Zygmunt Mikno, Michał Gradkowski

The Pneumatic Force System in Resistance Welding

Abstract: The study involved the analysis of the pneumatic force system, used in resistance welding machines, in relation to the dynamics of electrode displacement. The analysis was performed in relation to two phases of the technological cycle, i.e. positioning pneumatics (from the activation of the pneumatic valve to the moment when electrodes come into contact with the material being welded) as well as the pneumatics of force accretion before and during the flow of current. The analysis, performed using the Festo software programme (phase 1) as well as using elements of the automatics system (phase 2), was focused on two important elements, i.e. time at which electrodes reached their stabilised position and the kinetic energy of electrode impact.

Keywords: resistance welding, pneumatic force.

Introduction

In addition to welding current, welding machine electrode force is one of crucial parameters of the welding process. Resistance welding machines are usually equipped with the **pneumatic force system** (PFS). Such a solution has its both advantages and disadvantages. This article aims to turn the attention of users of above-named welding machines to existing limitations connected with the dynamics of electrode movements as well as to indicate possible optimisation of the force-related issues.

Electrode squeeze consists of two phases referred to as positioning pneumatics and force accretion pneumatics. The first phase includes the displacement of electrodes until they come into contact with a material to be welded, whereas the second phase involves the dynamics of force accretion when electrodes are pressed against the material being welded and the welding cycle (current flow) takes place.

The tests discussed in the article involved simulations of the pneumatic circuit of the welding machine and experimental tests. Because of available computing instruments, components of the pneumatic force system and testing equipment, the analysis of the positioning pneumatics phase was performed using a software programme developed by the Festo company [1]. In turn, the analysis of the subsequent phase, i.e. force accretion pneumatics, was performed using selected components of a pneumatic system manufactured by Festo [2][3].

dr hab. inż. Zygmunt Mikno(PhD (DSc) Habilitated Eng.) – Łukasiewicz – Instytut Spawalnictwa;
mgr inż. Michał Gradkowski (Msc Eng.) – Festo Sp. z o.o.

The article discusses part of the tests constituting a fragment of a larger whole, where the welding process is analysed paying special attention to the control of electrode movements and the new method of welding process control is implemented through the use of the **electromechanical force system** (EFS) [4]. The tests discussed in this publication are concerned with the pneumatic force system (PFS).

Pneumatic system of force control in the resistance welding machine

The characteristics of the pneumatic system in relation to the dynamics of force changes were developed on the basis of the schematic diagram of the pneumatic system of the welding machine presented in Figure 1 [5]. The primary components of the pneumatic system include:

1. air preparation unit (APU) along with the reducer,
2. conduit connecting the APU with the electrovalve of the actuator,
3. electrovalve (EV),
4. conduit connecting the electrovalve with the actuator,
5. pneumatic actuator (PA). Additional elements, important in terms of the PFS dynamics subjected to analysis, include the weight of the piston, piston rod and electrode.

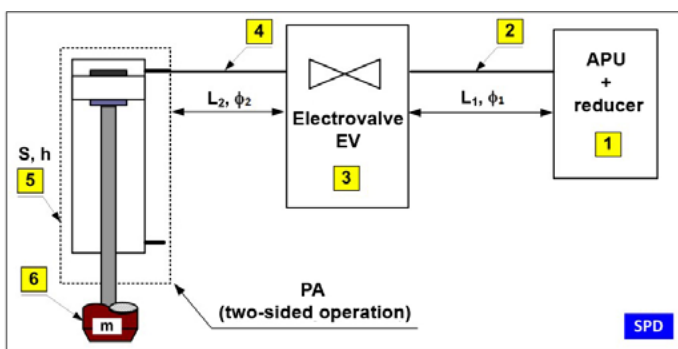Fig. 1. Schematic diagram of the pneumatic system of the resistance welding machine [5]

Computed model of positioning pneumatics

The tests involved the analysis of the PFS in relation to the so-called positioning pneumatics (Fig. 2a), involving the use of a software

programme enabling the performance of simulations of pneumatic systems (Festo) [1]. The software programme makes it possible to determine the characteristic parameters of the welding process, i.e. a time needed for the piston rod to reach its final position, i.e. the moment when the welding machine electrodes cone into contact with the material being welded, the velocity of electrode displacement and kinetic energy when the electrodes cone into contact with the material being welded.

The analysis involved six primary variables presented in Table 1, i.e.

