AUTOMATIC STRAIGHTENING OF HARDENED SHAFTS

ROBERT JANKOVYCH, MARTIN WEIGL, BORIS KUR
Brno University of Technology
Faculty of Mechanical Engineering, Institute of Production Machines, Systems and robotics, Brno, Czech Republic

DOI: 10.17973/MMSJ.2017_12_201782
e-mail: martin.weigl@mesing.cz;jankovych@fme.vutbr.cz

The main purpose of this article is to present a new way of straightening hardened shafts. The straightening of regular shafts is usually not difficult, but the situation is very different in case of hardened shafts. The regular shafts are usually straightened by bending of the shaft in the opposite direction than the original deformation. Sadly, this approach cannot be applied on hardened shafts, because of the brittleness of highly hardened material. Mesing Ltd. in cooperation with Brno University of Technology are now trying to automate the process of straightening by changing the stress inside of the hardened material. This method uses controlled impacts of a ram on the surface of the shaft which has to absorb the energy of the ram. The impact causes a plastic deformation of the surface of the shaft and changes the inner stress. At the end of this article is the design of such measuring and straightening setup shown and described.

KEYWORDS
dynamic measuring, hardened shafts, straightening ram, textile spindle, internal stress of hardened parts

1 INTRODUCTION

The hardening is very well known process and it is used to achieve very hard surface of the hardened parts. There are many hardening principles, but to achievehigh hardness, quenchingisusually used. The result of quenching ismaterial with more than 62HRC, depending on thecomposition of the material and the chosen soaking medium. The side effect of quenching is brittleness, which can lead to brittle fracture of highly loaded parts. Another side effect of quenching is the increased internal stress of the material [Benesova 2007] [Machek2013], which usually leads to deformation of original shape. Quenching is generally followed by heat treatment called tempering. This process is used to reduce the brittleness, but it also slightly reduces the hardness of the surface. Therefore, the tempering temperature must be chosen carefully to achieve the correct hardness of the material**.** [Zoch 2007] This process is used in lots of products, for example:

- drill bits;
- textile spindles;
- bearings;
- electric motors;
- cams and valves;
- medical devices;
- compressors.

The deformation mentioned above can be a difficult problem in further manufacturing steps. Any deformed parts which have to be ground after heat treatment are potentially problematic, becauseevery process needs as stable inputs as it is possible for the best results and for the shortest cycle time.

TEXTILE SPINDLE SHAFT

Figure 1. The textile spindle

The textile spindle (Fig. 1) is very important component used in a textile industry. The main purpose of the spindle is to hold a spool with a thread and ensure unfolding and loading of the thread into a sewing machine. High performance of the modern sewing machine requires very fast loading of the thread, so the spindle has to turn very quickly up to 25 000 RPM. The weight of the rotating spool can be up to 3kg. The spindle has to meet these high requirements.

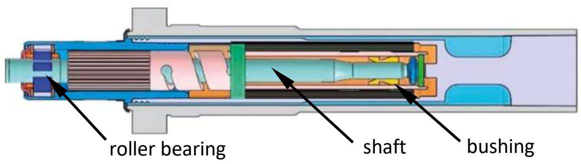

Figure 2. Schematic cut through mounting part

Fig. 2. shows the inner design of the mounting part. One side of the shaft is pressed into the spool holder and the other side is inserted into the mounting part. The bearing

