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“Optimizing operations through continuous improvement”

The metallurgical benefits of cold rolling high performance alloys instead of cold drawing to manufacture thin wall tubing

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Abstract

This paper will briefly touch on the origin of the HPTR rolling process and explain the mechanics and advantages of the original 3-roll lever-type HPTR and an improved 6-roll pinion driven variant. Examples will be included to illustrate the manufacturing and metallurgical benefits of cold rolling high performance alloys instead of cold drawing, the efficiency and lean potential of rolling, and how this process has been optimized in recent years to produce a wide range of thin wall tubing in conjunction with traditional pilger mills and draw benches.

Introduction

During the Cold War, Soviet engineers developed a tube rolling machine for the express purpose of making fuel cladding for nuclear reactors. Known as the HPTR, or High Precision Tube Roller, its ability to achieve extreme reductions in wall thickness in a single pass made it especially useful when making thin wall tubing in hard to draw alloys.

50 years later, vintage HPTR's are still making thin wall tubing from zirconium and other high value, hard to work materials. The very features that made it so good at making tubing for cladding have also proven perfect for other products that require a wall thickness of 1% to 2% of OD or less. In addition, its efficiency in terms of material waste and number of ancillary operations have shown its viability in a lean manufacturing environment.

In the past two decades, there has been a dramatic increase in the use of metal tubing for implantable medical devices ranging from small diameter tubes for coronary stents to larger tubes for artificial heart valve frames. Pacer wire for implantable defibrillators, pacemakers and neurostimulators

are often made from composites requiring metal tubing. Many well established alloys known for their fatigue strength, corrosion resistance, and overall high performance have been selected and in some cases metallurgically improved for such applications. A few examples include Ti-6Al-4V ELI, L605 (Haynes 25), and MP35N.

Other applications are convoluted thin wall tubing for metal bellows for pressure and temperature sensors. Controlled grain structure and wall uniformity are critical for successful convoluting. A scratch free, smooth surface finish is also required.

Many of these alloys are problematic to cold draw due to lubrication issues and high work hardening rates, a situation not made easier by the very thin, uniform wall specifications. While cold pilgering remains the optimum process for initial reductions, as the OD:W ratio approaches 100:1 or higher and wall thickness drops below 0.010", cold rolling with small diameter rolls becomes more viable than either cold pilgering or cold drawing. This is in part due to the increased difficulty that arises when the wall thickness is less than 1/250th of the diameter of the pilger die.

How Pilgers & Rollers Differ

It cannot be stated enough that the HPTR process is distinct from that of a traditional cold pilger mill. Confusion often arises due to the fact that both machines use a compressive rolling process. While there are similarities in tube control and mandrel location, the differences lie in number of dies, groove shape, and how dies are driven.

Cold pilger mill:

1. Two dies with variable cross-section groove are mounted above and below tube
2. Dies are driven by rack and pinion gear; never complete 360° rotation
3. Friction from slip at die-workpiece interface high due to fixed relationship of pinion and die diameter
4. Mandrels are generally curved or tapered
5. Not suited for thin walls due to large die diameter

3-Roll HPTR:

1. Three rolls with constant cross-section grooves arranged circumferentially around tube
2. Rolls are driven by lever system along profiled cams; rolls complete multiple 360° rotations
3. Ratio of roll to cam travel adjustable by kinematic linkage system resulting in “near zero” slip at roll groove-workpiece interface
4. Mandrels are generally cylindrical
5. Well suited for thin wall tubing due to small diameter rolls