– piston diameter ($\phi_{tł}$) – variant P1,
– piston rod step ($\Delta L_{tł}$) – variant P2,
– actuator working pressure – variant P3,
– length of conduit ZPP – EZ (L_{ZPP-EZ}) – variant P4,
– length of conduit EZ – S (L_{EZ-S}) – variant P5,
– weight moved (m_{el}) (electrode + piston + piston rod) – variant P6.

Selected additional configuration options and component operating conditions of the pneumatic system subjected to analysis (in numerical calculations) are presented below:

– actuator – two-sided operation,
– actuator housing angle – vertical system,
– piston rod movement direction – pushing out,
– check (non-return) throttle – NO/YES,
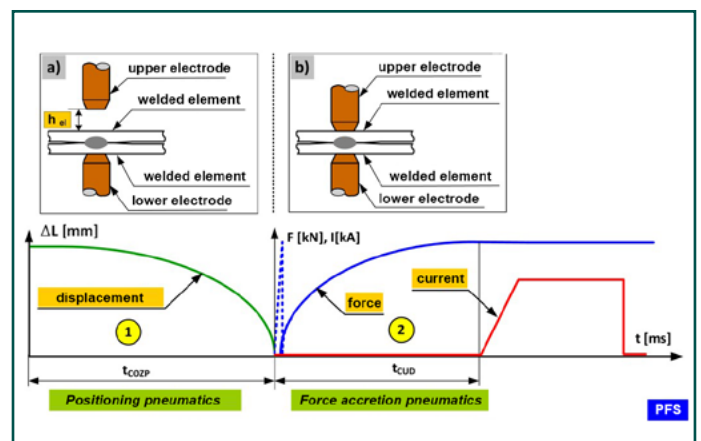– additional friction – NO,
– shock absorber – NO.

Fig. 2. Pictorial courses/curves of electrode displacement and force in relation to the PFS during the resistance welding process in relation to: a) positioning pneumatics and b) force accretion pneumatics

Table 1. Preset parameters and simulation results in relation to PFS (positioning pneumatics)

	No	Variant			P1					P2					P3				
Initial parameters		Two-sided operation actuator		type	DSBC-100-150-P-A					DSBC-100-(10-150)-P-A					DSBC-100-150-P-A				
		Connection (internal diameter)		mm	7,0					7,0					7,0				
		Direction of movement (pushing out)		Y/N	Y					Y					Y				
		Check throttle		Y/N	N					N					N				
		Additional friction		Y/N	N					N					N				
		Shock absorber		Y/N	N					N					N				
	1	Piston diameter	$\varphi_{tł}$	mm	100					100					100				
	2	Actuator piston rod step	$\Delta L_{tł}$	mm	150					10	20	50	100	150	150				
	3	Working pressure	P	bar	6					6					3	4	5	6	8
	4	Length of conduit APU-ZS	L_{ZPP}	m	1					1					1				
	5	Length of conduit EV-A	$L_{EZ\text{-}S}$	m	1					1					1				
	6	Weight moved	$m_{eł}$	kg	2	5	10	20	50	20					20				
Preset parameters	1	Delay time (ADOT)	COZ	s	0,35	0,35	0,35	0,34	0,33	0,04	0,06	0,13	0,24	0,34	0,34	0,33	0,33	0,33	0,34
	2	Mean velocity	$V_{śr}$	m/s	0,46	0,46	0,46	0,47	0,49	0,50	0,47	0,47	0,47	0,47	0,47	0,48	0,48	0,48	0,48
	3	Impact velocity	V_u	m/s	0,52	0,50	0,53	0,52	0,54	0,63	0,53	0,53	0,52	0,55	0,53	0,54	0,55	0,56	0,54
	4	Maximum velocity	V_{max}	m/s	0,54	0,54	0,54	0,55	0,55	0,75	0,65	0,56	0,55	0,55	0,54	0,56	0,56	0,56	0,56
	5	Impact kinetic energy	E_K	J	0,51	0,87	1,60	3,00	7,7	4,20	3,70	3,20	3,00	3,00	3,10	3,20	3,30	3,40	3,30
	6	Air consumption per cycle	v	l	17,0	17,0	17,0	17,0	17,0	2,1	3,2	6,4	11,7	17,0	9,7	12,1	14,5	17,0	21,9

