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BENDABILITY OF STRIP FOR HIGH-CURRENT CONNECTORS

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Bendability of strip for high-current connectors

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Abstract

The ongoing electrification of the automobile and the rapid development of electric mobility are leading to an increased demand for high-current connectors. As the currents to be transmitted increase, so do the cross-sections of the electrical cables. This also applies to the current-carrying cross-sections of the connectors. The basic materials used for this are highly conductive copper alloys in strip form. The strip thicknesses for high-current connectors are often between 0.5 and 1.5 mm, which is referred to as medium strip thicknesses. Information on bendability is publicly available for small strip thicknesses (≤ 0.5 mm) in the form of data sheets and in internet-based material selection programs. This is not yet the case for medium strip thicknesses. Here, the semi-finished product industry has so far made individual feasibility statements. This publication describes on the one hand the special features of the bending behavior (90°) of strips of medium strip thickness and on the other hand presents bendability data for selected high-current materials in the relevant thickness range.

1. Copper base materials for connectors and their properties

When selecting a copper material for a connector, the following four properties of the base material are of particular importance:

1. electrical conductivity
2. strength, especially yield strength
3. resistance to thermal relaxation
4. the forming capacity

Figure 1 shows the position of common connector materials in the form of strip in a conductivity-strength diagram. Each alloy is indicated by a box. Their position in the diagram is characterized by their conductivity (height on the Y-axis) and a certain strength range. All alloys in their represented strength ranges have the same forming capacity, characterized by the bendability r/t = 0.5 at 90° bending perpendicular to the rolling direction and standard bending width (statement in the text box at the bottom left of the diagram). Exceptions are the high-strength alloys K57 and K58, which do not meet this condition. These alloys are mainly used in applications with miniaturized connectors or springs (mobile phones, tablets, notebooks...). Due to the very narrow bending widths and low strip thicknesses in these applications, usually no problems occur during bending.

Copper alloys shown in red boxes in the diagram have excellent resistance to thermal relaxation, i.e. to the reduction of the spring forces of a connector when service temperatures are elevated.

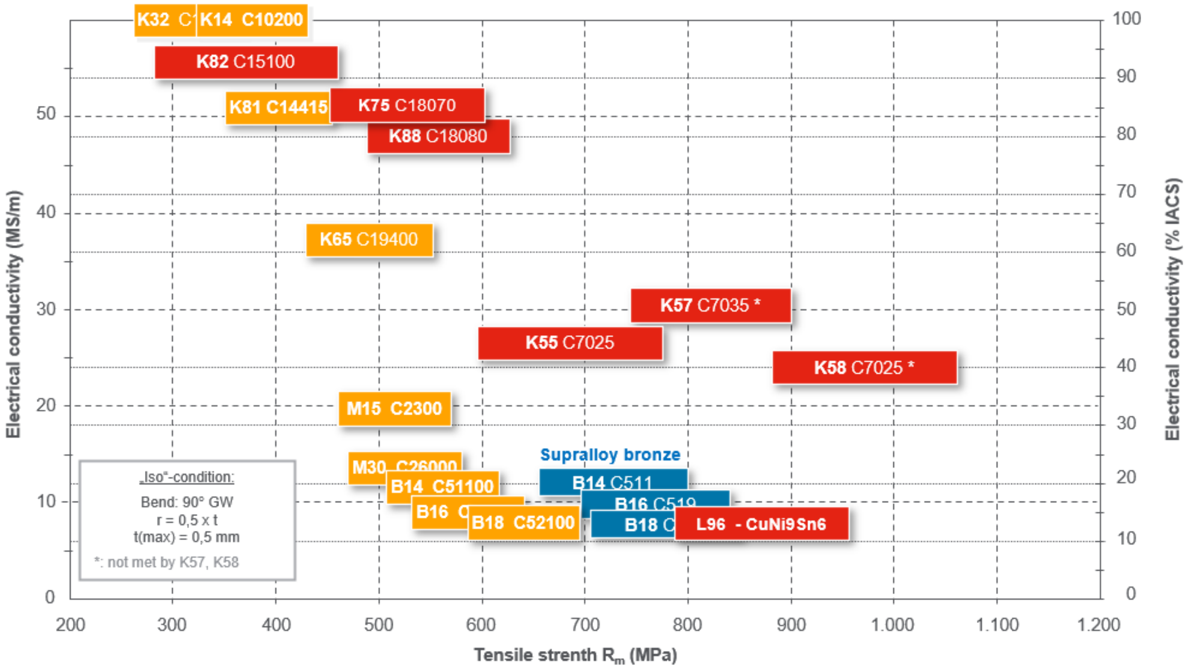


Figure 1: Conductivity-strength diagram for connector strip material.

