ADAPTIVE CONTROL IN THE STRAIGHTENING PROCESS OF CASE HARDENED PARTS.

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SUMMARY

This paper presents an application of adaptive control to the process of straightening casehardened mechanical parts. The proposed method allows drastic reduction in process time, and can be applied to automatic straightening machines obtaining good results, as shown by experimental data. The work deals in particular with problems relevant to the control algorithms that must be implemented on the CNC of the machine, to allow application of the proposed method.

Keywords: Automatic Straightening, Adaptive Control Straightening

1. INTRODUCTION

The process of cold straightening machined mechanical parts which have already undergone heat treatment prior to grinding, or on finished parts is considered here. Unlike adaptive bending, this process is carried out on pieces which must comply with certain precision requirements and which have strict geometrical tolerances. Moreover, the brittle martensitic surface is under risk of cracks that would compromise the integrity of the part undergoing straightening. The strokes are thus subjected to severe limitations that keep the plastic deformation of the part equal to or even less than the elastic one. Finally, there is a tendency toward the processing of small lot sizes that calls for implementation of simple and versatile straightening methods.

For these reasons, it is worthwhile to investigate on the possibility of extending the well-known adaptive control technique to the still uncovered field of straightening case hardened parts.

1.1 Automatic straightening methods used industrially

Automatic straightening machines, used in some manufacturing sectors, consist basically of hydraulic presses equipped with Numerical Control, sensors for dimensional inspection of parts and automatic devices for loading and unloading parts.[1]

In general, these machines are used to detect errors in linearity of the part through a measurement system able to distinguish between errors in shape and true linearity errors and to define the plane on which they appear.

A particular CNC program establishes the strategy of intervention of the machine and determines how and where to operate on the part to minimize the number of points of intervention, taking account of the individual local contribution.

The increments of displacement given to the piston stroke should decrease as the number of straightening cycles increases, and are established in relation to the residual error detected so as to avoid the risk of over-deforming the part, obtaining a new straightness as concerns overall straightening of the part.

In the working cycle, the load is applied on the piece positioned, with curve at the top, on V-blocks and a first value, derived from previous experience, is established for the piston stroke to barely exceed the elastic limit of the material of which the part is made. In this case it is impossible to predict the effects of the stroke applied. Accordingly, successive error measurements and successive piston strokes, with increasing displacement, are necessary to bring the linearity error within the established tolerance range.

In some cases, during straightening, the machine self-learns the pressing cycle, in order to apply it to each individual part in the lot.

In any case, this procedure may require as many as 5-7 piston strokes for each straightening point and these in turn may be as many as six for long, slender parts, so that it becomes time expensive.

1.2 Adaptive control methods applied .

Adaptive control is a technique that has been applied for many years in different sectors of mechanical production. It has been successfully applied to machines for chip removal, and is now increasing widely used in metal forming operations.

In the latter case, adaptive control is used to direct the process toward pre-established objectives, adapting the process itself to the characteristics of different material and taking account of the alterations they may undergo during machining.

Adaptive control methods have already been applied to processes such as bending [2] [3] [4], roll-bending [5] and to multiple bend profiles [6] in order to achieve narrower tolerances on the final part.

In the above mentioned processes the stroke assigned to the piston is long, and the principal problem is to develop a non-linear function that correlates the internal bending moment to the displacement of the punch, so as to understand the material properties of the piece undergoing machining and to foresee the springback at each point of the stroke.

The case of straightening is quite different. Here the punch stroke required to carry out the operation is very short, so that elastic and plastic deformation are approximately of the same magnitude. Consequently, there is no condition to fit a deformation model to the experimental load-stroke curve, and the evaluation of the springback is obtained by simplified considerations directly on the load-stroke diagram. Moreover, if the specimen-tool contact area is wide enough, there will be negligible deviation in the diameter of the specimen, so that no correction is needed on the straightening algorithm in order to compensate this effect.

Some authors have successfully applied adaptive control methods in the straightening of mechanical components, as in the case of pipes for the oil industry [7]. Some systems, which may be highly sophisticated, are complemented by expert systems used to orient selection of the machining process phases and of the technological parameters to be used, as in the case of a system developed for straightening turbine blades [8].