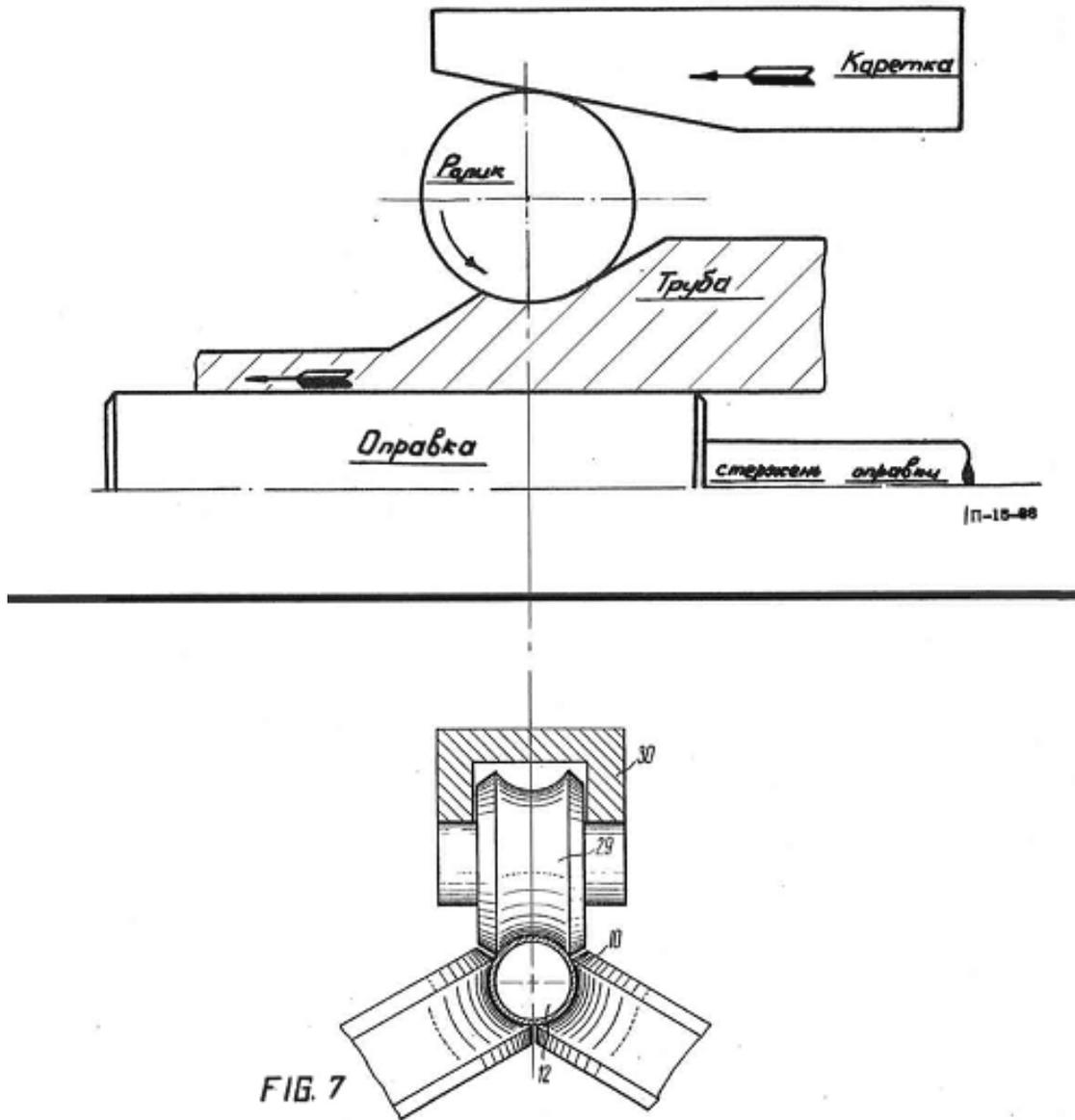
6-Roll Improved HPTR:

1. Two sets of three rolls with constant cross-section grooves arranged circumferentially around tube. Roll sets are off-set by 60° relative to one another and work in tandem
2. Rolls are driven by rack and pinion gears of different radii along profiled cams; rolls complete multiple 360° rotations
3. Ratio of roll to cam travel fixed due to pinion ratio; adjustment of roll trunion diameter still allows for “near zero” slip at roll groove-workpiece interface
4. Mandrels can be cylindrical, tapered or curved
5. Well suited for both thin wall and heavy wall tubing due to small diameter rolls and unique design