High-current connectors have the task of transmitting high currents. To do this, they require high electrical conductivity. This is particularly necessary in order to keep the current-induced heating as low as possible. Accordingly, the materials used for high-current connectors are found in the upper left corner of the diagram. For the transmission of signals moderate electrical conductivity is sufficient, as is the case with phosphor bronzes.

At the same time, spring forces must be applied, which requires a certain strength of the material.

In many cases, the operating temperature is permanently increased by the hardly avoidable current-induced heating. Of course, even then the spring forces of the connector may only decrease slightly. The material property that ensures thermal stability of the spring force is the resistance to thermal relaxation.

In addition to the functional properties, a high forming capacity of the base material is also necessary in order to survive the forming processes during production of the connectors, such as bending, stamping or even deep drawing processes without cracks. The 90° bendability is a frequently used criterion for formability, which is tested in quality tests and documented in the certificates of conformance.

2. Copper base materials for high-current connectors

In order to limit the heating caused by the current flow, high-current connectors usually use a comparatively high cross-section as well as copper base material with a high electrical conductivity. For this purpose, strip with a thickness of 0.5 to 1.5 mm is often used. The materials discussed below and shown in Table 1 are available in this thickness range.

a) Pure copper

The two pure coppers K14 (Cu-PHC, C10300, oxygen-free) and K32 (Cu-ETP, C11000, oxygen-containing) are commonly used for non-spring components, such as thick-walled supports for thin-walled springs made of high-performance alloys. Here, the pure coppers are also subject to bending operations. Figure 2a schematically shows such a construction. In the case of particularly high requirements to the formability as well as when using fusion welding processes, the oxygen-free pure copper K14 is preferred.

b) Solid solution hardening copper alloys

K81 (CuSn0.15, C14415) is the most common highly conductive solid solution hardening alloy. By adding 0.15 % tin, higher strengths in the material and thus higher spring forces in the connector can be achieved than is possible with pure copper. The conductivity is reduced by approx. 12 % compared to pure copper. This material is often used for high-current connectors when no current-induced heating is to be expected.

c) Precipitation hardening copper alloys

K75 (CuCrSiTi, C18070) is a highly conductive and thermally stable precipitation hardened high-performance material. Its electrical conductivity is 83 % IACS. The microstructure contains precipitations which lead to high strength and thus enable high spring forces in connectors. In addition, they provide excellent resistance to thermal stress relaxation. Because of these properties connectors made of K75 can be used at elevated operating temperatures. Thick-walled constructions for high-current connectors are often made of K75. Figure 2b shows such a construction schematically.

K55 (CuNi3SiMg, C70250) is also a precipitation-hardened high-performance material and focuses on applications which require very high strength of the copper base material. The resistance to thermal relaxation is also excellent. This material is used for high-current connectors when very high spring forces are required. The electrical conductivity is usually 43 - 50 % IACS.

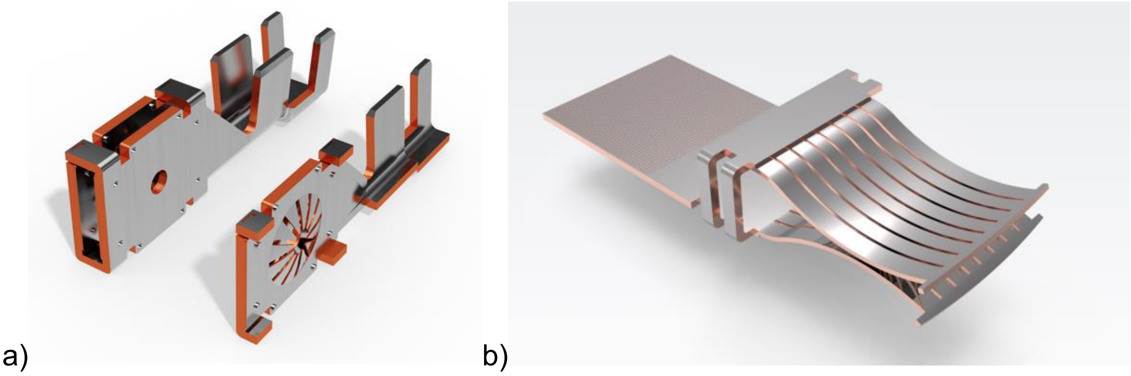


Figure 2: Schematic drawings of two different designs of high-current connectors, a) design made of two materials, a carrier made of pure copper strip with high strip thickness and a spring made of a high-performance copper material with thin strip thickness, b) thick-walled design made of a single precipitation-hardened high-performance material. Both schematic drawings represent connectors available on the market and have been kindly released for publication by the manufacturers.