	No	Variant			P4					P5			P6				P7	P8	P9
Initial parameters		Two-sided operation actuator		type	DSBC-(50-150)-150-P-A					DSBC-100-150-P-A			DSBC-100-150-P-A				DSBC-100- ---- -P-A		
		Connection (internal diameter)		mm	4,0	4,0	7,5	7,0	11,0	7,0			7,0				7,0		
		Direction of movement (pushing out)		Y/N	Y					Y			Y				Y		
		Check throttle		Y/N	N					N			N				N		
		Additional friction		Y/N	N					N			N				N		
		Shock absorber		Y/N	N					N			N				N		
	1	Piston diameter	$\varphi_{tł}$	mm	50	63	80	100	125	100			100				100		
	2	Actuator piston rod step	$\Delta L_{tł}$	mm	150					150			150				150	10	50
	3	Working pressure	P	bar	6					6			6				6		
	4	Length of conduit APU-ZS	L_{ZPP}	m	1					0,2	0,5	1	1				1	1	0,5
	5	Length of conduit EV-A	$L_{EZ\text{-}S}$	m	1					1			0,2	0,5	1	2	2	0,2	0,5
	6	Weight moved	$m_{eł}$	kg	20					20			20				2	50	20
Preset parameters	1	Delay time (ADOT)	COZ	s	0,26	0,45	0,21	0,35	0,23	0,35	0,35	0,35	0,31	0,33	0,35	0,40	0,41	0,05	0,12
	2	Mean velocity	$V_{śr}$	m/s	0,62	0,36	0,82	0,47	0,72	0,46	0,46	0,46	0,52	0,50	0,46	0,40	0,40	0,42	0,51
	3	Impact velocity	V_u	m/s	0,67	0,38	0,93	0,52	0,80	0,54	0,52	0,54	0,62	0,58	0,54	0,45	0,45	0,77	0,58
	4	Maximum velocity	V_{max}	m/s	0,72	0,40	0,96	0,54	0,83	0,54	0,54	0,54	0,63	0,59	0,54	0,45	0,46	0,78	0,60
	5	Impact kinetic energy	E_K	J	5,60	1,55	7,40	2,99	6,40	3,10	2,98	3,20	4,10	3,70	3,20	2,20	0,38	15,0	3,60
	6	Air consumption per cycle	v	l	4,10	6,60	11,1	17,0	27,0	17,0	17,0	17,0	17,0	16,8	17,0	17,5	17,0	1,7	6,10

Exemplary results of computing by the Festo software programme used for simulating pneumatic circuits (Variant 9) are presented in Figure 3.

The results contained in Table 1 enabled the identification of correlations of two important parameters of the welding machine pneumatic system, i.e. assumed displacement obtainment time (ADOT) and piston rod impact kinetic energy (PRIKE). The above-named parameters were identified for positioning

1. System parameters 2. Selection of actuator 3. System 4. Simulation 5. List of elements

GSED Simulation results   Drukuj

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Diagram: location/velocity/time

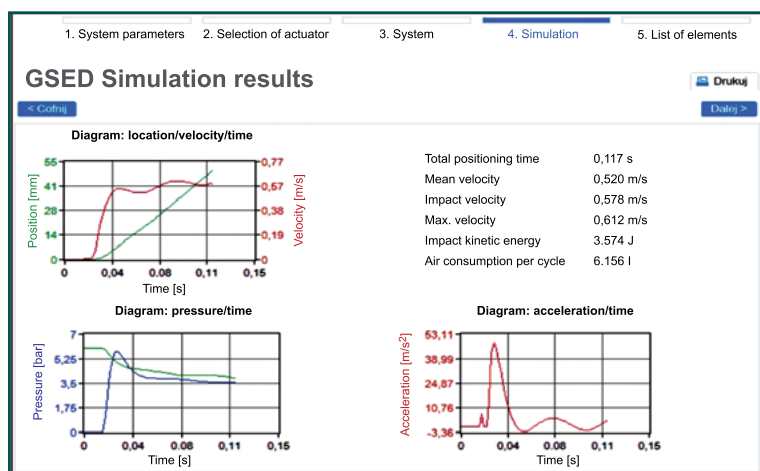| Total positioning time | 0,117 s |
Mean velocity	0,520 m/s
Impact velocity	0,578 m/s
Max. velocity	0,612 m/s
Impact kinetic energy	3.574 J
Air consumption per cycle	6.156 l

Diagram: pressure/time

Diagram: acceleration/time

Fig. 3. Exemplary results of computing by the Festo simulation software programme (Table 1, variant P9)

pneumatics in relation to process variables including electrode weight, piston rod step, pneumatic conduit length, working pressure and the diameter of the piston. The above-named correlations enabled the identification of PFS dynamics.

