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Technical note

Exploiting robotic link deflection for low-cost force measurement in manufacturing

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ABSTRACT

A custom, low-cost force measurement system for manufacturing is presented that exploits robotic link deflection for measurement purposes instead of utilizing a commercially purchased load cell. Force measurement can be an important aspect to many manufacturing processes, as it can allow for force feedback control or other process-planning related operations, such as tool-workpiece autozero or through-the-tool joint tracking. This system is demonstrated on a machine that is used for Friction Stir Welding research, and a Finite Element Analysis is also conducted on the robotic link that is used for axial force measurement purposes. This system may be particularly attractive to small businesses or low-volume manufacturers whose smaller operating budgets may normally prohibit them from implementing force measurement systems.

1. Introduction

Force measurement and feedback control can be important aspects in a variety of manufacturing processes [1]. In machining, force signals have been used to detect the occurrence and the severity of tool breakages [2]. In Friction Stir Welding (FSW), force signals can lend insight into weld quality, and force feedback control can be used to expand the applicability of FSW and even manipulate weld characteristics [3,4]. A low-cost force measurement method is presented here in a FSW application that exploits the deflection of the manufacturing robot itself as a means of measuring force, instead of utilizing a commercial load cell.

FSW is relatively new joining technique that is rapidly expanding to a wide range of industries. It was developed in 1991 at The Welding Institute (TWI) of Cambridge, England [5]. The process involves a rotating non-consumable tool, comprised of a shoulder and probe, which plunges into and traverses the joint line. Material is heated, plasticized, and transferred before being forged together at the rear of the tool probe. The operation is either performed using standard industrial robots or custom machines that are designed specifically for FSW. Forces can be measured using commercially available load cells, but researchers have also developed custom alternatives [6,7]. An application of a custom, low-cost force measurement system is presented here that involved instrumenting the FSW robot itself with strain gages in order to measure axial force during the FSW process.

2. Materials and methods

A custom force measurement system was developed for use at the Vanderbilt University Welding Automation Laboratory (VUWAL), specifically to be implemented on a Milwaukee #2K Universal horizontal milling machine that has been converted to a vertical orientation with a Kearney and Trecker head attachment for Friction Stir Welding purposes. This machine is pictured in Fig. 1. The motion drives on the machine have been retrofitted with motors and position sensors to allow for automatic welding programs and custom control schemes to be utilized. The machine is controlled by a Dell Vostro 230 PC with a custom user-interface.

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Fig. 1. FSW robot at VUWAL.

The force measurement system is displayed in Fig. 2. Axial force is sensed using a full bridge of Vishay Micro-Measurements C2A-06-250LW-350 strain gages mounted in a back-to-back bending configuration just behind the milling machine head. The bridge is powered by a precision 10 V Omega FAR-1 power supply, and the output of the bridge goes into an Omega DRF-LC signal conditioner that is designed specifically for use with load cells. The signal conditioner measures the difference between V_8 and V_9, which can be determined as follows:

$$V_8 = \frac{R_1}{R_4 + R_1} * V_{in} \quad V_9 = \frac{R_2}{R_3 + R_2} * V_{in}$$

The signal conditioner is powered by a standard 24 V power supply and features *offset* and *span* potentiometers for zeroing and amplifying the signal, respectively. The output of the signal conditioner is read by a National Instruments USB-6008 data acquisition device, which is configured to operate with custom code written in C# that runs on the weld control PC.

3. Theory and calculation

The milling machine head was modeled in AutoDesk Inventor and a Finite Element Analysis (FEA) was conducted using Comsol Multiphysics. The purpose of the analysis was threefold:

1. *Prove the concept.*
2. *Determine optimum strain gage mounting locations.*
3. *Examine cross-talk interference from horizontal (F_x and F_y) forces in FSW.*

Multiple loading scenarios were simulated, using different combinations of the forces labeled in Fig. 3. The magnitude of the axial load used in the simulations was 6000 N, and the traverse and side loads were selected as 400 N. Fig. 4 displays a sample of the simulation results in the form of von Mises stress for the 6000 N axial loading scenario. Optimum strain gage mounting locations were determined using these results, and the concept itself was also proved, as the loading resulted in stress and strain magnitudes that could be measured with confidence. This had been a concern, considering the stiffness of the robust milling machine head. It was also determined that the cross-talk interference from the side force during welding could be as high as 4%. Cross-talk interference, which results from other process forces such as F_x and F_y affecting the output of the axial force measurement system, was examined by comparing the stress at the strain gage mounting locations for different combinations of process forces.