Table 1: Common copper materials for high-current connectors used in strip thicknesses > 0.5 mm.

Material name	UNS-No.	Chemical composition	Type	Special properties
K14	C10300	Cu-PHC	Oxygen-free pure copper	Very high electrical conductivity, excellent formability
K32	C11000	Cu-ETP	Oxygen containing pure copper	Very high electrical conductivity
K81	C14415	CuSn0.15	Solid solution hardened	Increased strength compared to pure copper
K75	C18070	CuCrTiSi	Precipitation hardened	Clearly increased strength, excellent thermal relaxation resistance
K55	C70250	CuNi3SiMg	Precipitation hardened	Very high strength, excellent thermal relaxation resistance

3. Strip thickness ranges

With regard to the bendability of strip materials, the copper semis industry distinguishes between three strip thickness ranges:

3.1 Low strip thicknesses: t ≤ 0.5 mm

For strip thicknesses < 0.5 mm, bending data are available for all copper strip materials. The bendability is given with the smallest possible ratio r/t (bending radius / strip thickness) at which the bending edge is crack-free. This bending data is published in data sheets [1] and in the internet-based material selection programs (e.g. the Alloywizard of Wieland-Werke AG [2]). The data sheets usually present bendability at the bending angles 90° and 180° both perpendicular (good way) and parallel (bad way) to the rolling direction in a standard bend width of 15 mm, see Fig. 3. The internet-based material selection programs “Alloywizard” additionally shows the bendability at narrower widths. Narrower bending widths usually exhibit improved bendability compared to the standard width, see Fig. 4.

3.2 Medium strip thicknesses: 0.5 mm < t ≤ 1.5 mm

The bendability statements lose their validity for strip thicknesses > 0.5 mm. The local plastic strains at the outer edge of the bend increase with increasing strip thickness and cracking already starts at higher r/t values. Bendability data are not publicly available so far. Bendability statements are made individually by the manufacturers on the basis of internal feasibility considerations. Bendability data in this thickness range are particularly relevant for materials for high-current connectors. This publication is the first to publish bendability statements for strips with medium strip thicknesses.

3.3 High strip thicknesses: t > 1.5 mm

Strip thicknesses > 1.5 mm are occasionally used for connectors. However, the focus of applications of high strip thicknesses is on stamped current conductors (busbars). Such current conductors are usually connected by means of a screw connection (not by plugging), so that there are no requirements for normal forces. Pure copper is the preferred material. Requirements for bending are low and are usually fulfilled.

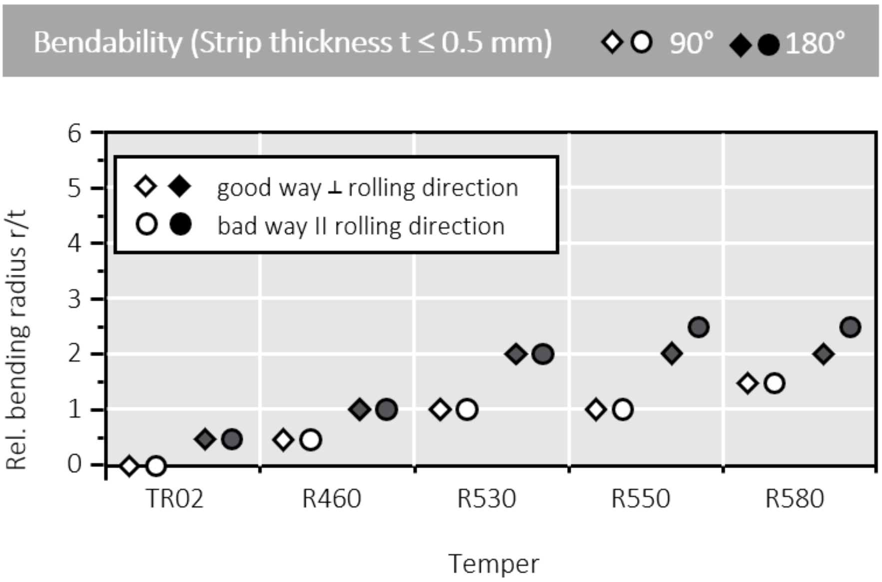


Figure 3: bendability chart on a data sheet of the strip material K75 (Cu-CrSiTi, C18070), valid for strip thicknesses ≤ 0.5 mm [1].

