DEVELOPMENT OF RESIDUAL STRESSES DURING MACHINING AND WORKHOLDING

Machining and fixturing prior to heat treatment are among the many potential sources for distortion and residual stress.

THERE HAS BEEN MUCH DISCUSSION ON THE DEVELOPMENT OF RESIDUAL STRESSES and distortion during heat treatment. There is an entire conference series called “Quenching and Distortion Engineering” held every five years that’s devoted to residual stresses developed during quenching and the control of residual stresses. The last event was in Chicago under the auspices of ASM and IFHTSE (International Federation for Heat Treatment and Surface Engineering), and the next one will be in Japan in 2018. This conference is a combination of the successful “Quenching and Control of Distortion” conference, originally started by ASM, and continued by IFHTSE, the International Distortion Engineering conference held by AWT (the German association for materials and heat treatment), in conjunction with The Foundation Institute for Materials Science at the University of Bremen.

The problem of distortion is universal across national borders and industry. A study by Thoben [1] indicated that the 1995 losses from heat treatment alone in the German machining, automotive, and transmission industry exceeded 850M € (1 billion USD). This does not include the rest of Europe, Asia, or the Americas. The problem is truly immense.

Distortion and residual stresses are not limited to heat treatment but are in each step of the manufacturing process. These sources of residual stress follow the manufacturing process chain. The primary sources of distortion or residual stresses are either volume changes due to phase transformations or precipitation or from elastic or plastic deformation (see Figure 1).

In the typical manufacturing process to manufacture a steel or aluminum part, incoming material is purchased; shaped by forming, forging, or casting; machined; heat-treated; and finish-processed (final machining, plating, or painting). This is illustrated in Figure 2.

There are many sources of distortion that have been identified. A fishbone chart illustrating some of the common sources of distortion is shown in Figure 3. It is not the purpose of this paper to review all the possible sources and permutations of distortion, but to highlight some of the important factors.

While Figure 3 indicates many potential sources for distortion and residual stresses, this article focuses on machining and fixturing prior to heat treatment. (Heat treatment and quenching will be discussed in later columns.)

Prior operations such as machining create residual stresses at the surface. This stress is relieved during heat treatment, resulting in distortion.

During turning or milling operations, the workpiece is held fixed by a chuck or jaws. The method of holding the workpiece can result in residual stresses. In one study [3], 100Cr6 (SAE 52100) bearing rings were evaluated on the influence of cutting speed, depth of cut, and feed rate on the roundness. Two different types of clamping mechanisms were used: a mandrel clamp and segmented jaws. The study showed that the residual stresses in the tangential direction of the two rings for the different clamping methods were nearly identical with a mean residual stress of 600 MPa (Figure 4). The segmented jaws show a periodicity of three around the circumference, with the tangential residual stress varying between 500 and 700 MPa.

The segmented jaws had a segment of approximately 120 degrees; however, the real contact was limited to a single point in the middle of each segment. Therefore, the clamping forces are induced at three locations 120 degrees apart. This results in the ring bulging at these locations. The mandrel supports the bearing uniformly around the circumference, resulting in a uniform residual stress.

The segmented jaws were not evaluated for their effect on surface roughness. Further work was conducted by Grote [4], comparing the residual stresses generated by different methods of clamping a workpiece during internal turning. In this work, four different types of jaws were used during internal turning.
of SAE 52100 using a TiN-coated carbide insert and a 3-percent oil emulsion coolant. The out-of-roundness was measured after machining. It showed that hard jaws exhibited significantly greater out-of-roundness than other forms of jaws (see Figure 5).

The influence of cutting parameters on residual stresses was also investigated for rings that were clamped by a mandrel. Four cutting parameters were examined: feed rate, nose radius, depth of cut, and cutting speed. The influence of the different parameters is shown in Figure 6.

Distortion and residual stress from machining is a particular problem when machining non-ferrous alloys. Common practice is to completely machine one surface before machining the opposite side. However, residual stresses from prior operations such as forging can significantly affect distortion. In one study [5], parameters of cutting speed and feed rate per tooth were examined on machining 7449-T76 using an oil emulsion coolant and cemented carbide inserts. The study examined the residual stress parallel and perpendicular to the direction of cutting.

The variation of cutting speed resulted in a decrease in feed and feed forces. In all cases, the residual stresses were compressive — with the residual stresses parallel to the direction of cut being significantly higher than those perpendicular to the machining direction. As cutting force increased, the residual stresses increased.

Tool geometry was also examined. Increasing the rake angle decreased feed and feed normal forces. Low force machining produced lower residual stresses. In the perpendicular direction, increasing rake angle decreased residual stresses (more compressive).

Tool corner radius reduces residual stresses after milling. As the tool corner radius is increased, the residual stress decreased. When cutting with a broad corner (wide radius), a nearly residual stress-free part was produced. During hobbing, residual stresses are introduced into the workpiece. These residual stresses can lead to distortion during heat treatment. In a study by Kohlhoff et al. [6], the influence of hobbing on residual stress was examined. The authors examined axial hobbing on tooth geometry. Three regions were identified: the entry, full cut, and exit. During the entry of the tool into the part, short, thick chips are generated. During full cut, the maximum material removal occurs with a relatively homogeneous chip shape. The exit of the hob exhibits short, thin chips. In this study, the authors found that contact area and clearance led to an increase in mechanical and thermal loads. This in turn resulted in higher residual stresses. Differences in distortion of the leading flank and trailing tooth flanks were observed during the machining operations.

Distortion engineering and the understanding of distortion causes are still fields of development. Further research is needed,
and a collaboration of industry and academia into the causes of distortion is necessary so that distortion-free parts can be produced. This research, as well as its application by industry, will contribute to substantial savings in manufacturing, including lower operating costs. Decreased warranty and longer component life will result.

REFERENCES

ABOUT THE AUTHOR: D. Scott MacKenzie, Ph.D., FASM, is a senior research scientist of metallurgy at Houghton International, a global metalworking fluids supplier. He obtained his B.S. from The Ohio State University in 1981 and his Ph.D. from the University of Missouri-Rolla in 2000. He is the author of several books and over 100 papers, articles, and chapters, and he is a member of ASM International. MacKenzie can be reached at smackenzie@houghtonintl.com.