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Evaluation of Shape Memory Alloy Bulk Actuators for Wear Compensation in Ball Screw Drives

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Abstract: In this paper we present an approach to reset a preload loss in ball screw drives which enables to compensate losses of positioning accuracy due to wear over lifetime. The main purposes are reduced maintenance, longer service life and improved workpiece quality by regenerating the desired preload conditions which leads to a higher profit for manufacturers.

For this purpose, a novel shape memory alloy (SMA) bulk actuator module for ball screw drives is designed. The device is developed to be implemented in standard drives without major changes in component design. It is installed between flanged nut and counter nut and replaces a spacer usually needed to set a defined preload. To achieve the required actuator performance SMA bulk actuators are investigated in detail. This covers their basic design and activation concepts. A prototype is designed and experimentally investigated; measurements show the proof of the concept..

Keywords: Ball screw drive, shape memory alloys, wear compensation, bulk actuator, machine tool

1. INTRODUCTION

Today's economic demands in manufacturing drives the requirements for high precision and productivity rates in machine tools design. One of the most common machine tool drives for linear motion is the ball screw drive (BSD), which converts rotational motion of the servo motor to linear motion of the machine tools structural components.

The advantages of modern BSD are high rigidity and low friction, and therefore a high efficiency of up to 98% compared to alternative systems like rack and pinion. Due to less friction and moderate operating temperatures, they achieve high life expectancies. However, to achieve the required accuracy, it is necessary to preload the BSD to avoid backlash which is caused by the clearance between the contacts of the ball bearings and the threads of nut and screw. Clearance however, is needed to prevent unnecessary friction during operation of the BSD. Different preload levels determine the rigidity and thus the maximum load a drive can carry. Beyond that it defines the amount of heat to be dissipated due to friction which also leads to wear of the components.

The conflict between these two requirements depends on varying rigidity and consequently in an altering inherent axial backlash or clearance between nut, balls and shaft. For this purpose, in current commercial BSDs, double nuts (see Fig. 1) are commonly preloaded to keep the desired pretension according to customers specifications.

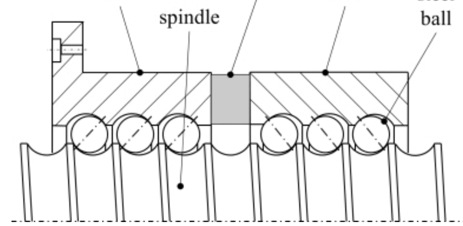

Fig. 1: Double nut ball screw drive with spacer ring.

Moreover, preloading likewise affects friction force and heat generation during the process. Thus, it causes a varying initial preload and hence affects the positioning accuracy and further the service life. In other words the higher the preload, the greater the stiffness and wear rate. Hence machine tool users have to change the BSD after certain service life between 2 and 4 years which results in costly repairs and consequently in reduced availability of the machine tool. In order to overcome this problem an active system to reset the pretension is required.

2. STATE OF THE ART

2.1 Wear compensation in BSD

In the past, many solutions to alter the preload of BSD were proposed. Some solutions concentrated on mechanisms being

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capable to readjust the preload without disassembling the ball screw (when BSD is in standstill state), such as expansion bolts (Raco 2004), differential rings (Warner 1998) or worm drives (Mannesmann 1989).

Beyond that, the first device to vary the BSD preload during operation appeared in literature as a hydraulic piston gear (Good 1969). Accordingly researchers enhanced the approach by developing actuators to control the preload (Johnstone 1984, Weule 1991, Black 1998, Chen 2000, Antonegui 2007, Frey 2010, Fleischer 2012) or to compensate preload shifts due to thermal loads (Chang 2009, Davim 2008) in BSD during operation. A component developed by Fraunhofer IWU which compensates thermal expansions caused by friction and therefor alters the preload of BSD dynamically was published in (Navarro 2014).

The previously mentioned systems are either pure mechanical adjustment mechanisms which require access to the BSD or they are rather complex and cost intensive active systems. None of the currently known active systems is exclusively designed for active wear compensation purposes at reasonable costs.