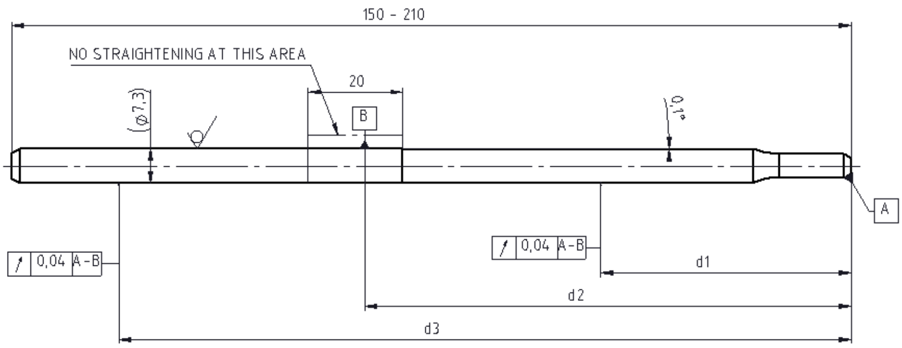

Figure 3. Drawing of the shaft

inside the mounting part consists of the outer ring, the cage, the needles, and the inner ring.The shaft itself is the inner ringas it is shown above. Because of this, the shaft must be very hard with fine surface texture. This is accomplished by quenching in a salt solution, tempering, and grinding.

C	Mn	Si	Cr	Ni
0,90-1,10	0,30-0,50	0,15-0,35	1,30-1,65	max 0,30
Cu	Ni+Cu	P	S	
max 0,25	max 0,50	max 0,027	max 0,030	

Table1. The composition of material 100Cr6 [Fürbacher 2006]

2 SHAFT PRODUCTION PROCESS

The production process of the shaft begins with material 100Cr6. The material composition is shown in Table 1. This composition is well known for its high abrasive resistivity and its ability to achieve hardness up to 65HRC after quenching. These properties makes this chrome steel widely used in roller bearing industry. The material is drawn into a form of rounded bars. The process of drawing causes hardening of the bars surface, and increases the internal stress of the bars. These side effects make further machining very difficult. The soft annealing is therefore used to remove these side effects. The bars after soft annealing are then fed into a CNC lathe and turned into the shape, which is shown on Fig. 3.

The turned shafts are heated on the quenching temperature, which is between 820-840°C, and are held for 25min on this temperature. The shafts should have stable austenitic structure in their whole volume after this time. The heated shafts are immediately soaked in the salt bath with temperature of about 200°C. This very fast cooling transforms austenitic structure into martensitic. The transformation is initiated on the surface of the shafts and creates very hard layer on the outside of the shaft. This layer traps untransformed austenite inside of the shaft. It is very important to know that during the austenite-martensite transformation the material increases its volume by Δv[Machek 2013].

$$\Delta v = 4{,}64 - 0{,}53 \cdot \text{ cont. } \%C [1]$$

The change of volume can be calculated using the formula [1]. As the transformation continues through the trapped austenite inside of the shaft, the internal stress increases and causes deformation of the shape. Tempering is the next step of heat treatment and should be performed promptly after the quenching. The tempering temperature is 160°C and it is held for 3 hours. The process of tempering quickens the transformation of the trapped instable austenite structure into marten site and lowers the internal stress and hardness of the shafts. The resultant shafts have hardness of about 61+2HRC, as prescribed in manufacturing drawing. This stress relief does not lead to straighter shape of the shaft.

The size of circular run-out after quenching depends firstly on the level of internal stress caused by previous operations, and secondly on the circular run-out of the shafts after turning. The first factor can be minimalized if the shafts go through another soft annealing before quenching. Nevertheless, this heat treatment cannot guarantee that the shafts will not have any shape deformations due to the transformation effect mentioned above. The soft annealing after turning would also greatly increase the manufacturing costs. Therefore, another soft annealing is not beneficial for this application and at this stage of the manufacturing process.

3 STRAIGHTENING OF THE SHAFTS

This means that the manufacturer must straighten significant number of shafts before the final operation, grinding. The straightening is provided manually by employees and the principle is very simple. The process is based on adding the compression stress by small plastic deformation of the shaft surface [Dvorak 2013].