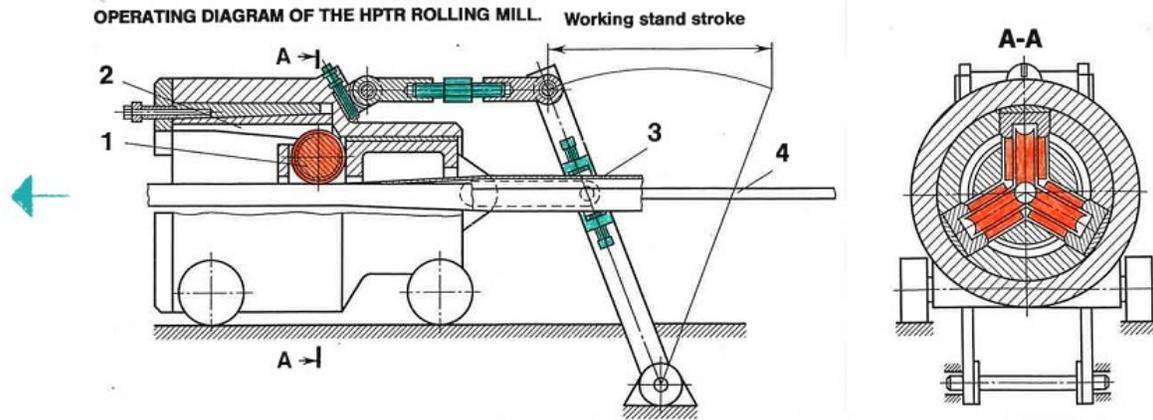
How Rollers Work

“HPTR mills, unlike other type tube mills, take advantage of the proven “Sendzimir” cold strip mill principle which uses multiple small size rollers to cold roll thin metal sheets. HPTR tooling includes a multiple of circumferentially oriented small rollers of simplified design which, upon reciprocating motion, cold roll the tubing over a cylindrical mandrel. Precise radial movement of the rollers is caused by special design roller support straps” ... from an early brochure by Patent Management Inc., an agency “specializing in the sale of Russian know-how to American companies.”

EARLY ILLUSTRATIONS HPTR PRINCIPLE OF OPERATION



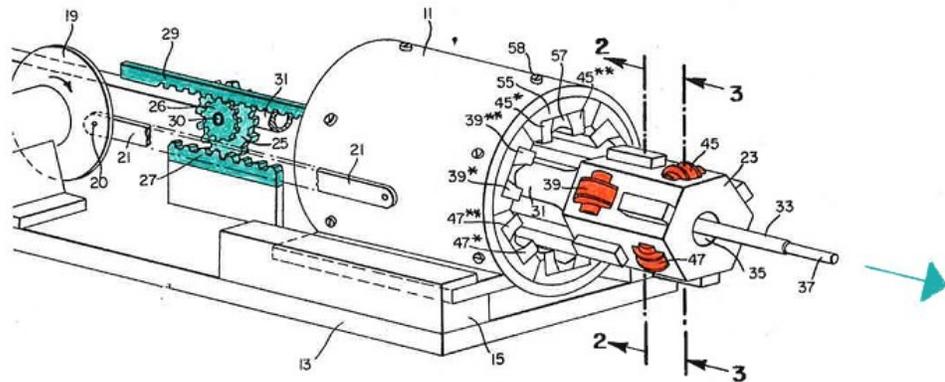
An early Russian diagram showing the relationship of cam, roll, and tube, with a mandrel and rod also indicated. The motion of the roll across the tubing surface results in a near-zero slip, as the rolls iron the wall thickness greatly reducing friction. At bottom is a later head-on picture showing the circumferential rolls converging on the tube.



RUSSIAN LEVER SYSTEM ... 3 ROLL

IMPROVED PINION SYSTEM ... 6 ROLL

Fig 1



A comparison of the Russian lever system and our improved pinion system; highlighted in green. The pinion system has fewer moving parts and is more robust, allowing for pilger-like reductions in addition to the traditional HPTR wall reductions. While both roll arrangements are circumferential around the tube, the six-roll has a second set offset 60° working in tandem.

