VeraCAD Technology Chat	
Title:	**Calibration sequence – General rules – Best practice – Golden rule no. 2**
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This article explains:

- Basic considerations for reducing cross-sections
- Suitability of calibration sequences
- Selection of a calibration sequence depending on the cross-sectional reduction

The article gives an insight into the technological context of calibration sequences and is intended to help, finding suitable calibration sequences for the design of roller parts.

1. Basic considerations for reducing cross-sections

Reducer rolling generally serves to produce pre-profiled bars, which then come as close as possible to a desired mass distribution. Therefore, reducer rolling is particularly well suited to produce long parts with harmonious transitions. These rolled parts are mostly preforms and only in rare cases are finished parts with small tolerances.
During reducer rolling three things will happen simultaneously in one cross-section:

- The cross-sectional area is reduced - this is desired.
- The rolled part gets longer – this is a consequence of volume consistency.
- The cross-section is becoming wider (spreading) – we accept this.

The amount of possible reduction is between 0 and 40% (for steel) or 0 to 45% (for aluminium). Undoubtedly, the reduction rate has the greatest influence on the spreading. By spreading we mean the oval-shaped deformation of the cross-section during reduction. In numerical terms, the spreading can be written as a ratio of width to height.

$$\beta = \frac{B}{H}$$

With a high reduction (40%), long deformed sections and large roll diameters, the spreading can reach values of ß > 3. If the "spreading pass" (usually an oval) is not designed to be wide enough, the material can flow into the flash gap and a “wing” is produced. In order to avoid this common rolling defect, the cross-sectional reduction must be smaller. For this purpose, the reduction is divided into steps, resulting in several rolling passes.
For the individual cross-section, this means that it runs through a calibration sequence up to the finished product shape, which begins with the shape of the raw material and ends with the final shape of the finished product. Both cross-sectional shapes and their dimensions are determined at the beginning of the design and should not be changed later. This already determines the necessary total reduction at start of construction. The required number of roll passes is also predetermined. The following table gives an indication of the total reduction rate that can be achieved depending on the number of passes. In principle, more than 5 passes are possible. The considerations made here cover the main application field of reducer rolling.

Passes	1	2	3	4	5
Steel	40 %	60 %	75 %	83 %	90 %
Aluminium	45 %	65 %	80 %	87 %	93 %

Table 1: Achievable total reduction depending on the number of rolling passes

Calibration sequences that run through a series of “spreading” and “non-spreading” cross-sectional shapes have proven to be practical (Figure 1).

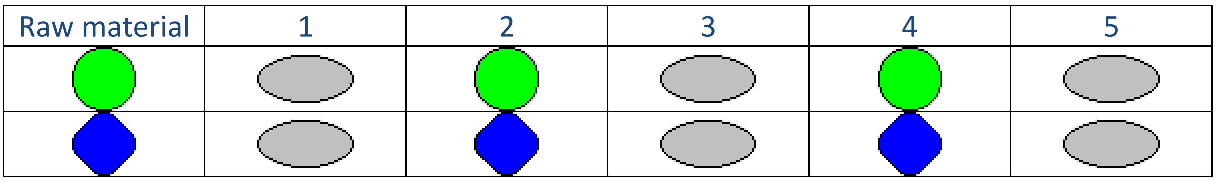


Figure 1: Change between “spreading” and “non spreading” calibres

With the calibration sequence shown above, the problem arises for an odd number of roll passes (1,3,5 passes) that there is an oval shape in the finished product. In a few cases, this is favourable for the further forging process. If the finished product is to be a circle or square, this usually leads to an even number of passes.

2. Suitability of calibration sequences

Before the actual selection of a calibration sequence is made, it is necessary to clarify what a calibration sequence is particularly suitable for. The main characteristic is the minimum and maximum reduction.