To the knowledge of the authors, there are no relevant scientific reports on the adaptive straightening of case hardened parts.

1.3 Straightening of case-hardened parts

The straightening of steel mechanical parts which have undergone case-hardening or hardening treatment is a particular application of significant interest to industry for the following reasons:

- the mechanical parts on which automatic precision straightening is performed prior to grinding are in most cases case-hardened and hardened parts. Thanks to straightening in fact, the machining allowance to be removed by grinding is limited and the case-hardened layer, after grinding, is more uniform over the entire part;
- there is a very close link between thickness of case-hardened layer, extent and mode of straightening and the generation of surface cracks on the part. Experimental determination of these phenomena is of great interest to those applying the treatment since the depth of case-hardening to be realized on the part is selected according to the thickness of the case-hardened layer required on the finished part, in relation to possible straightening and subsequent grinding. On the other hand, the different depths of case-hardening give rise to different deformation of the part;
- case hardened parts are in a critical situation during straightening, inasmuch as they are bend stressed and the stress is greater in the outer

fibers, which are most rigid and brittle.

Conducting straightening tests in these conditions should guarantee the same success also in more favorable conditions.

2. OBJECTIVES OF THE WORK

Analysis of the bibliography available on the one hand and the needs of industry on the other has revealed interest in the development of an adaptive control system that is simple and easily to apply, suitable for use in precision straightening of case-hardened parts whose geometry and dimensions may vary significantly and which may be built of materials having different characteristics.

Accordingly, the objectives of the work were the following:

- verifying the possibility of adopting adaptive control techniques in the straightening of case-hardened parts
- developing a simple, flexible system that could be integrated with the CNC of modern presses for automatic straightening, particularly designed for the machining of small and medium-sized production lots, with the aim of limiting to a minimum the time required for machine set-up as well as drastically reducing machining time.

3. THE SYSTEM DEVELOPED

- **Nomenclature**

F	current load
y	current position of the punch
F_0	contact load
y_0	contact position of the punch
α	elastic stiffness of the specimen, $\alpha = F/y$
F^*	transition load
R_e	elastic springback, $R_e = F/\alpha$
R_c	permanent deflection, $R_c = y - Re$
R_c^*	straightness error to be eliminated
y'	stroke to be assigned to the punch in order to correct the error
v_p	punch speed

- **General arrangement of the straightening system**

In its current stage of development, the Straightening Control System (SCS) developed consists of a unit independent of the straightening machine, which must be integrated with the CNC and with the measurement system of the machine.

The SCS controls all stages of the process: the straightness error input, the start of the process, the evaluation of the stroke to be assigned to the punch, the stopping command, and the no-load return stroke of the punch.

During the loading cycle the system reads the values of force and deflection measured in process, and determines the stroke to be assigned to the press by predicting the elastic springback of the part, in order to obtain the established tolerance value in a single stroke of the piston for each selected point of application.

On the basis of this criterion, the characteristics of the material, the geometry of the piece and the distance between the rests need not be taken into account directly.

This procedure enables substantial reduction in the time necessary for completing the straightening procedure on the entire part [9]. This kind of approach has been studied also by other researchers using both analytical and experimental methods [10] [11].

The System processes the values read by the force and position transducers, with which the machine must be equipped (Fig.1), to furnish the CNC the y’ value of the piston stroke in order to correct the error detected.

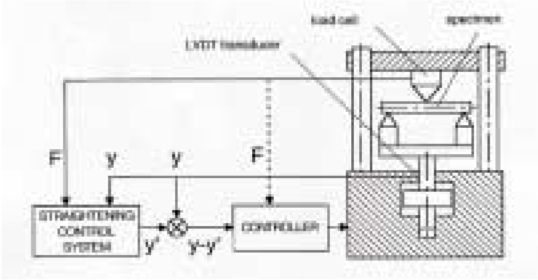

Fig. 1 - General arrangement of the straightening system

The general architecture of the system is outlined in Fig.2.

In a preparatory phase, the programming functions of the process are entered, such as the straightness error R_C* to be eliminated and the speed v_p of the punch in the various sections of the stroke. Then, the press is started.

At the start of the process, no reliable elastic stiffness value is available. As the stiffness function $\alpha=\alpha(t)$ is unstable, it cannot be used for subsequent processing. Thus, a contact identification routine is used.