4. Results

The axial force measurement system was calibrated using an Omega Model LCCA-15 k load cell with a 15,000 lb capacity. Loads were increased at pre-determined levels from 0 N to approximately 5000 N by raising the milling machine table after the signal conditioner had been zeroed at the no-load state. Fig. 5 displays the calibration chart with a linear trendline fit to the data. The calibrated gain for the system is 17,760 N/V, and with the 12-bit USB-6008 device set to a range of −0.1 V to 1 V, the axial force resolution is 4.8 N. For each particular machine application, the gain would have to be determined in this way in order to quantify the stiffness of the robotic link.

Several friction stir welds were conducted to initially test the new axial force measurement system. Fig. 6 dis-

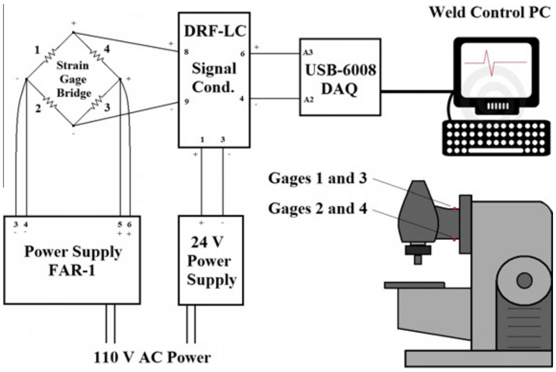

Fig. 2. Axial force sensing circuit.

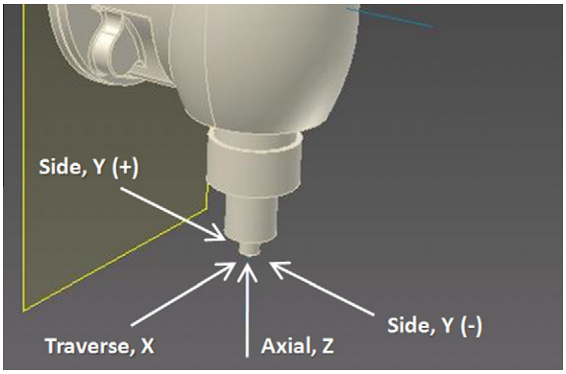

Fig. 3. FEA simulation loads.

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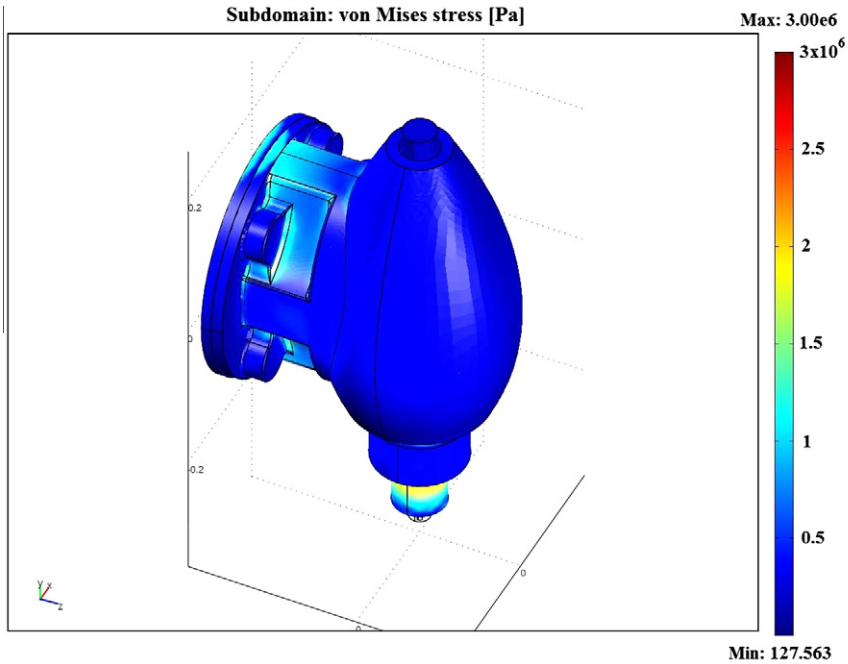

Fig. 4. FEA simulation results.