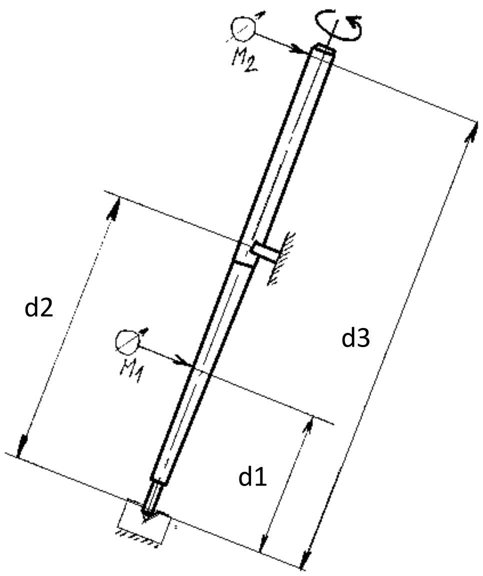

Figure 4. Manual measuring device of circular run-out

The straightening is realized in these few steps:

1) measuring of the circular run-out of the shaft, using a simple device (Fig. 4.);
2) marking of the biggest positive deviation of gauge M1, or M2 on the shaft;
3) hitting the shaft with a hammer with several hits, right in the marked position, against an anvil;
4) measuring of the resultant run-out and repeating the steps above, if necessary.

This process is not difficult and does not require precision in positioning of the shaft around its axis. The forces of the hits should be the same, to obtain consistent decrease of the run-out, but the size of the strike force depends mostly on an operator. This means, that the operator has to learn how many hits are needed to straighten certain run-out value. These hits create plastic deformation of the shaft surface. Creation of compression stress is then result of this plastic deformation. There also will be reinforcing effect in the place of hit [Dvorak 2013]. It is very important to avoid hitting the shaft in the position where it is measured by the gauges, because the next measurement would not be correct. The straightening must not be performed also at the position where the roller bearing will be mounted. Any straightening at this area would have negative impacts on inner homogeneity of the material so the roller bearing would not have the standard properties. Even though the described manual straightening process is not difficult, it is very easy for an operator to make a mistake, such as:

- incorrect measurement of the run-out;
- straightening in prohibited areas;
- the shaft wrongly positioned;
- accidentally skipped shaft;
- over-straightening.

Over-straightening is not an issue in general, because the shaft can be straightened back, but it makes the overall straightening process unnecessarily longer. The demand of the shafts is around 3375pcs on one shift. It is needed to employ at least 4 operators to meet this demand, which increases the costs of the whole process. Therefore the manufacturer contacted the Mesing Ltd. with request for an automatic straightening machine, to minimize these expenses and to eliminate some of the mistakes caused by the operators.

4 AUTOMATIC STRAIGHTENING MACHINE

The automatic straightening machine are nothing new. There are lots of manufacturers of such devices and all of them are working on the same principle. This principle is the plastic deformation of a straightened part, which means that the parts are bended against the original deformation to obtain plastic deformation [Geng 2004]. This process is realized via very powerful ram and two prisms which hold the part.

Figure 5. Alternative straightening machine [Galbadini 2012]

Such straightening device with several prisms is shown in the Fig. 5. The number of prisms determines the positions, where can be the part straightened. This design is more than suitable for long hardened parts, or the not hardened parts which are after the final machining. This design also provides very small and precise final run-out values.
Unfortunately, this concept cannot be used for straightening of the spindle shaft for one reason. The shortest shaft is around 150mm long and the tip of the shaft (Fig. 3.) is very thin, so the prisms would have to be further from the very end. This gives us the pitch around 110mm that can be used for straightening, between the prisms. It is necessary to bend the shaft over the elastic deformation up to plastic deformation to obtain permanently straightened shaft. It is very important to keep in mind, that the shafts are highly hardened, so the material structure is still brittle, even though the shafts have been tempered. This bending of the shafts combined with material brittleness leads to crack nucleation which can lead to fatigue fracture [Fahlkrans 2015]. That can be very dangerous given to the speed and weight of the rotating spindle with the spool.
The Faculty of Mechanical Engineering of the Brno University of Technology and Mesing ltd. have made a decision to solve this problem by designing the automatic straightening machine with principle of straightening based on the principle used so far by producer of the spindles.