IMPROVED PINION SYSTEM
6 ROLLS – DUAL CAPABILITY
PILGER-LIKE REDUCTIONS (CURVED MANDREL)
 OR
HPTR REDUCTIONS (CYLINDRICAL MANDREL)

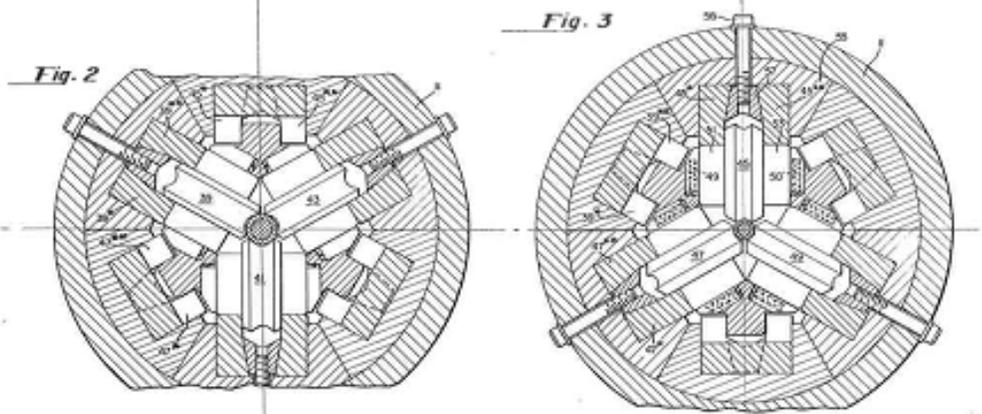
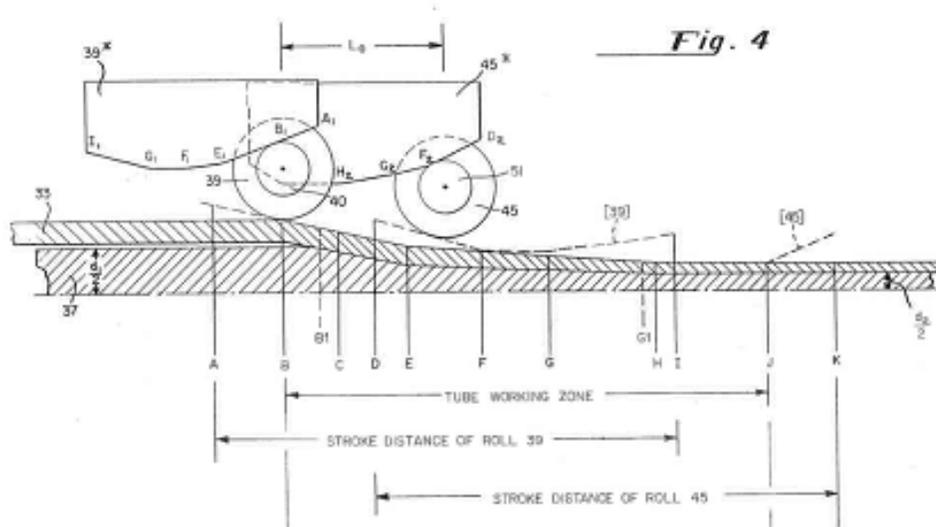
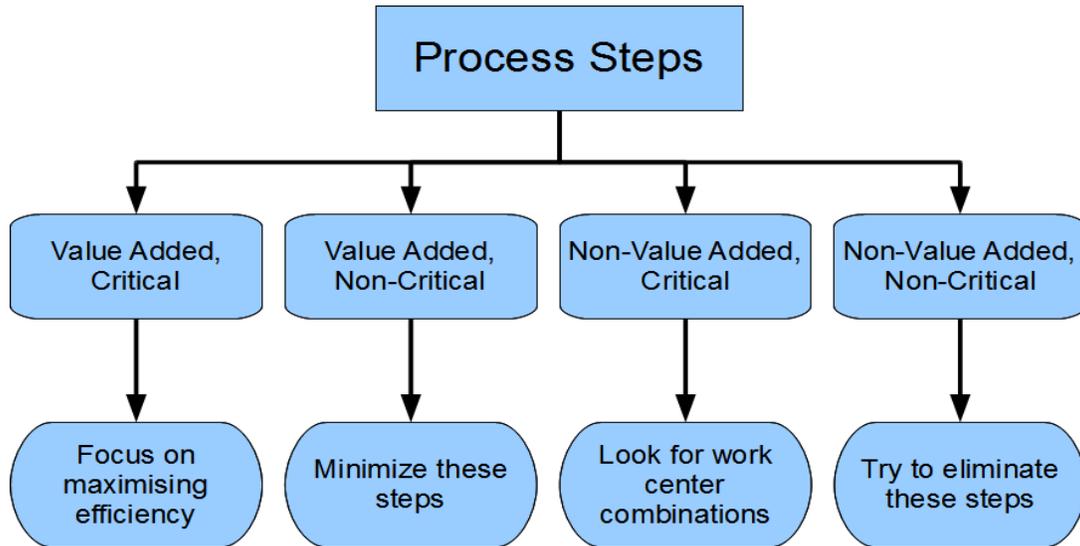