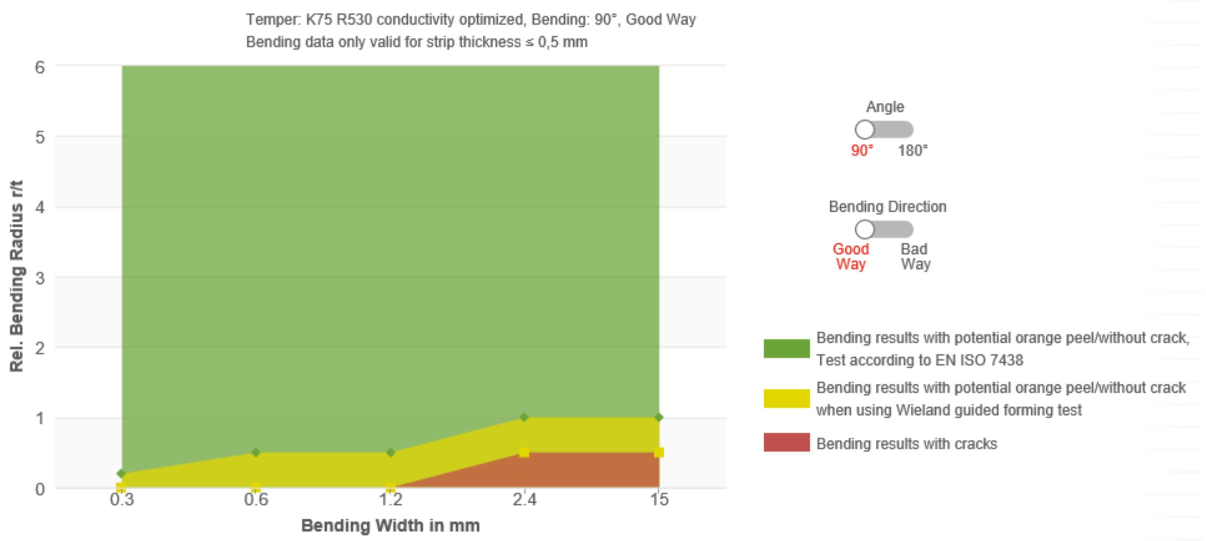


Figure 4: Bendability chart in the program "Alloywizard" of the strip material K75 (CuCrSiTi, C18070), valid for strip thicknesses ≤ 0.5 mm. Bending data are shown for bending specimens with standard width (15 mm) and smaller bending widths [2].

4. Bending test and evaluation

4.1 Bending test according to DIN EN ISO 7438

Bending tests on copper strip materials are usually carried out according to DIN EN ISO 7438 [3]. Widely used is the method “bending into the V-die”, described in the standard as a method with a "bending device with a V-shaped die and a former". Figure 5 shows a schematic of this test method. A bending test is considered successfully passed if the strip survives the test with a given (specified) bending radius without cracking. The standard defines the bending radius “r” as the inner radius of the bent specimen after bending. For bending tests on strip with thickness t ≤ 0.5 mm, this procedure is usually works without problems and the bending radius r corresponds to the radius at the punch of the bending tool. The length of the bending test specimen is 25 mm, the commonly used width of the test specimen is 15 mm.

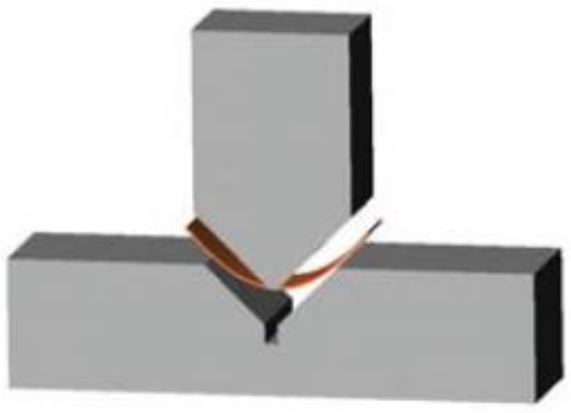


Figure 5: Bending test by means of " bending device with a V-shaped die and a former", schematic drawing.