Figure 4 presents selected results of the simulation of the welding machine pneumatic circuit in relation to the so-called **positioning pneumatics** for 6 variants (P1–P6). The results can be discussed as follows:

1. Greater weight of the piston rod and electrodes (Fig. 4a) slightly reduced **assumed displacement obtainment time** (ADOT) – Figure 4a (A1, ADOT = 350 ms and A2, ADOT = 330 ms). However, **piston rod impact kinetic energy** (PRIKE) increased significantly – Figure 4a (A3, PRIKE = 0.5 J and A4, PRIKE = 7.7 J). In practice, the above-presented situation leads to the unfavourable oscillation and vibration of welding machine arms, where the electrode squeeze stabilisation time is extended by a time necessary for the disappearance of the above-named vibration. As regards oscillation, it is favourable to use the lowest possible weight being moved.

2. Within the range subjected to analysis (10–150 mm), the length of a piston rod step (Fig. 4b) significantly (approximately 9 times) increased the value of ADOT (B1, ADOT= 40 ms and B2, ADOT = 340 ms) and reduced PRIKE by approximately 30% (B3, PRIKE = 4.2 J and B4, PRIKE = 3.0 J). The extension of ADOT is an unfavourable and, consequently, undesirable phenomenon in the welding process. In view of the foregoing, the use of the smallest possible step of the piston rod seems favourable in relation to the above-presented applications.

3. The length of the pneumatic conduit between the APU and EV did not significantly affect ADOT and PRIKE; differences only amounting to a few percent (Fig. 4c).

4. The length of the pneumatic system conduit between the electrovalve (EV) and the actuator (A) changed both ADOT and PRIKE (see Fig. 4d). The length of the conduit L_{EZ-S} = 0.2 m was related to the minimum ADOT – see Fig. 4d (D1, ADOT = 310 ms) but to the maximum value of PRIKE– see Fig. 4d (D3, PRIKE = 4.1 J). An increase in the length of the conduit L_{EZ-S}, (from 0.2 m to 2.0 m) extended ADOT by approximately 30% – see Fig. 4d (D2, ADOT = 400 ms) and, at the same time, reduced PRIKE by approximately 50% – see Fig. 4d (D4, PRIKE = 2.2 J). As regards the reduction of ADOT, it is advisable to use the shortest possible length of the pneumatic conduit L_{EZ-S}.

5. The value of working pressure did not significantly affect ADOT and PRIKE; differences being below 10% of the mean value (Fig. 4e).

6. Because of automatic changes introduced by the Festo software programme, the analysis concerning the effect of the piston diameter on ADOT and PRIKE values could not be performed directly within a wide range of the parameter subjected to analysis. The software programme linked the diameter of the pneumatic conduits to the diameter of the piston used in the actuator subjected to analysis. In relation to a greater piston diameter, calculations automatically included a necessary (greater) conduit diameter. However, the above-presented approach adopted by Festo enabled the presentation of results in relation to a piston diameter restricted within the range of 50 mm to 125 mm (in the form of a bar chart). ADOT delay times were restricted within the range of 230 ms to 450 ms and were shorter in relation to a greater piston diameter and, consequently, greater diameters of pneumatic conduits. In turn, changes in the value of PRIKE were restricted within the range of 1.55 J to 7.4 J (see Figure 4f).