Calibration sequences for low or no reduction (0% to 5%)

If the reduction rate is 0% or close to 0%, the cross-section type cannot be changed. Without reduction, a circle remains a circle and a square a square. Even with a small reduction (up to 5%) it is possible to realize the deformation with the same cross-section type. The necessary space for spreading on both sides is achieved by applying draft angles or a larger flash corner radius.

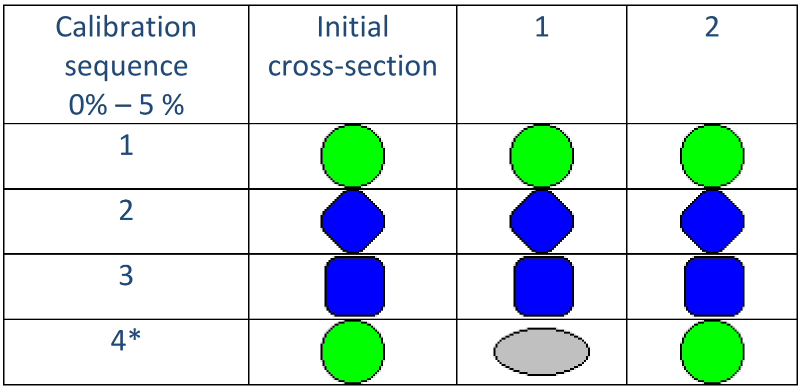


Table 2: Calibration sequence 0% – 5%

*A special feature is the calibration sequence 4, circle-oval-circle. Here the oval is almost a circle. The width is only a little larger than the height. It is a so called "thick oval". Options to make more space on the side are not necessary here. This calibration sequence can therefore be used very universally.

Calibration sequence for medium reduction (5% to 12%)

If the reduction goes beyond 12%, it is no longer possible to create enough space on both sides simply by use of a draft angle. There is a clear deformation of the cross section and thus the spreading. This is only possible with "spreading cross-section types". Nevertheless, the target cross-section still is similar to the previous cross-section shape. Table 3 shows the possible calibration sequences.

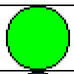
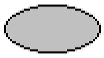
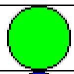
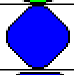
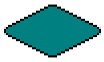
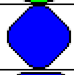
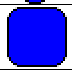
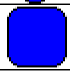
Calibration sequence 5% – 12%	Initial cross-section	1	2
1			
2			
3			

Table 3: Calibration sequence 5% – 12%

Since the reduction still is small (< 12%), the initial cross-section and the deformed cross-section (pass 1) are similar. The oval in pass 1 is a "thick oval", with a small reduction the rhombus behind the square has side bevels close to 45°, the lying rectangle becomes wider the more reduction it gets and with reduction of 0% it still remains a square.

Calibration sequence for high reduction (12% to 40% steel, 45% aluminium)

With higher reduction rates, the cross-section spreads more. This can be achieved particularly well with an oval or a lens. Both the oval and the lens can be easily reshaped into the corresponding “non-spreading” cross-sections. The difference between oval and lens is rather small. In addition to an apex radius, the oval also has 2 smaller side radii, while the lens has only a continuous apex radius.

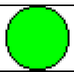
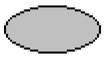
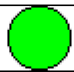
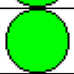
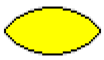
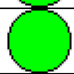
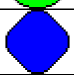
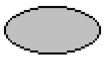
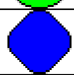
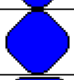
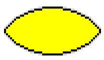
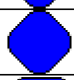
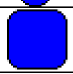
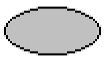
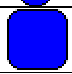
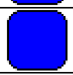
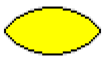
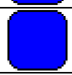
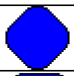
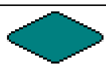
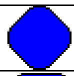
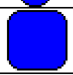
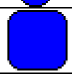
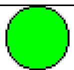
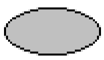
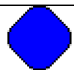
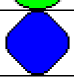
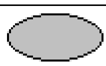
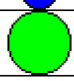
Calibration sequence 12% – 40%	Initial cross-section	1	2
1			
2			
3			
4			
5			
6			
Semi similar cross-sections			
7			
8			
Mixed forms			
9			
10			