After the punch has contacted with the part, the load and position are considered. In this “position control module” the system simply evaluates the stiffness, without any consideration about the permanent deformation of the specimen. This module is active until reliable values of the stiffness α and the elastic springback R_e are available.

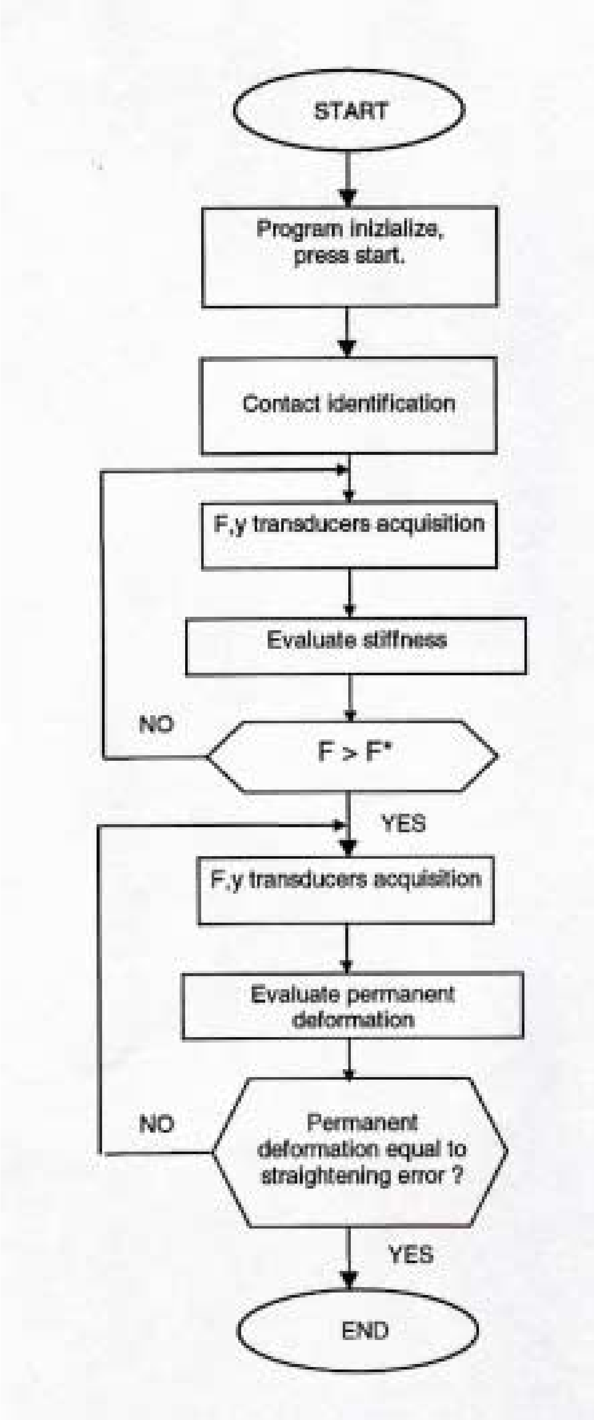

Fig. 2 - Block diagram of the Straightening Control System.

The subsequent “deformation control module” evaluates the permanent deformation of the billet and compares it with the linearity error to be eliminated. During this stage the control allows different speeds to be set for the punch in relation to the travel reached in percentage terms in respect to the value R_C*, so as to define decreasing values of speed, in order to obtain a slowdown approaching stop which renders negligible the inertial phenomena of the hydraulic press system.

To pass from one control to another, on the basis of analyses carried out through simulation programs developed for this purpose, a threshold value F* has been introduced for the load, below which there is position control and above which the system goes on to deformation control.

- **Contact identification**

A subroutine for identifying the contact between punch and specimen has been developed, in order to avoid anomalous behaviours of the system. In particular, when the press is started, a step to step displacement of 5μm/cycle (corresponding to 0.5 mm/s ram speed) is actuated, until a threshold value of the load, F_0, can be read from the load cell. This threshold value must be set in relation to the specimen to be processed and represents a compromise between the need to have rapid identification of the contact and to avoid background noise from the load cell.