4.2 Special features during bending test of thicker and higher-strength strip

With increasing strip thickness and higher strength of the base material, there is a risk of the occurrence of a mechanical instability during the bending process. The bending specimen buckles during the test and the actual radius r_{actual} on the inner side of the bending specimen is much smaller than the expected bending radius. The specified bending radius r is sometimes significantly undercut. The bending test is therefore "sharper" than intended. The plastic strain at the outer bending edge is higher than intended. As a consequence, cracks appear at the outer bending edge and the test unexpectedly fails. Figure 6a shows such a case. Affected are strips with thicknesses t > 0.5 mm (sometimes even below) and with a strength above approx. 500 MPa.

The buckling can be avoided by changing the forming path. An intermediate step is introduced in the form of a pre-bend with a larger radius R_{PB}. The use of a bending tool with a pre-bending radius R_{PB} of up to 10 x t has proven to be effective here. The second step is the final bending with the specified radius r, which is now safely achieved in the inner bending edge. The bending test is then passed successfully as expected, no cracks appear, see Fig. 6b. In the beginning, this procedure was discussed with customers if necessary. In the meantime, it has become state of the art and is always used when the risk of buckling is present.

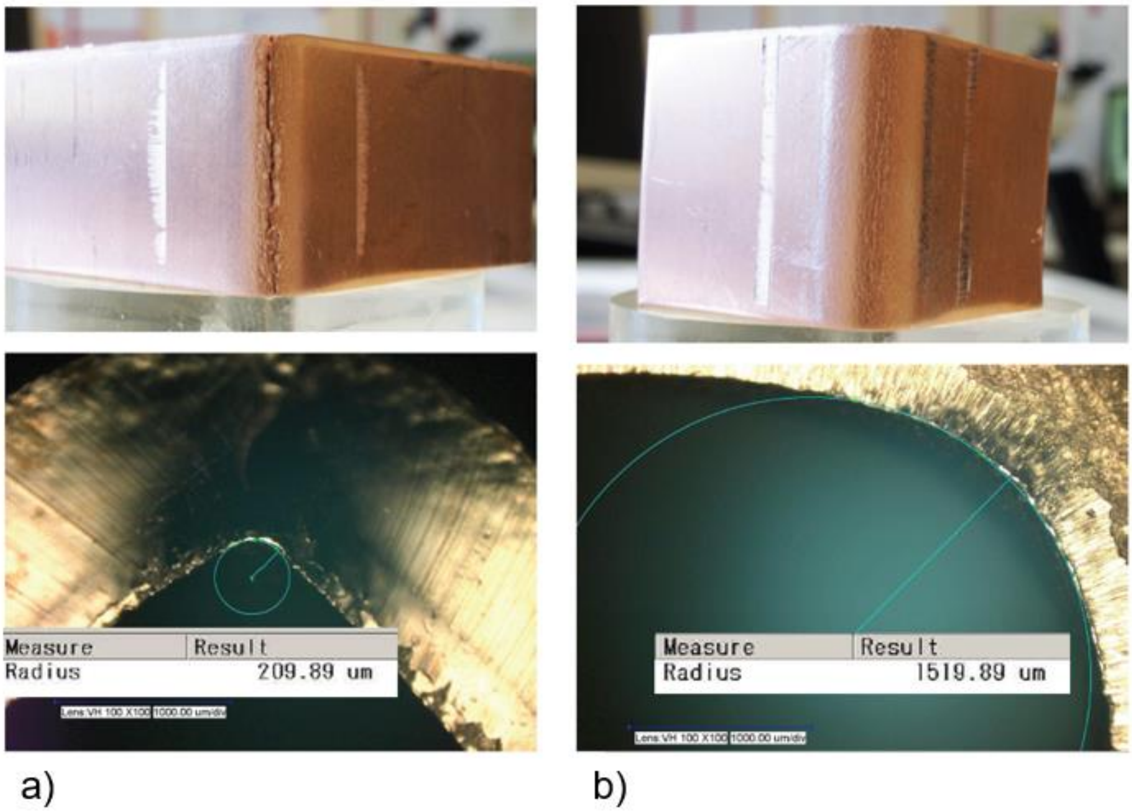
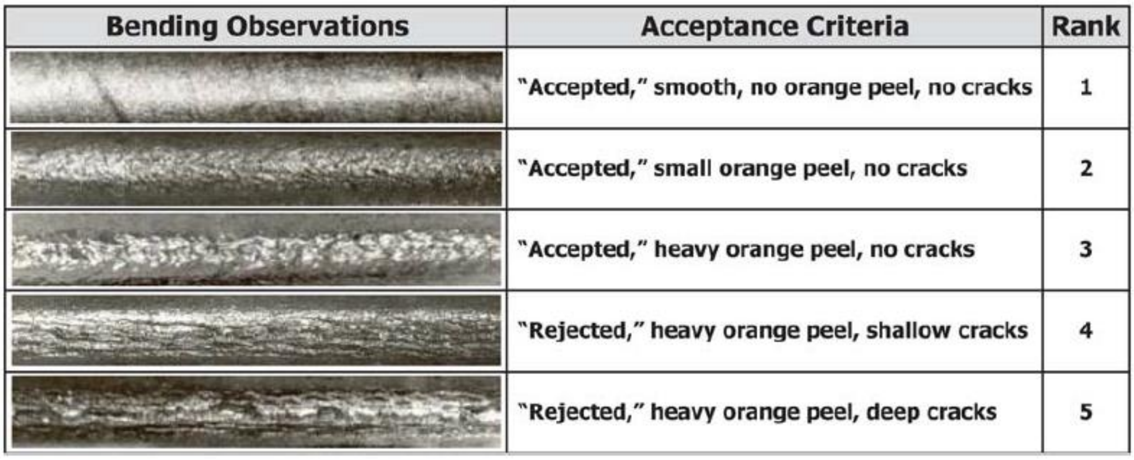