Table 4: Calibration sequence 12% – 40%

In principle, it is possible to use the "semi similar" cross-sectional shapes rhombus and rectangle for high reduction. For the sake of completeness, these are listed in lines 7 and 8 for high reduction. However, usually the problem arises that the round corners of the rectangle and the upper and lower radius of the rhombus are not filled completely. Therefore, you must increase these radii significantly. In this case you can directly use an oval or a lens instead.
Mixed forms, where the same cross-section as the initial shape is no longer achieved in the second pass, of course are also useful and have specific advantages (see below). Lines 9 and 10 contain mixed-form calibration shapes of common use.

Calibration sequence for extremely high reduction (> 40% Steel)
There are roller parts where an extremely high total reduction is required, but at the same time the number of passes is limited. Then reduction rates of more than 50% are required in a single pass or the maximum reduction must be used in all successive passes. This only works with a calibration sequence in which several ovals are connected in series.

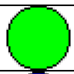
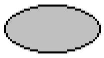
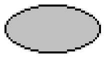
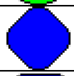
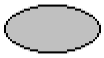
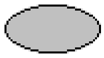
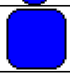
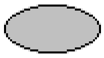
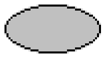
Calibration sequence > 40%	Initial cross-section	1	2
1			
2			
3			

Table 5: Calibration sequence, total reduction rate > 40%

In the second oval, the reduction can effectively be > 40%. The idea here is that the deformation (pass 2) takes place in two sub-steps a, b.

a) First a transformation from oval to circle or oval to square (2a).
b) The deformation does not stop when the circle/square is reached but goes much further and again an oval is created (2b).

In the first sub-step (2a) the reduction is

$$P_{2a} = 0.8 \cdot P_1 \quad \text{or} \quad P_{2a} = 0.85 \cdot P_1$$

In the second sub-step (2b) the deformation of the circle/square continues, and an oval is created. This deformation P_{2b} should be at least 12% (see above).
A total reduction of $P_2 = P_{2a} + P_{2b}$ can be achieved in pass 2.

Example:
If the maximum value of 40% is used for reduction P_1, an intermediate circle shape has been reached in pass 2a after 32% reduction or a square after 36%. The deformation then continues and an oval with is created by reduction P_{2b}. P_{2b} should be at least 12%, resulting in a total reduction of $P_2 = P_{2a} + P_{2b}$ = 32% + 12% = 44% (steel) or P_2 = 36% + 12% = 48% (aluminium).

Invalid calibration sequences
There are also invalid calibration sequences, which inevitably lead to rolling defects.

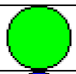
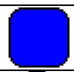
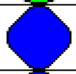
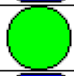
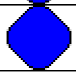
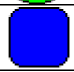
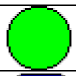
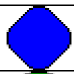
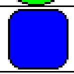
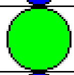
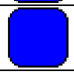
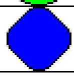
Invalid calibration sequences	Initial cross-section	1
1		
2		
3		
4*		
5*		
6*		

Table 6: Invalid calibration sequences

Invalid calibration sequences usually arise when 2 "non-spreading" cross-sections with different cross-section types follow each another. Here the initial cross section is usually already wider than the cross section in the next pass. It therefore immediately covers the flash corner radius or the flash gap and automatically leads to "wing formation".
*Exceptions to this are calibration sequences in lines 4,5 and 6. Here, 2 “non-spreading” cross-sectional shapes follow each other, but there is still space for spreading on both sides, so that there are no rolling defects.