The F_0 value and the corresponding y_0 value are then used as the new origin of the axis in the load-displacement plot. It can be demonstrated that the displacement of the origin does not affect the stiffness evaluation, if this is done by means of the mean square method [12]. Thus, all the values read from the transducers are depurated of F_0 and y_0 before they are processed by the system.

- **stiffness evalution**

Once the punch is in contact with the part, the load F and the displacement y of the piston are processed, so as to determine, in the elastic region, the stiffness α.

Two methods have been tested for α evaluation (Fig.3).

In the first, the stiffness line is updated at each new point by linking it to the axis origin; in the second, a vector of the last twenty (F, y) measured values is used as the basis for evaluating the interpolating line with the minimum square method.

The second method gives higher values of the stiffness, because the slope of the curve is not at its maximum value from the beginning, even if a high contact load F_0 is chosen. The $\alpha = \alpha(y)$ function obtained with the minimum square method is plotted in Fig.4.

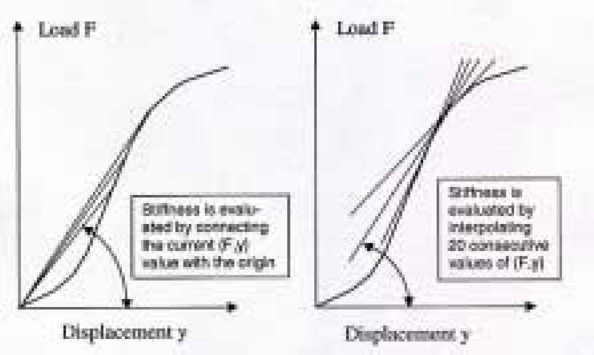

Fig.3 – Two methods have been used to evaluate stiffness

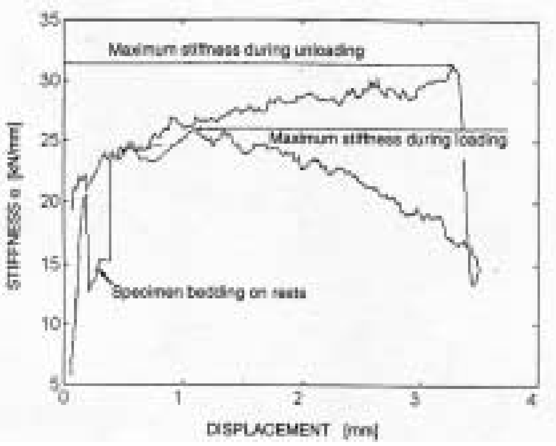

Fig.4 – Typical stiffness function during loading and unloading

The slope of α values during the loading of the specimen is evident, whereas during unloading the hysteresis of the mechanical system leads to ever decreasing stiffness values, with the maximum at the beginning of the unloading stage. It is also evident from Fig.4 the transitory drop in stiffness in the early stage of loading, due to the bedding of the specimen on the rests.

- **Data filtering**

Fig.4 shows the continuous scattering of the signal, which is due not only to the background noise of the load and position transducers, but primarily to stick-slip phenomena at the interface between the specimen and the rests. An array with the maximum 15 computed values of stiffness is thus continuously updated. The arithmetic mean of these values is used as stiffness evaluation.

The behaviour of the coefficient α during the active stage of the punch with and without a filtering algorithm, is shown in Fig. 5.