5 DESIGN OF MEASURING AND STRAIGHTENING SECTION

The technical specification has to meet the needs of the costumer. Some of the most important specifications are these:

- 100% run-out check;
- 100% straightening, if the run-out exceeds 0,04mm accordingly to Figure 3.;
- no more than 3 straightening attempts;
- parts with run-out over 0,7mm are automatically rejected;
- cycle time has to be 8s per one piece;

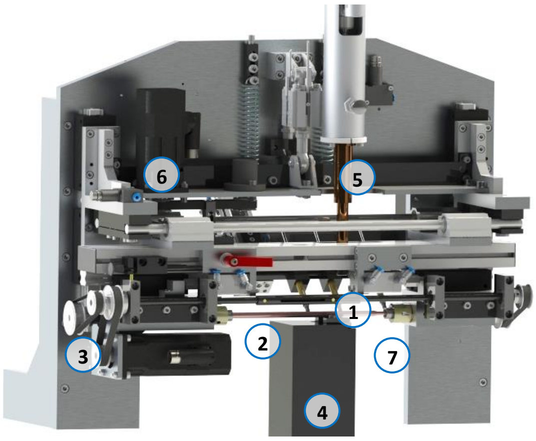

Figure 6. The design of measuring and straightening section

Another very important condition is to evenly distribute the hits over the shaft surface. The validity of mentioned reinforcing effect was verified during the experimental phase. This effect caused that only the first hit creates significant plastic deformation, and therefore compression stress leading to straightening of the shaft. The second hit then must have much more impact energy to obtain the same, or similar results as in case of the first hit. This applies only if the position of the impact was the same. In other words two and more hits must always be side by side.
All of the mentioned requirements were met and the final design of the main measuring and straightening section is shown in Fig.6. The marked parts are the most important:

1) measuring gauges S1; S2; S3; S4;
2) the shaft;
3) servo-motor with the countershaft;
4) anvil;
5) pneumatic piston with bronze hammer;
6) servo-motor for linear positioning;
7) holder of the shaft (cup shape).

$$H_1 = S_2 - k_1 \cdot (S_3 - S_1) + S_1 \quad [2]$$

$$H_2 = S_4 - k_2 \cdot (S_3 - S_1) + S_1 \quad [3]$$

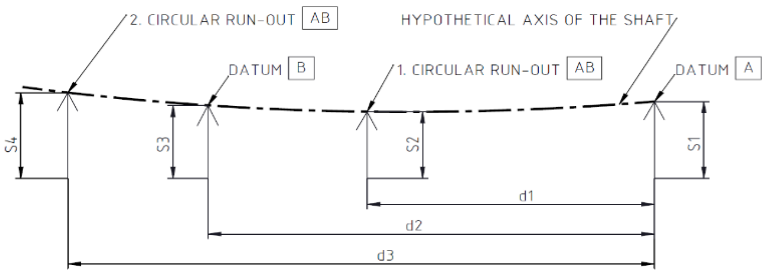

Figure 7. The basic principle of circular run-out calculation

The straightening on device described above is very similar to the principle of manual straightening performed by the operators. The shaft is loaded into the two holders (7) which are connected together via countershaft (3). This allows to

drive both holders with only one servo-motor (6). The four gauges (1) are measuring and evaluating actual value of circular run-out during the rotation of the measured shaft, using the formulas [1] and [2]. The gauges are moved away from the shaft after the measurement and the shaft is rotated to an angle where is the biggest value of the circular run-out facing up. The shaft is then moved downwards and placed on the anvil. The number of hits and the effectiveness zone is chosen, based on the value of the circular run-out. The hammer (5) then hits the shaft with predefined force and with the precise number of hits (see Table 2.).