3. Selection of calibration sequence depending on the cross-sectional reduction

Starting with VeraCAD 4.0, a calibration plan always is present. Roller parts cannot exist without a calibration plan. The default rolling project (after the command "File New") has round raw material and consists of 2 roller passes.
After the finished product has been completely entered, the calibration plan still consists of 2 passes. This can result in reduction rates of individual passes, that are much too high (> 40%). Such calibration plans do not work in practice and the user must increase the number of passes. This is done using the settings for process control and then the command "Create new calibration plan". Future versions of VeraCAD will offer more options and an automatic optimization mode.
The number of roller passes should be determined based on the largest total reduction (see Table 1). Then you can check in the calibration plan navigation window, whether individual roll passes exceed the maximum reduction rate (display value “Reduction”). This strategy corresponds to “Golden rule 1”.

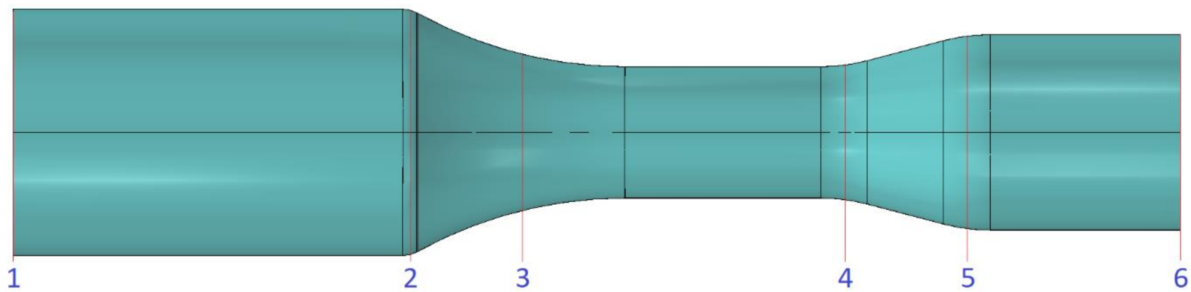


Fig. 2: Rolled part for a connecting rod with 6 cross-sections

In the next step, the calibration sequences are determined. The connecting rod from Figure 2 serves as an example. It has 6 cross-sections with total reduction according to Table 7.

Cross-section	1	2	3	4	5	6
Total reduction	0%	0%	72%	72%	38%	38%

Table 7: Total reduction in the individual cross-sections of the connecting rod

Since the largest total reduction is 72% (cross-section 3 + 4), the part can also be produced with 3 passes (see Table 1). Both versions with 4 and 3 passes are presented here.
The processing should take place from left to right for each individual cross-section.

Variant with 4 passes

Cross-section 1 + 2
These cross-sections are not in the roller part, they cannot be deformed. Therefore, the reduction in each pass must be 0%. The cross-section type corresponds to the raw material circle or square. Here only Table 2 comes into question. The only calibration sequence across all 4 passes is:

Cross-section 1 + 2 0%	Initial cross-section	1	2	3	4
1	●	●	●	●	●
2	◆	◆	◆	◆	◆

Cross-section 3 + 4
These cross-sections are strongly reduced. Table 4 comes into question for the total reduction of 72% (high reduction).

Cross-section 3 + 4 72%	Initial cross-section	1	2	3	4
1	●	⬬	●	⬬	●
2	●	⬬	◆	⬬	●
3	◆	⬬	●	⬬	◆
4	◆	⬬	◆	⬬	◆

Depending on the raw material and the desired final cross-section, there are 2 alternatives. The best alternatives are calibration sequences in line 2 and 4. Here pass 2 is designed as a square (diamond), giving two advantages:

- The calibration sequence Oval - Square offers a larger reduction.
- The oval from pass 1 is vertical in the corners of the square, which means that it cannot twist (twisting of the cross-section).

Cross-section 5 + 6
These cross-sections have a medium total reduction of 38%. Table 3 comes into question (medium reduction). First, however, it should be explained why the calibration sequences used for cross-sections 3 and 4 (72%) are no longer useful.