The analysis of the results presented in Figure 4 reveals significant correlations. In terms of ADOT, particular attention should be paid to the step of the piston rod – Figure 4b and the
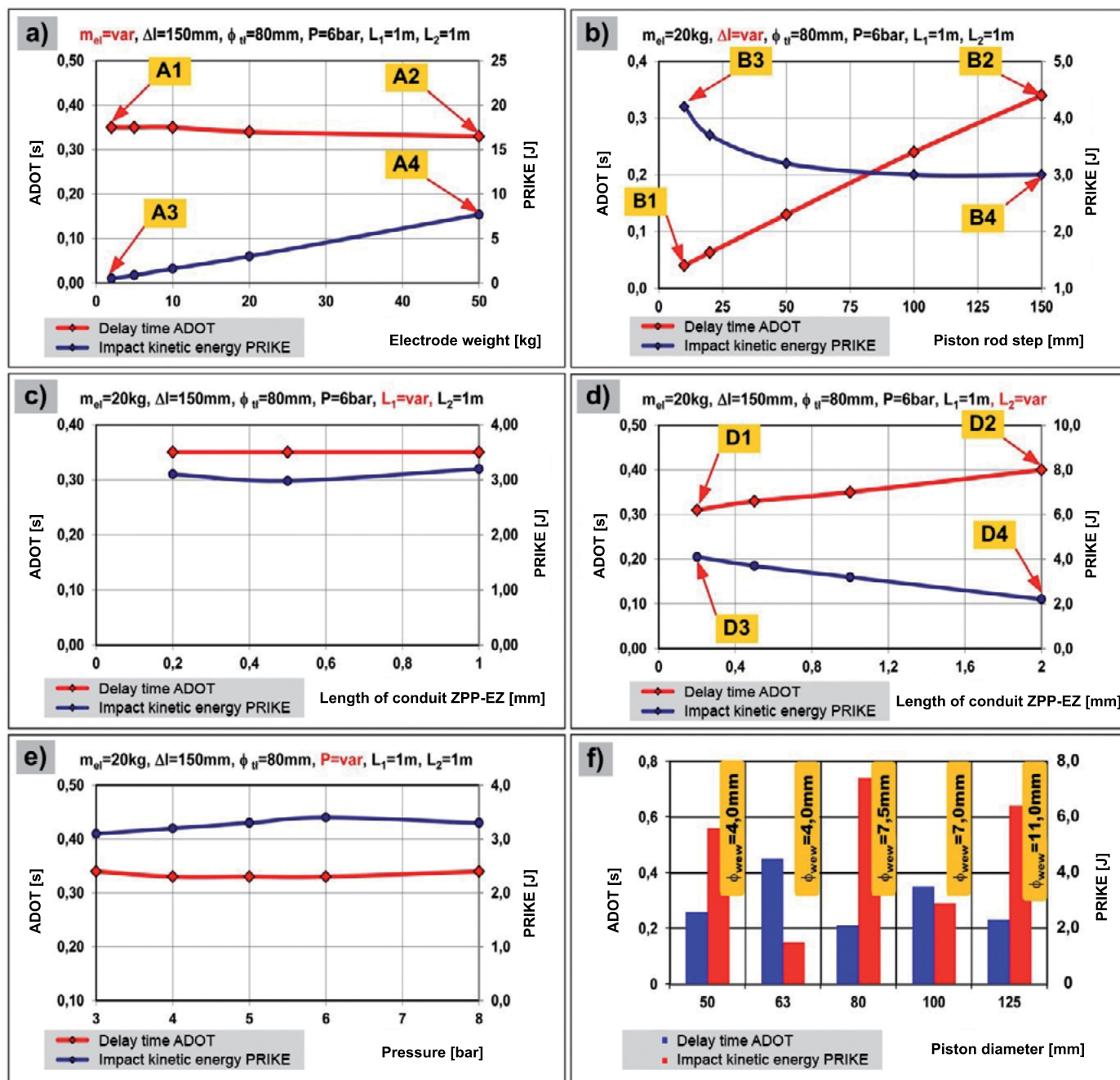
Fig. 4. Results of the simulation of the welding machine pneumatic system in the positioning mode. ADOT and PRIKE dependent on the weight of the electrode, piston rod step, length of pneumatic conduits, working pressure and the piston diameter

length of the conduit L_{EZ-S} (electrovalve – actuator) – Figure 4d. In both cases, an increase in the above-named parameters is accompanied by a very unfavourable increase in ADOT. In the first case, ADOT increases 9 times, whereas in the second case, ADOT increases by 50%.

Simulations also involved three additional parameters, primarily in relation to the analysis of ADOT, but also PRIKE, i.e. in relation to P7 – worst case, P8 – most favourable case and P9 – optimised practically applicable parameters of actuator design and operation (Table 1).

In relation to variant P7, an ADOT of 410 ms was unfavourably long, whereas EKUE = 0.38 J. In relation to variant P8, an ADOT of 50 ms was relatively short, yet an EKUE of 15 J was very high (approximately 25 times higher in comparison with P7).. In relation to variant P9, where ADOT= 120 ms and PRIKE = 3,6 J, ADOT could be favourable in terms of the PFS, yet it is also necessary to note that the above-named parameter is only related to the positioning pneumatics subjected to analysis (Fig. 2a).