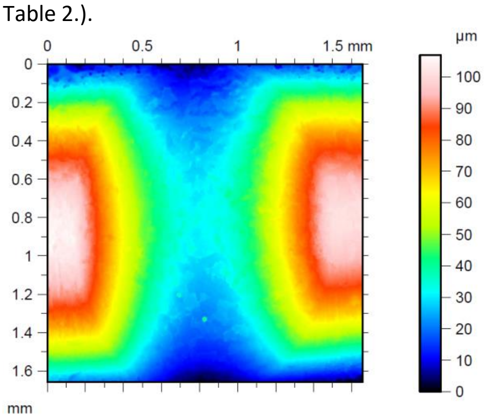

Figure 8. CCI measurement of plastic deformations of the shaft surface after one hit

The shaft is moved forwards, or slightly turned between each hit to avoid hitting one spot two times. The resultant circular run-out is measured and evaluated and the process is repeated if it is necessary.

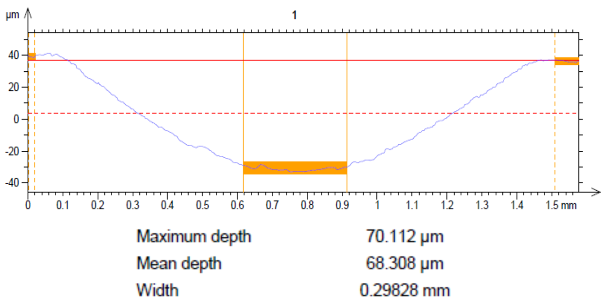

Figure 9. Evaluation of maximum depth of the plastic deformation

The impact energy of the hammer is important parameter, but it does not have to be exactly calculated. This energy is determined by the weight of the hammer and by pressure of the air which is fed into the cylinder. The pressure of the air can be easily manipulated with, so it was used as a variable. There are two aspects used to determine the pressure. First aspect is to reliably straighten the smallest deviation from desired tolerance of circular run-out without the risk of over-straightening. The second aspect is to achieve plastic deformation that will be reliably ground off in the next manufacturing step. One of these deformations was measured on CCI as shown in Fig.8. The maximal amount of deformation was evaluated based on this measurement (see Figure 9.).

Circular run-out [mm]	Zone1 [# of hits]	Zone2 [# of hits]	Zone3 [# of hits]
0-0,04	$h_{1,1}$	$h_{1,2}$	$h_{1,3}$
0,04-0,05	$h_{2,1}$	$h_{2,2}$	$h_{2,3}$
0,05-0,07	$h_{3,1}$	$h_{3,2}$	$h_{3,3}$
0,07-0,9	$h_{4,1}$	$h_{4,2}$	$h_{4,3}$
0,09-0,13	$h_{5,1}$	$h_{5,2}$	$h_{5,3}$
0,13-0,17	$h_{6,1}$	$h_{6,2}$	$h_{6,3}$
0,17-0,21	$h_{7,1}$	$h_{7,2}$	$h_{7,3}$

Table2. Example of straightening scheme

The Table 2. is an example, because the values are different for every type of the shaft and they are still being modified. The effectiveness zones were identified during the first tests on the model device. The model device had the same layout as Fig. 6. The number of hits was found experimentally by measuring a large number of shafts, sorting them into groups with very similar values of circular run-out, and then trying to straighten them with certain number of hits. During this tests, the results were continuously evaluated and the numbers of hits were changed, as were the zones.

6 RESULTS

The sample of 100 shafts was measured, and their initial circular run-out values were recorded and so were the angles were was the maximal run-out deviation. Then the shafts went through first straightening attempt with straightening scheme defined previously. The second run-out was measured and the values have been recorded. This process was repeated until the shafts were straightened into specified tolerance of run-out. Maximal number of straightening attempts was set to 3. Changes of the run-out and the angles are shown in Table 3. The straightening scheme was evaluated based on the results in Table 3.