Diagram of the improved six-roll machine showing the two sets of rolls working in tandem, increasing feed rates and doubling the length of the working zone as compared to a three-roll machine. The first stage provides initial reduction while the second stage reduces to finish. The 60° offset of the roll clusters is shown at bottom.

Optimizing Rolling Technology



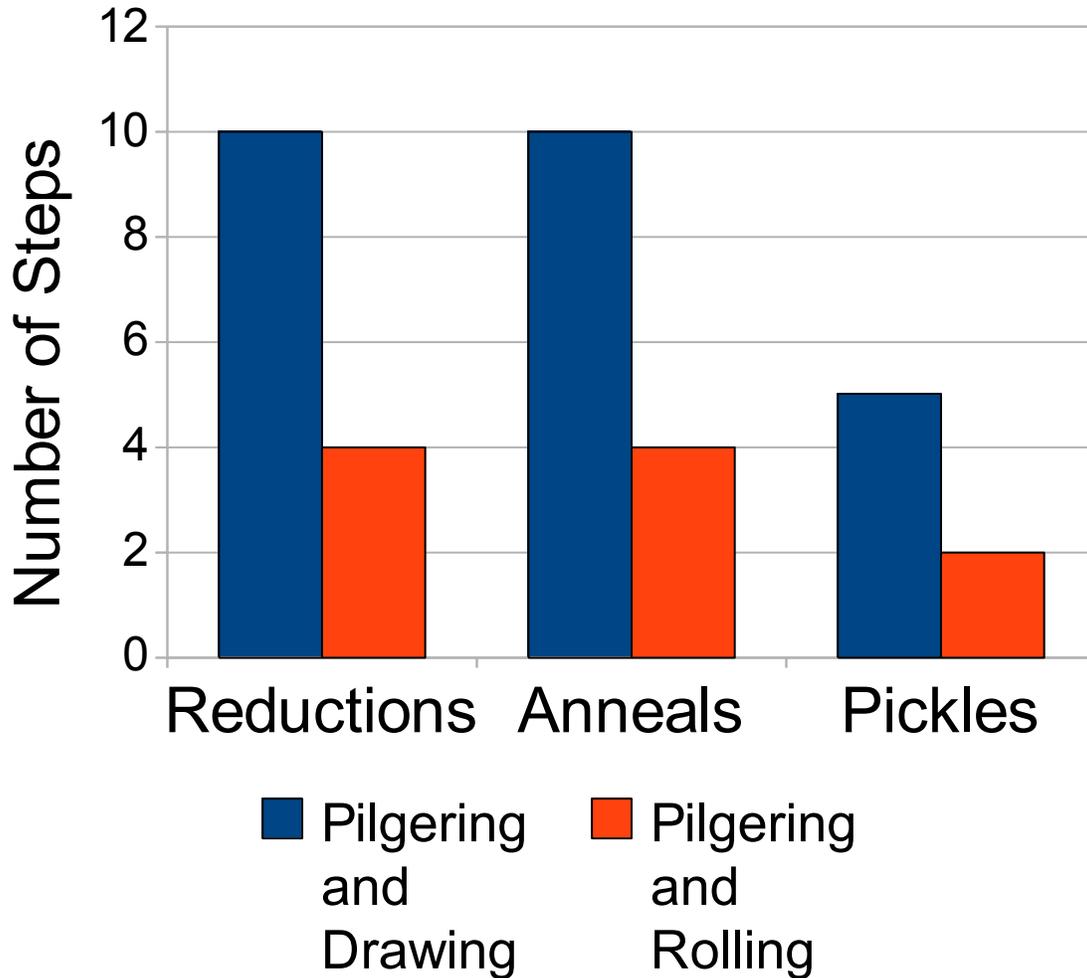
Our objective in manufacturing is to minimize or eliminate non-value added steps wherever feasible. This includes such processes as tagging, coating, in-process annealing, pickling, etc. In some cases, these steps are vital to tube production. In others, they can potentially be removed from the process entirely by an improved route design.