Figure 6: Bending test on strip made of K55 (CuNi3SiMg, C7025), condition R650, strip thickness 1.5 mm. Bending requirement is 90° GW with r = 1.5 mm.
a) Buckling during bending with tool radius r = 1.5 mm leads to an actual radius r_{actual} = 0.2 mm at the inner edge and to cracks at the outer bending edge. Test is failed.
b) Two-step bending procedure with pre-bending and final bending, where the pre-bending radius R_{PB} = 3.0 mm and the final bending radius r = 1.5 mm. Result: Specified radius r = 1.5 mm at the inner edge of the bending test is achieved and the test is successfully passed.

4.3 Evaluation of bending edge

The evaluation of the bending edge is usually done by visual inspection using an optical microscope with 25-fold magnification and an evaluation scale similar to that proposed in ASTM B820 [4], see Fig. 7. For the bendability data generated in this study, the following extended inspection and evaluation methodology was used:

- Evaluation of the bending edge under a microscope with 25-fold magnification.
- Make a transverse section through the bending edge and evaluate it under the microscope at min. 100-fold magnification.
- If no cracks are found in both tests, the bending test is considered sucessfully passed.
- To determine the minimum bending radius which is applicable without cracks, the bending radius r is successively reduced.
- In case of buckling: repeat the bending test with a pre-bend, where $R_{PB} > r$, and the final bend with the final bend radius r.



Bending Observations	Acceptance Criteria	Rank
	"Accepted," smooth, no orange peel, no cracks	1
	"Accepted," small orange peel, no cracks	2
	"Accepted," heavy orange peel, no cracks	3
	"Rejected," heavy orange peel, shallow cracks	4
	"Rejected," heavy orange peel, deep cracks	5

Figure 7: Evaluation score from ASTM B820 [4] for bending edges after a bending test. Grades (from top to bottom): 1 = passed, smooth surface, no orange peel, no cracks; 2 = passed, light orange peel, no cracks; 3 = passed, heavy orange peel, no cracks; 4 = failed, heavy orange peel, light cracks; 5 = failed, heavy orange peel, heavy cracks.

5. Determination of bending data in the medium strip thickness range

5.1. Investigated high-current materials, tempers and strip thicknesses

The aim of the present study was to provide the public with bending data of copper strip materials in the medium strip thickness range 0.5 mm < t ≤ 1.5 mm. These bending data are particularly relevant for copper materials used for high-current connectors. The subject of the investigation were the materials presented in chapter 2 in the following strip thicknesses and tempers, see Table 2.

