 s^{-1}

The printable paste P1 has the highest viscosity (52 vol.% flux) and the dispensable D1 the lowest (62 vol.-% flux) as expected. The two modifications of P1 contain 59 vol.-% flux (mod1) and 62 vol.-% flux (mod2). Although P1mod2 has the same share of flux as D1, their viscosities slightly differ. However, the dispensing behavior could be significantly changed as will be shown in the next chapter.

IV. PROCESSING EVALUATION

To evaluate the processing behaviour of the solder paste at first dispensing was tested, where special focus was put on dispensability of printable pastes. For all dispensing experiments an identical needle with an inner diameter of 510 µm [G21] was used. As expected dispensing was possible for J1 and P1, while clogging appeared for the printable paste P1, as though the maximum particle size is factor 10 smaller than needle diameter. Failure mechanism was a blocking of the needle by solder particles and a subsequent pumpout of the flux matrix. In Figure 8 with the right picture this effect can be seen – after the top depot is dispensed OK, the middle dot is already lacking solder and the last dot does only contain flux.

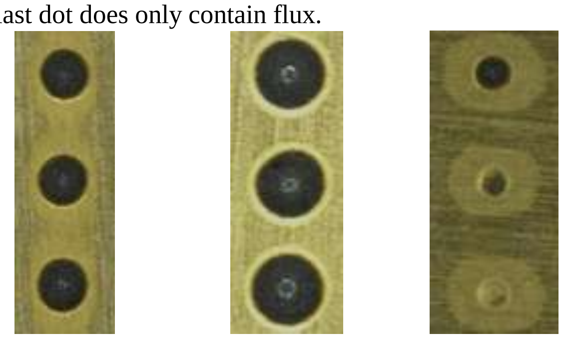

Figure 8: Dispensed depots of materials J1 (left), D1 (middle) and P1 (right).

Looking at process statistics as depicted in Figure 9 for the dispensable and jettable paste during the jetting of 5000 dots shows that dispensable paste D1 with a higher flux content yields larger solder depots with an average diameter of 620 µm and a standard deviation of ±20. Jettable paste J1 yields smaller depots with an average diameter of 520 µm and a higher standard deviation of ±40. Reason for the larger dots of paste D1 is the lower viscosity (see Figure 3) and a resulting higher flow rate for identical parameters.
The bimodal dot size distribution for paste J1 is caused by stabilizing effects during dot dispensing – for the first ~1000 dots, larger dots are dispensed (570 µm) while after process stabilization the dot size goes down to 510 µm with a standard deviation of only ±10.

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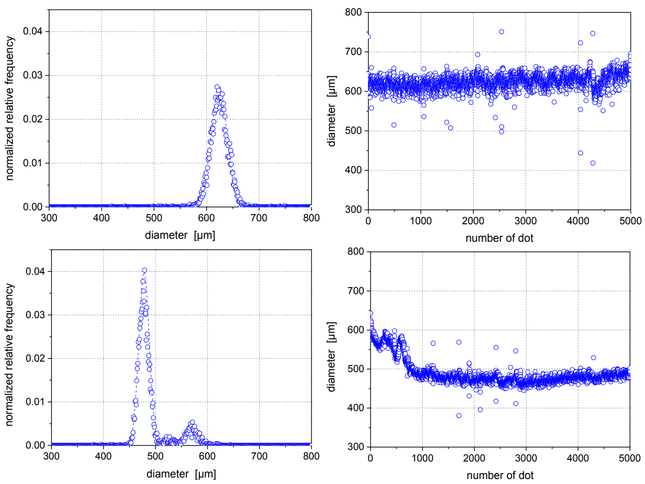

Figure 9: Distribution of diameters (left) and sequence of diameters (right) of dispensed dots of solder paste D1 (top) and J1 (bottom)

With the modified printable pastes P1mod1 and P1mod2 (see Figure 7) identical dispensing evaluation was performed – both modifications could be dispensed without clogging the needle and with a homogeneous size distribution.

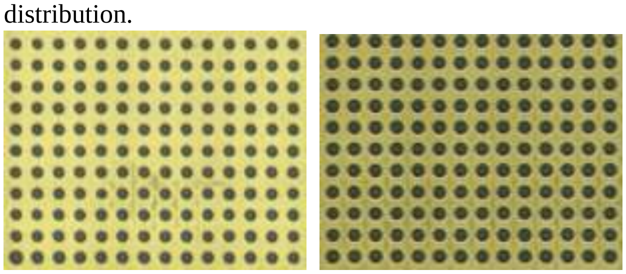

Figure 10: Dispensed depots of modified material P1: P1mod 1(left) and P1mod 2 (right)

This is a clear indication, that the flux matrix has a major influence on processability and that increasing flux content of printable pastes is a possible way to make it available for alternative processing – dispensing and possibly also jetting.