SHAFT	Initial run-out [µm]	Angle of max.[°]	Run-out after 1st attempt [µm]	Angle of max. [°]	Run-out after 2st attempt [µm]	Angle of max. [°]	Run-out after 3st attempt [µm]	Angle of max. [°]	Final run-out [µm]	Attempts
1	80	198	26	180	-	-	-	-	26	1
2	40	322	28	326	-	-	-	-	28	1
3	88	65	39	60	29	52	-	-	29	2
4	63	216	16	196	-	-	-	-	16	1
5	93	326	33	349	-	-	-	-	33	1
6	28	0	-	-	-	-	-	-	28	0
7	82	121	38	143	29	154	-	-	29	2
8	60	138	10	153	-	-	-	-	10	1
9	49	140	36	142	28	137	-	-	28	2
10	148	207	55	224	41	211	30	221	30	3
11	48	290	36	297	26	296	-	-	26	2
12	96	185	31	203	-	-	-	-	31	1
13	295	111	57	78	27	171	-	-	27	2
14	20	149	-	-	-	-	-	-	20	0
15	308	18	44	358	30	355	-	-	30	2

Table3. Initial run-out dimensions and run-out values after first, second, third straightening attempt and the angle of maximum deviation

7 CONCLUSION

The whole automatic straightening machine is not complete yet, but the first result indicates that automatic straightening of such parts is possible. The most important part is a correctly defined table with effectiveness zones and the numbers of hits. Not only because of the straightening attempts limitation by the costumer, but also because the cycle time, which gets longer with every unnecessary attempt. Further analysis of reliability and of a statistical data is needed, but for this analysis the whole system must be finished.

ACKNOWLEDGEMENTS

This work has been supported by Brno University of Technology, Faculty of Mechanical Engineering, Czech Republic (Grant No. FSI-S-14-2401, FV 16-37).

REFERENCES

[Benesova 2007] Benesova S. Material modeling and numerical simulation as a tool for the development of technological processes (in Czech). Plzen: University of West Bohemia in Pilsen, 2007, 119p.

[Dvorak 2013] Dvorak, M., Gajdos, F. a Novotny, K. Forming technology: sheet and mass forming (in Czech). Ed.5., Brno: Academic publishing CERM, 2013. ISBN 9788021447479.

[Fahlkrans 2015] Fahlkrans, J. Effects of manufacturing chain on mechanical performance: Study on heat treatment of power train components. Stockholm, 2015. Licentiate thesis. School of Industrial Technology and Management.

[Fürbacher 2006] Fürbacher, I., Steidl, J. a Macek, K. Lexicon of technical materials with foreign equivalents. Praha: Verlag Dashöfer, 2006. ISBN 80-86229-02-5.

[Galbadini 2012] Straightening machines, automatic and manual machines - Galdabini [online]. [quoted 2016-04-10]. Available from: http://www.galdabini.it/wp-content/uploads/2012/11/PAS-Straightening-rack.png

[Geng 2004] Geng, H. Manufacturing engineering handbook. New York: McGraw-Hill, c2004. ISBN 0071398252.

[Machek 2013] Machek, V. Metallic materials 1: structures of metallic materials (in Czech). Prague: Czech Technical University, 2013. ISBN 978-80-01-05248-8.

[Zoch 2015] Zoch, H.-W. Distortion Engineering 2015.Bremen, Germany, 2015. ISBN 978-3-88722-749-4

CONTACTS:

doc. Ing. Robert Jankovych, CSc.
Ing. Martin Weigl
Brno University of Technology
Faculty of Mechanical Engineering
Institute of Production Machines, Systems and Robotics
Technicka 2896/2 Brno, 616 69. Czech Republic
Tel.: +420 605 440 420, e-mail: jankovych@fme.vutbr.cz
Tel.: +420 774 922 842, e-mail: martin.weigl@mesing.cz