## Cold-working

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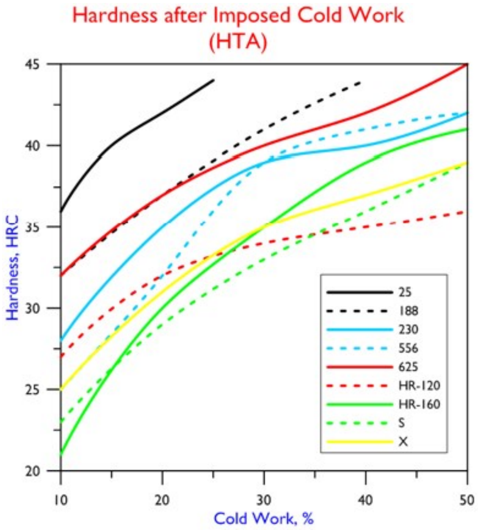
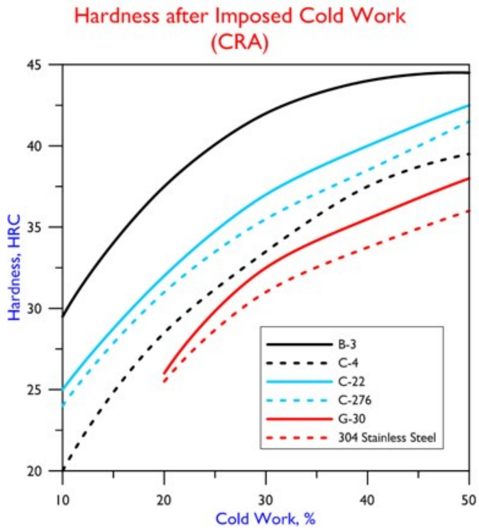
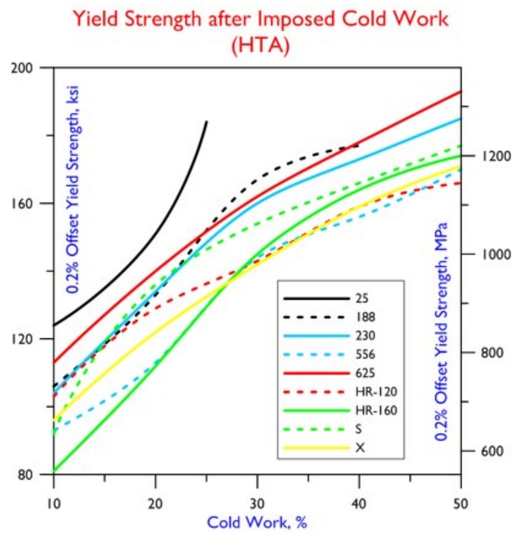
The HAYNES® and HASTELLOY® alloys can be readily formed into various configurations by cold-working. Since they are generally stronger, and work harden more rapidly, than the austenitic stainless steels, the application of greater force is normally required to achieve the same amount of cold deformation. The higher yield strengths of the HAYNES® and HASTELLOY® alloys may also result in greater spring-back after cold forming, relative to the austenitic stainless steels. Furthermore, rapid work hardening may necessitate more frequent annealing treatments between forming steps, to attain the final shape. Graphs illustrating the effects of cold-work upon the hardness, yield strength, and ductility of some of the HAYNES® and HASTELLOY® alloys are shown below.

**Effect of Cold-work on Hardness Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

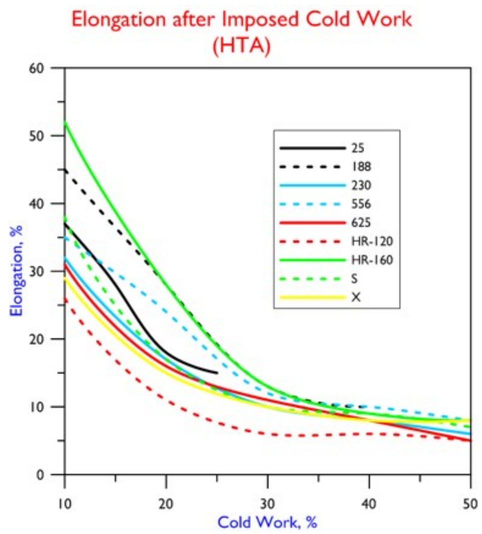



**Effect of Cold-Work on Yield Strength:**
**High-temperature Alloys**




**Effect of Cold-work on Elongation Applicable to:**
**High-temperature Alloys**




Generally, as-supplied materials (annealed at the Haynes International mills) have sufficient ductility for mild forming. However, for higher levels of cold deformation, where cracking is a possibility due to a reduction in ductility, a series of successive forming operations is recommended, each followed by an intermediate annealing treatment. Under most circumstances, this should be a solution anneal (the temperatures for which are given in the Heat Treatment section). A final (solution) anneal is recommended after the completion of such successive forming/annealing operations, to restore the material to its optimum condition and properties. This is particularly important for restoring resistance to stress corrosion cracking, in the case of the corrosion-resistant alloys.