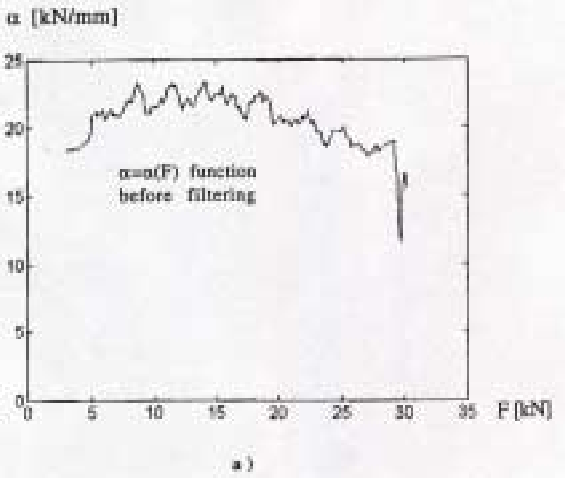

Fig.5 – $\alpha=\alpha(F)$ function before filtering

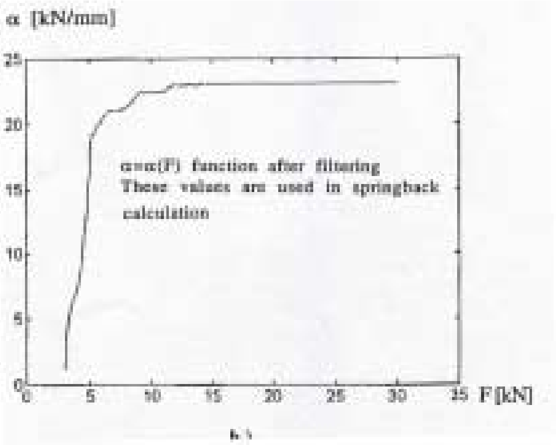

Fig.5 – $\alpha=\alpha(F)$ function after filtering

- **Permanent deformation evaluation**

From the analyses of the loading and unloading pattern of stiffness (Fig.4), it can be seen that, even in presence of intense hysteresis in the load-travel diagram, the maximum value of stiffness during the loading cycle is approximately equal to the mean value of the stiffness during unloading. This has also been confirmed by other experimental tests conducted by the authors. It is thus assumed that during the unloading phase the elastic springback predicted for the part undergoing machining is given (Fig.6) by

$$R_e=F/\alpha \qquad (1)$$

so that the permanent deformation predicted for each pair of F and y values will be:

$$R_c = y - F/\alpha. \qquad (2)$$

When the plastic region with a reduced α value is obtained, the system compares the instantaneously calculated value of R_C with the R_C* value set at the beginning (linearity error); as this reference value approaches, punch speed is reduced and the punch is stopped when the value is reached. The operation of the system is illustrated in the block diagram in Fig.7.

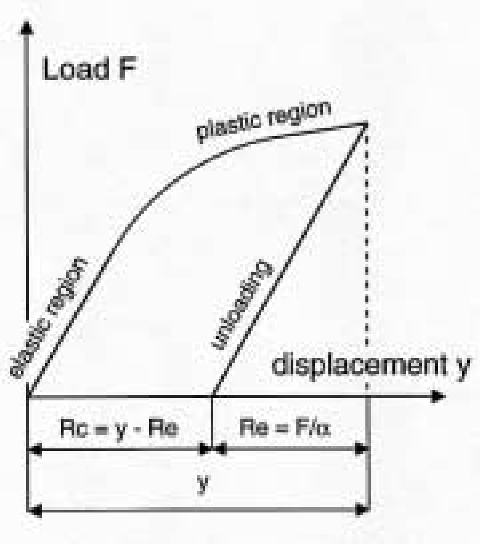

Fig.6 – Model for evaluating the permanent deflection

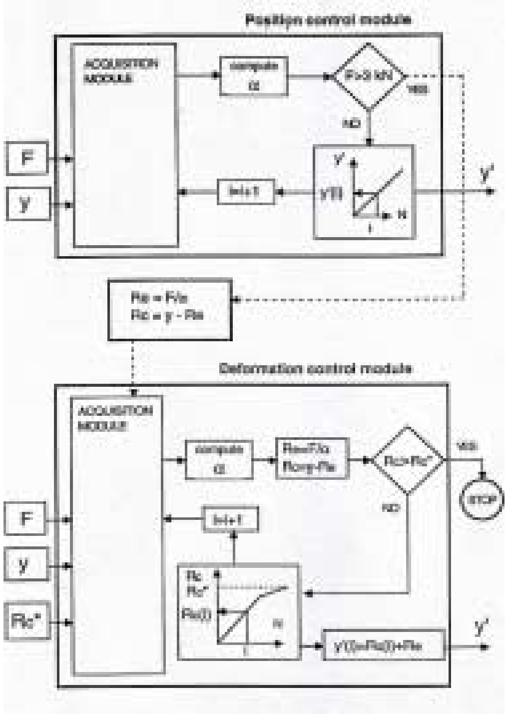

Fig.7 – Block diagram of position and deformation control modules

4. EXPERIMENTAL TESTS AND RESULTS

Within the context of testing the applicability and reliability of the system and the validity of the method adopted, the tests performed, with the intent of having repetitive conditions available, were in reality bend tests; that is, the permanent deformation values to be obtained on the part (linearity errors) were set and the results were verified, by evaluating the error. A hydraulic press for testing materials Instron 8032, equipped with CNC, with its own LVDT displacement transducer and with 100 kN load cell, was used. The machine was also equipped with another displacement transducer Heidenhhain MT25K, for verifying the final deformation on the test specimen.