Cross-section 5 + 6 38 %	Initial cross-section	1	2	3	4
1	●	⬭	●	⬭	●
2	●	⬭	◆	⬭	●
3	◆	⬭	●	⬭	◆
4	◆	⬭	◆	⬭	◆

The deformation oval - square and square - oval requires a reduction of at least 12%. Such a calibration sequence can be found in lines 2, 3 and 4. However, if at least 12% must be reduced in pass 2, the reduction in previous pass must also be over 12%. Using the formulas

$$P_2 = 0.8 \cdot P_1 \quad \text{or} \quad P_2 = 0.85 \cdot P_1$$

vice versa for the previous pass

$$P_1 = \frac{P_2}{0.8} \quad \text{or} \quad P_1 = \frac{P_2}{0.85}$$

So, the reduction in the previous pass is at least 15% or 14.1%. The total reduction across all 4 passes is then at least (14.1%, 12%, 14.1%, 12%). It is already 41% and the resulting cross section becomes too small. The calibration sequence in line 3 performs even worse (14.1%, 12%, 15%, 12%) and achieves an overall reduction of 43%.
Only the calibration sequence at line 1 is suitable, because the calibration sequence circle-oval-circle also occurs in Table 2 (low reduction) and Table 3 (medium reduction).
A combination of the calibration sequences from Tables 2 and 4 provides a remedy.

Cross-section 5 + 6 38%	Initial cross-section	1	2	3	4
1	●	⬭	●	●	●
2	●	●	●	⬭	●
3	◆	⬭	◆	◆	◆
4	◆	◆	◆	⬭	◆
5*	●	⬭	●	⬭	●

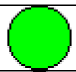
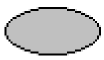
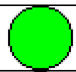
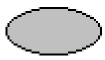
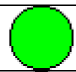
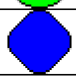
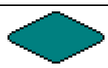
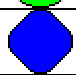
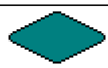
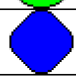
In lines 1 and 3, a calibration sequence for high reduction is used first. Almost the entire reduction of 38% is generated in the first two passes. There is no problem in achieving the required minimum reduction of 12%. After that, however, there is no reduction left to convert the cross-section into another type. The calibration sequence circle-circle-circle or square-square-square is added, which is also satisfied with a reduction of 0%. In practice, however, it has proven useful to leave a remaining reduction in pass 1 + 2. So e.g. in pass 1, 2 to reduce only 32%. Then you can reduce approx. 3% each in pass 3 + 4. This gives two advantages:

- Contact pressure to the roller part is maintained. This ensures the necessary transportation of the part.
- Complete filling of the calibre is more successful if there is still a reduction.

An alternative could be lines 2 and 3. At first, no reduction is generated in pass 1 + 2. The cross-section remains constant and the reduction is close to 0%. Again, the safe transport of the roller part must be considered. The required high reduction is then generated in pass 3 + 4, again using a calibration sequence from Table 4 (high reduction).
Although these calibration sequences work, they do have 2 disadvantages:

- Passes 1 + 2 have a significantly higher forming potential than passes 3 + 4. This means that in pass 1 + 2, massive deformation (high reduction can be achieved) without the risk of "wings". In pass 3 + 4 the spreading ß is much higher and there is more risk of wing formation. Therefore, the reduction usually must be less in the later passes. The advantage of a high reduction potential in pass 1, 2 is given away in the variants at lines 2 and 4.
- When designing rolling processes, an attempt must be made to keep the width of the rolled part as constant as possible (top view, golden rule 3). Neighbouring cross-sections that are spreading extraordinarily strong, try to pull out their neighbours (into the flash gap). If the neighbour shall not spread himself because he has no reduction, this can lead to wing formation. This is avoided with a constant width in the top view. However, since cross-section 3 + 4 already requires a large reduction in pass 1 + 2, the variants from line 2 + 4 no longer achieve a constant width.