Table 2: High-current materials used, tempers and strip thicknesses

Material	Tempers	Strip thicknesses
K14, Cu-PHC, C10300	R290, R360	Each temper 0.8 and 1.2 mm
K32, Cu-ETP, C11000	R290, R360	Each temper 0.8 and 1.2 mm
K81, CuSn0.15, C14415	R360, R420	Each temper 0.8 and 1.2 mm
K75, CuCrSiTi, C18070	R460, R530	Each temper 0.8 and 1.2 mm
K55, CuNi3SiMg, C70250	R620, R650	R620: 0.8 and 1.2 mm, R650: 0.8 mm

For even higher tempers of the material K55 and for higher thicknesses than 1.2 mm of all materials, individual feasibility statements on bendability are still necessary.

5.2 Bending tests carried out

Bending tests were carried out with a bending angle of 90° in the directions perpendicular (good way, GW) and parallel (bad way, BW) to the rolling direction. In addition to the standard bending width of 15 mm, reduced bending widths of twice, four times and eight times the strip thickness were used. Table 3 lists the widths used. In order to exclude side effects, such as a rough punched edge, the bending samples were produced by means of water jet cutting.

Table 3: Bending widths used (t = strip thickness, w = bending width)

Strip thickness t	w = 2 x t **	w = 4 x t	w = 8 x t	Standard width
0.8 mm	1.6 mm	3.2 mm	6.4 mm	15 mm
1.2 mm	2.4 mm	4.8 mm	9.6 mm	15 mm

**: The bending width 2 x t is not subject of the quality test after production.

6. Results

Tables 4 and 5 show the results of the bending tests in the form of smallest possible r/t values of successfully passed bending test without cracks for the standard bending width and the reduced bending widths. Figure 8 shows the results for the standard bending width in a graph similar to those displayed in the material data sheets. Changes in bendability with increasing strip thickness (t ≤ 0.5 mm, t = 0.8 mm and t = 1.2 mm) are easily recognizable in this diagram.

Table 4: Smallest possible r/t - values for 90° bends at a strip thickness of 0.8 mm

Material	Temper	Direction	Width 2 x t (1.6 mm)	Width 4 x t (3.2 mm)	Width 8 x t (6.4 mm)	Standard width 15 mm
K14	R290	GW	0	0	0	0
		BW	0	0	0	0
	R360	GW	0	0	0	0
		BW	0	0	0	0
K32	R290	GW	0	0	0	0
		BW	0	0	0.5	1.0
	R360	GW	0	0.25	0.75	1.0
		BW	0	0.5	1.5	2.0
K81	R360	GW	0	0	0	0
		BW	0	0	0	0
	R420	GW	0.5	1.0	1.0	1.0
		BW	0	0.75	1.0	1.0
K75	R460	GW	0.5	0.5	0.5	0.5
		BW	0.5	0.5	0.5	0.5
	R530	GW	0.75	1.0	1.0	1.0
		BW	0.75	1.0	1.0	1.0
K55	R620	GW	0.5	0.75	1.0	1.5
		BW	0	0.25	0.25	0.5
	R650	GW	0.5	0.75	1.25	1.5
		BW	0	0.25	0.25	0.5

Tabelle 5: Smallest possible r/t - values for 90° bends at a strip thickness of 1.2 mm

Material	Temper	Direction	Width 2 x t (2.4 mm)	Width 4 x t (4.8 mm)	Width 8 x t (9.6 mm)	Standard width 15 mm
K14	R290	GW	0	0	0	0
		BW	0	0	0	0
	R360	GW	0	0	0	0
		BW	0	0.5	0.5	0.5
K32	R290	GW	0	0.5	0.5	0.5
		BW	0	1.0	1.0	1.0
	R360	GW	1.0	1.0	1.0	1.0
		BW	2.0	2.0	2.0	2.0
K81	R360	GW	0	0	0	0.0
		BW	0	0.5	0.5	0.5
	R420	GW	0.5	1.0	1.0	1.0
		BW	0.25	1.5	1.5	1.5
K75	R460	GW	0.5	0.5	0.5	0.5
		BW	0.5	0.5	1.0	1.0
	R530	GW	1.25	1.25	1.25	1.5
		BW	0.75	1.0	1.75	2.0
K55	R620	GW	0.5	0.75	1.0	1.5
		BW	0.25	0.5	0.75	0.75