***However, the annealing of material subjected to low levels of cold-work (less than about 7 to 10% outer fiber elongation) is generally not suggested since it can result in abnormal grain growth, leading to a surface condition known as "orange peel" or "alligator hide", and significantly affect properties.  Please refer to any additional 'Fabrication and Welding' information for the specific alloy or contact Haynes International for further guidance.***

As discussed below, it is very important that any lubricants, or other foreign matter, be carefully removed from the surfaces of the workpiece prior to any intermediate (or final) annealing treatment, to prevent the diffusion of detrimental elements into the alloy.

It is highly recommended that any scales (i.e. surface films) caused by intermediate annealing treatments be removed prior to the next forming operation by pickling or mechanical means.

Lubrication is a significant consideration for successfully cold-working the HAYNES® and HASTELLOY® alloys. Although lubrication is not normally required for simple bending operations, the use of lubricants may be essential for other forming operations, such as cold-drawing. Mild forming operations can be successfully completed using lard oil or castor oil, which are easily removed. More severe forming operations require metallic soaps or chlorinated/sulfo-chlorinated oils. When sulfo-chlorinated oils are used, the work-piece must be carefully cleaned in a de-greaser or alkaline cleaner, after each step (to prevent sulfur diffusion into the alloy during subsequent annealing).

***Lubricants that contain white lead, zinc compounds, or molybdenum disulfide are not recommended because they are difficult to remove and can cause lead, zinc, or sulfur to diffuse into the alloy during subsequent annealing, resulting in severe embrittlement. For the same reason, any die materials, lubricants, or foreign matter should be carefully removed from the work-piece before any intermediate or final annealing treatments.***

**Bending, Roll-Forming, Roll-Bending, and Press-Braking**

**Recommended Procedures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

HAYNES® and HASTELLOY® sheets and plates are amenable to simple bending, roll-forming, roll-bending, and press-braking operations. Lubrication is not generally required for such operations. Minimum bend radius guidelines are given in the table below, but may vary from alloy to alloy.

| Material Thickness | | Suggested Minimum Bend Radius* |
|---|---|---|
| in | mm | |
| <0.050 | <1.27 | 1T |
| 0.050-0.187 | 1.27-4.75 | 1.5T |
| 0.188-0.500 | 4.76-12.70 | 2T |
| 0.501-0.750 | 12.71-19.05 | 3T |
| 0.751-1.000 | 19.06-25.40 | 4T |

*T = Material thickness

Thick sections may require multiple steps, with intermediate annealing treatments to restore ductility. These treatments should be performed in accordance with the recommendations given in the Heat Treatment section, and again care must be taken to clean the surfaces of the work-piece prior to annealing.

**Deep Drawing, Stretch Forming, and Hydroforming**

**Recommended Procedures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

The HAYNES® and HASTELLOY® alloys are amenable to deep drawing, stretch forming, hydro-forming, and such like. Lubrication is generally required for these processes. In the case of the high temperature alloys, fine-grained starting material possessing superior forming characteristics may be available. As with bending operations, thick sections may require multiple steps, with intermediate annealing treatments to restore ductility. These treatments should be performed in accordance with the recommendations given in the Heat Treatment section, and again care must be taken to clean the surfaces of the work-piece prior to annealing.

As a guide to the formability of the high-temperature alloys, Olsen Cup (lubricated) test results are provided below for some of the alloys, along with 310 stainless steel for comparison.

| Alloy | Average Olsen Cup Depth* | |
|---|---|---|
| | in | mm |
| 25 | 0.443 | 11.3 |
| 188 | 0.490 | 12.4 |
| 230® | 0.460 | 11.7 |
| 556® | 0.480 | 12.2 |
| 625 | 0.440 | 11.2 |
| S | 0.513 | 13.0 |
| X | 0.484 | 12.3 |

| | | |
|---|---|---|
| 310 Stainless Steel | 0.505 | 12.8 |

*Average of 3 to 12 measurements on 0.040-0.070 in (1.0-1.75 mm) thick sheet

**Spinning and Shear Spinning**

**Recommended Procedures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

Spinning is a deformation process for forming sheet metal or tubing into seamless hollow cylinders, cone hemispheres, or other symmetrical circular shapes, by a combination of rotation and force. There are two basic forms, known as manual spinning and power (or shear) spinning. In the former method, no appreciable thinning of the metal occurs, whereas in the latter, metal is thinned as a result of shear forces.