Best Calibration sequence for cross-section 5 + 6
The best calibration sequence for cross-sections 5 + 6 therefore can be found in lines 1 + 3. They use the high forming potential of the first passes and ensure a constant width in the top view of all passes. A possible reduction sequence would then be (Circle: 21%, 16.8%, 3%, 3% or Square: 20.5%, 17.4%, 3%, 3%). This ensures the transport and a good filling of the cross-sections in pass 3 and 4.
*A good alternative can still be found in line 5. The first two passes assume the high reduction of up to 32% and the remaining small reduction is distributed over the calibration sequence circle-oval-circle of pass 3 + 4. The reduction sequence has changed slightly to (Circle: 21%, 16.8%, 3.5%, 2.8%).
If you proceed strictly according to Table 3 (medium reduction) and want to keep the reduction in all passes the same, calibration sequences will result as below.

Cross-section 5 + 6 38 %	Initial cross-section	1	2	3	4
1					
2					

Both calibration sequences try to keep the reduction across all passes the same. The reduction sequences could be, Circle: 12.5%, 10%, 12.5%, 10% or Square: 12.2%, 10.4%, 12.2%, 10.4%.
These calibration sequences work, but they do not consider the points mentioned above under “Disadvantages”. They should only be selected if the materials cannot tolerate large reduction rates (e.g. titanium steels).

Variant with 3 passes
According to Table 1, the largest reduction in cross-section 3 + 4 can also be achieved with 3 passes. In that case, however, the cross-sectional shape in the finished product would be an oval or in previous passes an oval-oval calibration sequence must be selected.

Cross-section 1 + 2

Here the same applies to the variant with 4 passes. There is no deformation and a calibration sequence with a constant cross-section according to Table 2 must be selected.

Cross-section 1 + 2 0%	Initial cross-section	1	2	3
1				
2				

Cross-section 3 + 4

To achieve the high reduction of 72% with 3 passes, there are the following variants:

Cross-section 1 + 2 72%	Initial cross-section	1	2	3
1				
2				
3				
4				

In lines 1 and 3, the required high reduction is achieved through the oval-oval calibration sequence (see Table 5).

In rows 2 and 4 there is a remarkably high reduction twice (pass 1 and pass 3). However, an oval remains in the finished product.

The advantages of these variants are the shorter cycle time and the lower tool costs.

In some cases, it can also be an advantage that the temperature does not drop so much compared to the 4-pass version. On the one hand, because the process runs faster, on the other hand, more heat is generated in each pass due to the higher deformation.

Occasionally, the width of the machine is too small and does not allow 4 passes next to each other (width of shaft).

Cross-section 5 + 6

The required total reduction of 38% is no problem for 3 passes. The reduction per pass is neither too large nor too small.

Cross-section 5 + 6 38 %	Initial cross-section	1	2	3
1				
2				
3				
4				

Again, at the beginning, the high forming potential of the first passes is used and then only slightly reshaped (Tappet = constant calibration sequence). This is shown in lines 1 and 3. The reduction sequences for this are circle: 22%, 17.6%, 3.5% or square: 21.5%, 18.3%, 3.5%.
Lines 2 and 4 are alternatives. If the oval-oval calibration sequence is used in cross-section 3 + 4 due to the high reduction of 72%, then the selection according to lines 2 and 4 results in a rolling pass, which has the same cross-sectional shape from cross-section 3-6. With reducer rolling, it is advantageous if the cross-section keeps a constant shape over the entire roller product. The cross-sectional area is generally not constant because the rolled product is supposed to be profiled. However, if the entire product has the same cross-sectional shape, this results on the one hand in a smooth, harmonious surface for the roll impression, and on the other hand it is easier to avoid rolling defects. A possible reduction sequence for row 2 is circle: 12%, 20%, 9% or row 4 square: 14%, 20%, 10%.