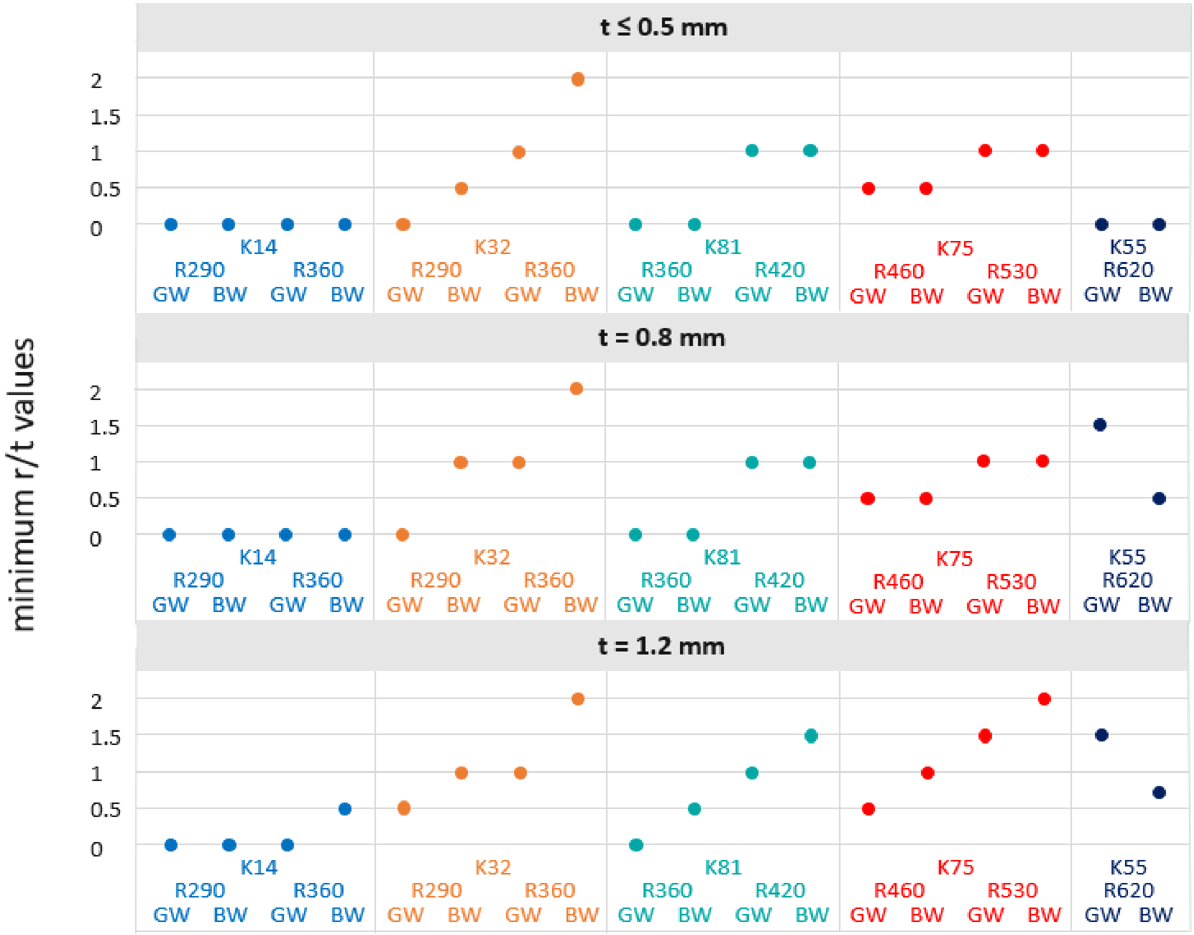


Figure 8: Bending properties of strip for high-current connectors in the form of the minimum r/t values that can be achieved without cracking, shown as a function of the various high-current materials, their tempers and the bending direction. Bending width: standard width 15 mm.

7. Concluding remark

The public availability of bendability data is an important aid for designers and design engineers in the electronics industry, especially for the design of connectors. The bendability data of strip for high-current connectors in the medium strip thickness range between 0.5 and 1.5 mm presented here are based on systematic internal studies in a statistically relevant scope. They replace the individual feasibility considerations that have been necessary up to now.

Literature

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