Nearly all HAYNES® and HASTELLOY® alloys can be spin formed, generally at room temperature. The control of quality, including freedom from wrinkles and scratches, in addition to dimensional accuracy, is largely dependent upon operator skill. The primary parameters that should be considered when spinning these alloys are:

- Speed
- Feed Rate
- Lubrication
- Material
- Strain Hardening Characteristics
- Tool Material, Design, and Surface Finish
- Power of the Machine

Optimum combinations of speed, feed, and pressure are normally determined experimentally when a "new job" is set up. During continuous operation, changes in the temperature of the mandrel and spinning tool may necessitate the adjustment of pressure, speed, and feed to obtain uniform results.

Lubrication should be used in all spinning operations. The usual practice is to apply lubricant to the blank prior to loading of the machine. It may be necessary to add lubricants during operation. During spinning, the work-piece and tools should be flooded with a coolant, such as an emulsion of soluble oil in water.

***Sulfurized or chlorinated lubricants should not be used, since the spinning operation might burnish the lubricant into the surface, resulting in detrimental surface effects (due to diffusion of sulfur and/or chlorine) during any subsequent annealing treatments. If these types of lubricant are used accidentally, they should be thoroughly removed (by grinding, polishing, or pickling) prior to any intermediate or final anneal.***

The tool material, work-piece design, and surface finish are all very important in achieving trouble-free operation. Mandrels used in spinning must be hard, wear-resistant, and resistant to the fatigue resulting from normal eccentric loading.

As is the case for other cold-forming operations, parts produced by cold spinning should be intermediate and final annealed in accordance with the recommendations in the Heat-Treatment section of this guide.

**Tube-forming**

**Recommended Procedures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

The HAYNES® and HASTELLOY® alloys can be cold formed in standard pipe and tube bending equipment. The minimum recommended bending radius, from the radius point to the centerline of the tube, is three times the tube diameter, for most bending operations. When measured from centerline to centerline of the “hairpin” straight legs, it is six times the tube diameter. On the other hand, there are some combinations of tube diameter and wall thickness where a bending radius of twice the tube diameter is possible (from the radius point to the centerline of the tube).

As the ratio of tube diameter to wall thickness increases, the need for internal and external support becomes increasingly important, in order to prevent distortion. If too small a bending radius is used, then wrinkles, poor ovality, and buckling can occur (in addition to wall thinning).

**Punching**

**Recommended Procedures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

Punching of the HAYNES® and HASTELLOY® alloys is usually performed at room temperature. Perforation should be limited to a minimum diameter of twice the gage thickness. The center-to-center dimension should be approximately three to four times the diameter of the hole.

| **Punch to Die Clearances per Side** | |
|---|---|
| Annealed Sheet up to 0.125 in (3.2 mm) | 3-5% of Thickness |
| Annealed Sheet or Plate over 0.125 in (3.2 mm) | 5-10% of Thickness |

**Cutting and Shearing**

**Recommended Procedures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

In view of the high strengths and high work-hardening rates of the HAYNES® and HASTELLOY® alloys (relative to many austenitic stainless steels), band saw cutting is generally ineffective. For flat products, shearing can be successful on “scissor-type” shears rated for carbon steel thicknesses at least 50% above the alloy thickness involved.

Generally, alloy thicknesses up to 0.4375 in (11.1 mm) are shear-able, while thicker material is normally cut by abrasive saw or plasma arc. Abrasive water-jet cutting is not normally recommended, but may be practical in some cases. Bar and tubular products are normally cut using abrasive saws.

Resin-bonded, aluminum oxide wheels are used to successfully cut the HAYNES® and HASTELLOY® alloys. A typical grain and grade designation is 86A361-LB25W EXC-E.

The HAYNES® and HASTELLOY® alloys can be plasma arc cut using any conventional system. The best arc quality is achieved using a mixture of argon and hydrogen gases. Nitrogen gas can be substituted for hydrogen; however, this will result in a cut of reduced quality. Shop air and oxygen-containing gases are unsuitable and should be avoided when plasma cutting these alloys.

Oxy-acetylene cutting of these alloys is not recommended. Air carbon arc cutting is feasible, but subsequent grinding, to remove any carbon contamination, is likely to be required.