The following examples will show how optimizing the rolling technology can be utilized to achieve process efficiency. In cold drawing, the last three cold work/anneal cycles are typically the most critical from the standpoint of process control, be it grain size, surface finish, wall tolerance or mechanical properties. With convoluting grade tubing, final acceptance of the product is linked to the ability of the tubing to withstand the convoluting process.

When producing tubes in the range of 0.004" to 0.008" wall thickness on a 0.375" to 0.5" diameter, precise control of wall thickness is an extremely critical aspect. This is one of the basic advantages of a compressive reduction process like tube rolling. This is especially true when dealing with hard to draw materials.

By controlling the wall thickness better control of grain size is also achieved. A minimum of three grains across the wall is required to avoid the "orange peel effect" on the surface and prevent sudden failure during the convoluting process. The improved reduction route requires adjustments to intermediate annealing parameters. Once properly adjusted, the result is a more uniform grain size distribution and therefore less chance of failure in convolution or end use.

Convoluting Grade Tubing



The other significant advantage is minimizing the risk of handling damage by reducing the number of process steps. For the example above, we managed to reduce a bench draw/anneal cycle of 82 steps down to 32 steps. This included fewer reduction operations, as each cycle had significantly higher wall reduction. As a result, the in-process loss due to handling dents in thin wall sizes was minimized.