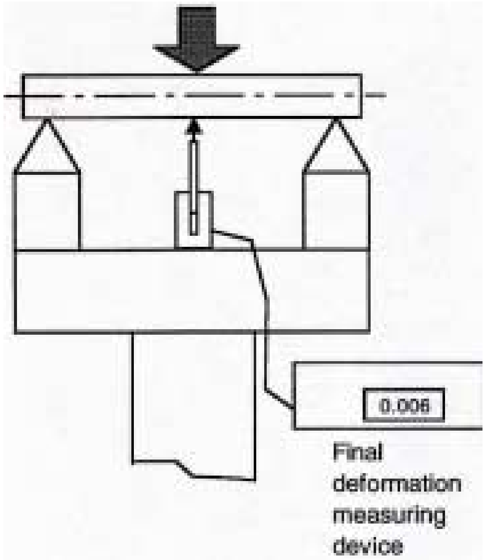

Fig.8 – Measuring device for straightening performance evaluation

The system software was developed on a 90 MHz PENTIUM personal computer interfaced, through A/D converter card, with the machine transducers and also interfaced to the CNC of the press.

The data acquisition system was developed with analogic signal for the load, coming from the load cell of the press, and in both digital and analogic form for the displacement. The acquisition speed in the second case was 100 Hz in spite of 67 Hz obtained with digital acquisition. This is due to the fact that the digital signal needed more channels to be separately read and composed in order to obtain the desired value.

The tests were conducted on test pieces made of 16NiCrMo5 (UNI 16NCD5) steel with diameter ϕ=18 mm and length L=120 mm, case-hardened with thickness of 0.5 and 1.0 mm.

Three supporting devices for the test specimens were used: a simple V block with sharp edges, and two V pins of 6 and 8 mm diameter respectively (Fig.9).

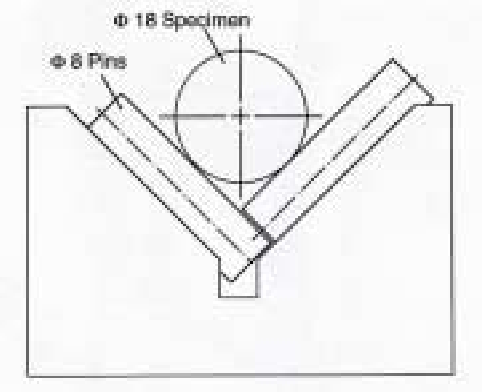

Fig.9 – Φ 8 [mm] pins supporting device

The punch, installed on the piston of the press, also was V shaped, in order to share the specific load on the billet and minimize both indentation phenomena of the martensitic layer and deviations in the diameter of the specimen.

The test campaign, after initial development of the various software modules and of the instrumentation needed for data acquisition, was carried out in the following conditions:

- test specimen supported on V blocks
- distance between the blocks 120 mm.- slenderness ratio approximately 6.6
- punch speed in the position control module 0.45 mm/sec;
- punch speed in the first ramp of deformation control module 0.4 mm/sec;
- punch speed in the second ramp of deformation control module 1.15 mm/sec;
- threshold value for load F* = 3 kN;
- connection between first and second ramp of deformation module at 85% of R_C*.

The main objectives of these tests were those of verifying the precision and repeatability of the results furnished by the system for the various values of permanent deformation entered.

In a first set of tests, case hardened test specimens with thickness of 0.5 mm, positioned on various types of V block, were tested. The results are shown in Fig.10.