V. JET PROCESS APPLICATION

For prototyping and small scale production a Mycronic MY500 solder paste jetting system is used at Fraunhofer IZM, that has proven to be an effective tool to yield high precision solder paste depots and resulting good soldering quality without the need to design and order stencils. For this system there is one small drawback – the number of certified jettable solder pastes is limited, especially as a research institute it is of interest to have a broad choice of materials available.

To further explore the versatility of available jettable and dispensable pastes experiments have been carried using standard jetting valves, designed to dose higher viscosity pastes but not adapted to the special demands of solder pastes. One of the tested jetting systems was a MDS 3200A from Vermes Microdispensing, which is a Piezo driven “nozzle-tappet-system”. Nozzle-tappet-systems work with a movable tappet, which blocks the nozzle orifice in the closed position of the valve. To create a droplet the tappet lifts up from the nozzle to free the passage through the nozzle orifice for the fluid or paste. The fluid is pressurized in its reservoir and the pressure will force the paste into the gap between the lifted tappet and the nozzle, but not fast enough through the nozzle orifice. It is important to know that no droplet can be created with a high viscosity paste only by using the potential energy of the pressurized reservoir. The droplet will be created by moving the tappet with a high speed back into the closed position. The droplet generation will be stopped abruptly, when the tappet impacts on the nozzle.

This impact is the main reason for problems while working with solder pastes because the solder particles can be pressed together easily and so form a thin metal film which clogs the nozzle orifice.

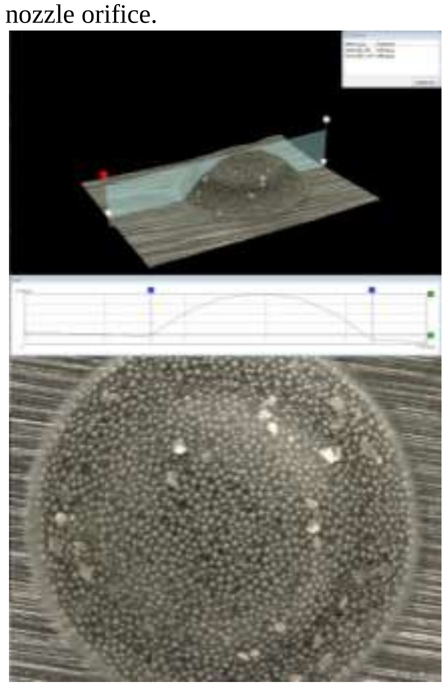

Figure 11: Analysis of a solder paste depot achieved by jetting using a standard Piezo driven valve

Two major developments in the last few years have reduced clogging of solder paste particles while the tappet impacts on the nozzle.

- The first development concerns the nozzle and the tappet shape itself. Here the reduction of the probability of hitting solder particles, without changing the workflow of the nozzle-tappet-principles, was the main task. This may be

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combined with a specialized moving curve for the clothing flank of the tappet.

- The second development concerns the solder pastes. Here the rheology adaptation from printable solder pastes to dispensable and finally to jettable ones improved the compatibility to jetting systems in general and especially to nozzle-tappet-ones. This is supported by the trend to use finer and spherical solder particles within the solder paste to allow finer pitches.

Today type 5 solder pastes as J1 can be jetted with a standard tapped-nozzle-system and not only with specialized solder paste jetting systems. A droplet diameter of less than 500 µm on the target has been achieved as depicted in Figure 11. Also visible is the effect of the tappet impact on the solder particles leading to a deformation of the solder particles – from spherical to flake like shape.

VI. CONCLUSION

With our investigation on solder paste composition, rheology and resulting processability by dispensing and jetting we targeted to better understand how to apply printable solder pastes for tool less prototyping. With solder pastes available for dispensing and jetting we could demonstrate the processability with a dispensing system. Based on these findings a printable solder paste was modified by increasing flux content to be dispensable, thus allowing prototyping by dispensing and production by printing a paste with identical metallurgy. This is essential especially for pastes that are available only in a printable formulation.

Furthermore we found solder pastes in the market adapted to jetting, that could be processed using not only specific solder paste jet valves but also by using standard nozzle-tappet-systems, so additional versatility was gained by this – resulting in the possibility to use a conventional dispensing/jetting platform for solder paste dispensing also.

Future work will focus on process development for jetting of high viscosity solder pastes, possibly also dispensable pastes for conventional SMD technology and for 3D circuitry also.

VII. ACKNOWLEDGMENT

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