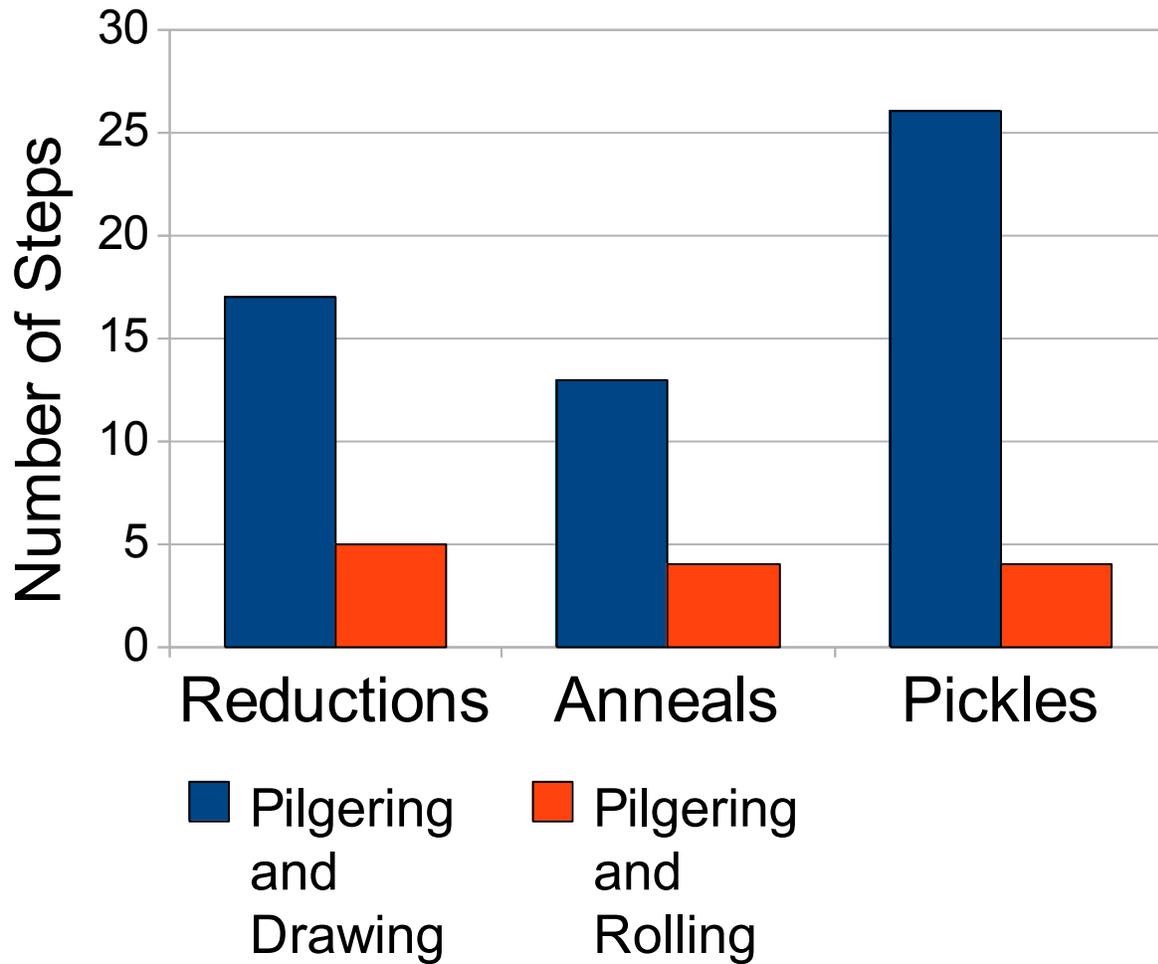
Unlike bench drawing, rolling requires no pre-coating. This helps improve the surface finish of the resulting tube. From an average 20-25 RA finish, a 10-15 RA finish could be consistently achieved, giving the product better fatigue resistance. Rolling also eliminates the need for tagging, which is a non-value added but necessary step when bench drawing. The corresponding loss of material yield is likewise eliminated.

Another example of the advantages of rolling comes when making zircaloy tubing. Producing 0.004" to 0.008" wall zircaloy tubing by drawing is an enormous challenge. By nature, reactive metals are difficult to draw and need additional pre-coating to protect the metal from severe scratches. In turn, the removal of the coating becomes critical to avoid contamination, which then creates problems with fabrication and results in an unacceptable end product. Preparatory steps like tagging or pointing for drawing in thin wall sizes also lead to a serious problem with cracks and splits. Losing a full length of tubing due to a split is not uncommon. Furthermore, a circumferential rather than radial texture is often critical for the end application, and can only be achieved by compressive reduction.

As such, tube rolling is often a viable alternative to drawing reactive metals. Rolling zircaloy on an HPTR tends to result in much better wall size control in light wall sizes, as plug drawing is not a viable option for zircaloy.

Tube rolling is not without its disadvantages, the primary one being that it is a much slower process than bench drawing. However, one must look at overall process efficiency rather than individual work center efficiency when selecting a process. For several lots of material, yields were approximately 60% more finished tubing despite starting with the same weight and size. Once the process bugs were worked out, the waste factor was lowered significantly and target shipping quantities met or exceeded requirements.

Thin-wall Zircaloy Tubing



As has been mentioned, rolling zircaloy also requires no pre-coating or tagging. However, rolling does require that the tube ends are square and burr free (not chamfered) to avoid the ends telescoping as the hollows are fed forward over the mandrel.

Conclusion

As mission critical applications for thin wall tubing emerge, the 3-roll HPTR and its 6-roll variant will remain viable; complimenting the capabilities of cold pilger mills and draw benches.

Advantages:

- Highly accurate dimensional control and improved surface finish
- High reductions assure fine grain control and improved mechanical strength
- Material yield virtually 100%
- Design and fabrication of tooling relatively simple
- Ancillary operations and delays dramatically reduced

The novelty and over-all simplicity of the technology have proven beneficial to producers of niche, highly engineered tubes.