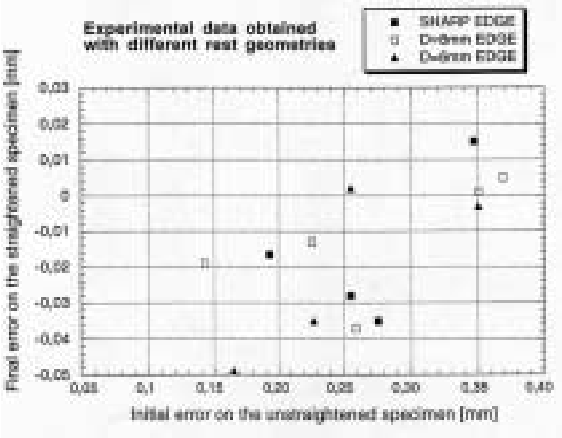

Fig.10 - Linearity errors after straightening 0.5 mm case-hardened depth specimens
using different rest geometries

A better performance was observed with blocks consisting of pins ϕ 8 mm, which were then used in a second set of experiments on test specimens with casehardening thickness of 0.5 and 1.0 mm. The results are shown in Fig.11.

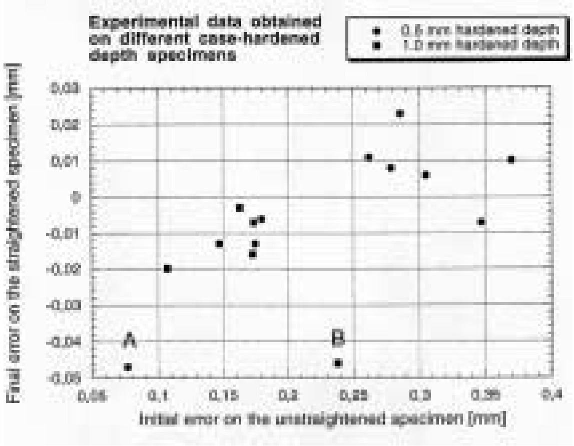

Fig.11 - Linearity errors after straightening 0.5 and 1.0 mm case-hardened depth specimens.

5. DISCUSSION

From the first test results (Fig.10) conducted on 0.5 mm casehardened depth specimens, it can be observed that the rests with round pins of 8 mm in diameter gave the least scatter of final linearity error; namely, 0.04 mm of global tolerance range. The 6 mm diameter pins and the sharp edge gave 0.05 mm of tolerance range. Consequently, the first type of rest was adopted in the subsequent tests.

The straightening process of specimens with 1.0 mm casehardened depth is subject to greater limitations in load, in order to avoid the occurrence of cracks on the martensitic layer. As an example, test specimen B of Fig. 11 is out of tolerance, expressly because of the occourring of this phenomenon in the final stage, which determined a different stiffness value in the unloading phase. The tolerance range for the uncracked specimens is in this case +/- 0.01 mm.

The minimum deformation that the system, in its current state of development, is able to correct effectively is approximately 0.1 mm, as shown by test specimen A.

The existence of a correlation in the distribution of the final errors on the specimens suggest that the calculation algorithm should be improved in order to restrict the tolerance range still further. In particular, understimation of stiffness leads to overstraightening of the specimen, whereas overstimation of stiffness produces understraightened parts. It is thus evident that the system overstimates the stiffness at low loads (because the specimens are understraightened below 0.2 mm in linearity error) and understimates it at high loads, where overstraightening occurs. Further research is thus needed to understand the mechanics of the process, in order to eliminate these systematic errors from the straightening system, thus reducing the tolerance range achievable on the part.

6. CONCLUSIONS

1 - The feasibility of adaptive control straightening procedures on casehardened components within the tolerance ranges normally required in industrial practice has been demonstrated.

2 - A control system interfaceable with any CNC press equipped with load and displacement transducers has been developed.

3 - The system, although subject to further improvement, guarantees effective straightening of test pieces within the permissible tolerance limits.

4 - The entire system of experimental type will be suitable, once it has undergone further testing for the most widely varying working conditions and after real tests have been conducted on mechanical parts with errors in linearity, for implementation using a dedicated microprocessor, which can be connected directly to the CNC of a press expressly designed for the straightening process.

ACKNOWLEDGEMENTS

The authors would like to thank ing. V. Ciavatti and Mrs V. Roversi for providing laboratory facilities and MURST (Ministry of University and of Scientific and Technological Research) for financial support.

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