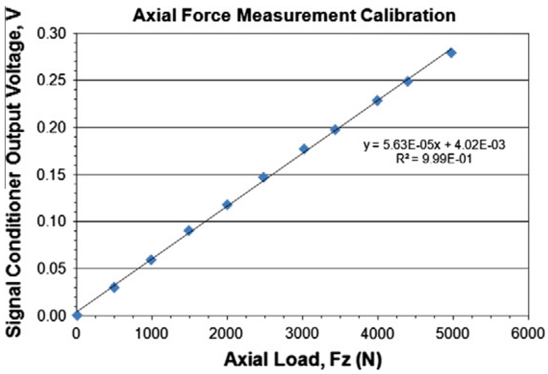

Fig. 5. Axial force measurement calibration.

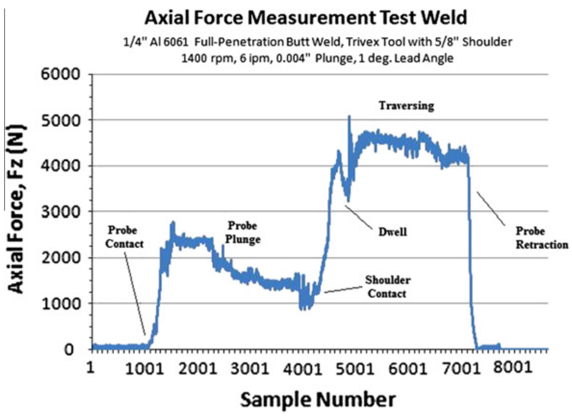

Fig. 6. Axial force measurement test weld.

plays the results from one of these test welds in which 0.25 in. thick Al 6061 plate was welded in a butt joint configuration using a Trivex tool. The welding parameters were 1400 rpm and 6 ipm with a 0.004 in. plunge depth and a 1° lead angle. The system performed well in the tests and has been in use now at VUWAL for over a year.

5. Discussion

One of the great advantages of this type of system is its low cost. The total cost to develop and implement this system is outlined in Table 1. There are some uni-axial load cells that are available commercially for approximately the same price, but they would still have to be installed on the particular manufacturing robot on which measurements are to be made, which might include custom machining and modifications. In the system presented here, the manufacturing robot itself becomes the load cell, and its deflection is monitored using strain gages for force measurement purposes. Assuming the user has at least some experience with instrumentation, a system of this nature should be relatively low-cost and straightforward to setup and calibrate.

The cross-talk interference discussed in the FEA modeling section is relatively low at 4%. This would be acceptable for most measurement and control situations in manufacturing; however, cross-talk will vary from application to application, depending on the design of the manufacturing robot and the particular process being monitored. Interference of this nature can also be eliminated if the side force, in this case, can be measured in real-time as well.

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Table 1
Cost of force measurement system.

Item	Description	Qty	Cost
Power supply	Omega FAR-1 precision 10 V	1	$123.00
Power supply	Standard 24 V, 500 mA	1	$12.42
Signal conditioner	Omega DRF-LC signal conditioner	1	$180.00
Strain gages	Vishay Micro-Meas. C2A-06–250LW-350	4	$28.52
Data acquisition	National instruments USB-6008	1	$169.00
Total cost			$512.94

In industry, force measurement allows manufacturers to implement force feedback control and other processes such as tool-workpiece autozero, which can greatly improve the efficiency of a manufacturing process. Research has also shown that in the field of FSW, force signals can be used to implement through-the-tool joint tracking algorithms, which can significantly simplify process planning procedures [8,9]. The low cost force measurement system presented here could especially have a significant impact on small businesses that are interested in implementing some of these features in their manufacturing processes but cannot afford the typically high-priced commercially available load cells.

6. Conclusions

A low-cost force measurement system for manufacturing was presented that exploits the deflection of the manufacturing robot, instead of utilizing a commercially purchased load cell. Commercially available load cells can be relatively high in cost and may create some restrictions for small businesses or low-volume manufacturers who want to implement force feedback control or other similar control schemes in their manufacturing processes. The system was calibrated and demonstrated on a machine that is used for Friction Stir Welding research purposes. A Finite Element Analysis of the robotic link was also conducted to examine the cross-talk interference, which was found to be relatively low.

Acknowledgment

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