2.2 Shape Memory Alloys

Due to their high specific workloads and relatively small spatial requirements, shape memory alloys (SMA) possess an outstanding potential to serve as miniaturized positioning devices in smart structure and mechatronic applications. Compared to other actuators such as hydraulics, electric motors or piezoelectric actuators, SMA based-actuators have the highest mechanical work output per volume.

SMAs show the certain ability to recover a seeming plastic deformation, called pseudoplastic deformation (see Fig. 2 path AB), when heated up above the transformation temperature (see Fig. 2 path BC). A subsequent cooling below transformation temperature doesn´t induce any macroscopic changes (see Fig. 2 path CA). This unprompted process, between the low temperature phase (known as martensite (α´)) and the high temperature parent phase (known as austenite (γ)), is described as the one-way shape memory effect. When the forward (γ→ α´) and reverse (α´→ γ) phase transformations occur under external stresses, the phenomenon is designated to be the extrinsic two-way memory effect (TWMSE), as shown in Fig. 2.

Further, the mechanical behavior is asymmetric and highly non-linear with a significant change in stiffness. In order to apply SMA in actuator devices, a reiteration of extrinsic TWMSE (see Fig. 2 path BC) must be realized. To achieve that, an external load is required to reassume the martensite shape whilst cooling. In most applications these external loads are realized by conventional pretensioned springs.

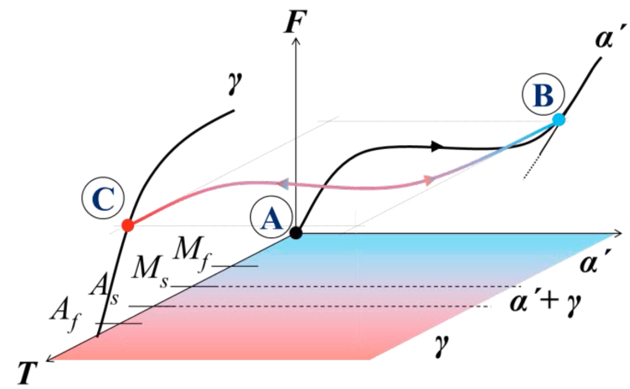

Fig. 2. Force-displacement-temperature diagram of the extrinsic two-way shape memory effect.

When an SMA element interacts with a spring load, the element directly transforms thermal energy into mechanical energy and generates a work output (i.e., displacement and/or force). This work varies according to service temperatures, to the initial pseudoplastic state and to the amount of deformation achieved by the SMA element under the applied spring load. Fig. 3 shows the working principle of such SMA actuator. Actuator recovery force ΔF and stroke Δl are represented by the spring constant in path D-E.

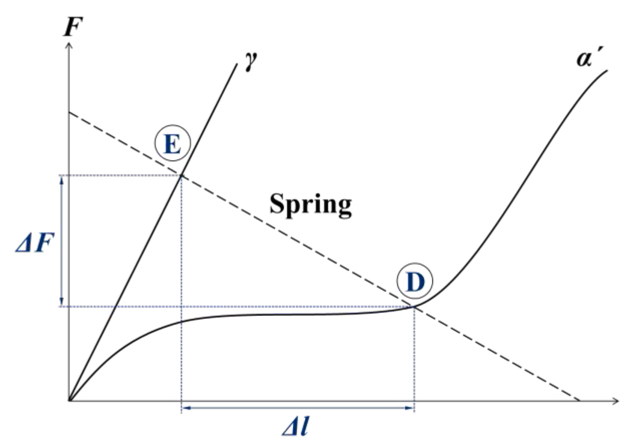

Fig. 3. Working principle of a spring loaded SMA element (ΔF: actuator recovery force, Δl: actuator recovery stroke)

Literature about SMA actuators (Fredericksen 1985, Pemble 1999, Neugebauer 2012) mostly describes approaches related to small wire diameters or thin wall strips which apply pulling forces. In these cases, electrical current for resistive heating or heating foils are used for activation and/or peltier cooling units (Luo 2000) for reduced backward transformation times. In fact, this conventional way of heating results in completely controllable and relatively fast actuators. However, the achievable forces of such systems are usually only a few newtons.

In contrast, machine tools like BSDs are subjected to huge loads and forces and require a high structural rigidity. Their deformations caused by thermal load, stress or wear ranks