The results presented in Figure 4 do not allow

for the effect of the check throttle. As a result, in the above-presented case, favourable minimum ADOT values were obtained for all of the presented variants. In practice, throttles are used to absorb the impact of electrodes when they come into contact with the material being welded (entailing the extension of ADOT). Figure 5 presents the effect of the throttle on ADOT and PRIKE in relation to various lengths of the conduit L_{EZ-S}. PRIKE is significantly reduced (by between ten and twenty times) at the expense
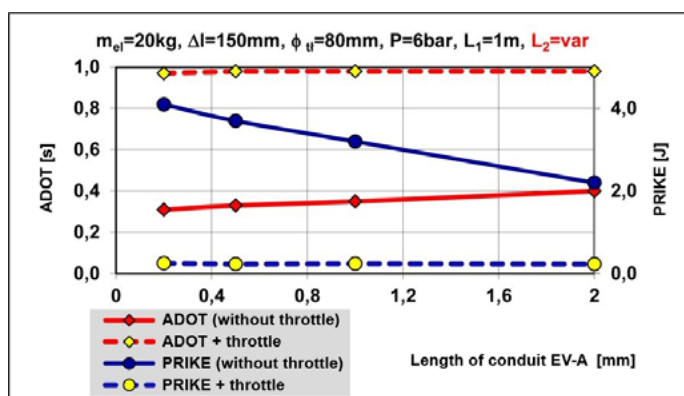
Fig. 5. Effect of the throttle on ADOT and PRIKE in relation to L_{EZ-S} (Table 1, variant P6)

of the three-fold extension of ADOT.

Experimental tests of force accretion pneumatics

The software for pneumatics systems, used in the simulations discussed in the article, only enables the performance of calculations within the first range presented in Figure 2a, i.e. in relation to the so-called **positioning pneumatics**.
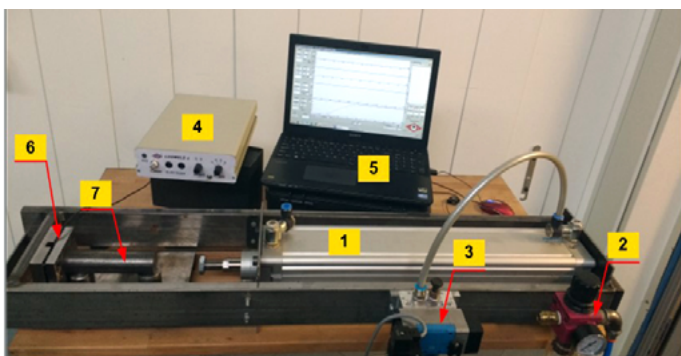

Fig. 6. Fig. 6. Testing station for force pneumatics tests (Fig. 3.2b: 1) actuator (Festo; type DNC-100-500-PPV-A), 2) reducer, 3) electrovalve (MN1H-5/2-D-2-FR-S-C), 4) device for force measurements (LogWeld), 5) PC, 6) force sensor, 7) piston rod step stoppers

In terms of the welding cycle, it is important to delay time and stabilise force when electrodes are pressed against elements being welded, i.e. in relation to the so-called **force accretion pneumatics**. Because of the unavailability of software enabling the above-named simulations (Fig. 2b), experimental tests involved various piston rod step values and various values of working pressure. The experimental tests involved an actuator provided with the PFS and manufactured by the Festo company (type DNC-100-500-PPV-A) – see Fig. 6.

The testing station parameters related to the PFS were the following: piston diameter = 100 mm, maximum piston rod step = 200 mm and pneumatic conduit internal diameter = 7 mm.

The experimental tests aimed at the verification of **electrode squeeze stabilisation time** (CUD) in relation to two process variables, i.e. a piston rod step and working pressure. By adjusting various distances between the electrodes it was possible to obtain various piston rod step values (actuator chamber height). Various working pressure values were adjusted on the reducer. The preset parameters and results obtained in the tests are presented in Table 2 and Figure 7 respectively.

The **electrode squeeze stabilisation time** (ESST) resulting from the stabilisation of electrode (squeeze) force, in relation to force accretion pneumatics and the typical piston rod step length amounting to 200 mm (depending on working pressure) was restricted within the range of 560 ms to 900 ms (Fig. 7). The above-named time was excessively long, thus precluding the modelling of squeeze force value during the flow of welding current, e.g. for t_{PP} = 200 ms, typical of two-sided overlap (1 mm + 1 mm) welding cycles [6]. For this reason, the value of squeeze force during the entire welding cycle must be unfavourably high in order to ensure that the welding machines follow the welded material undergoing plasticisation. The PFS-related results, particularly concerning the force accretion pneumatics and positioning pneumatics,

indicate significant delays (mechanical inertia) in such a control method. The foregoing constitutes a limitation to electrode squeeze force control, particularly during the flow of current.
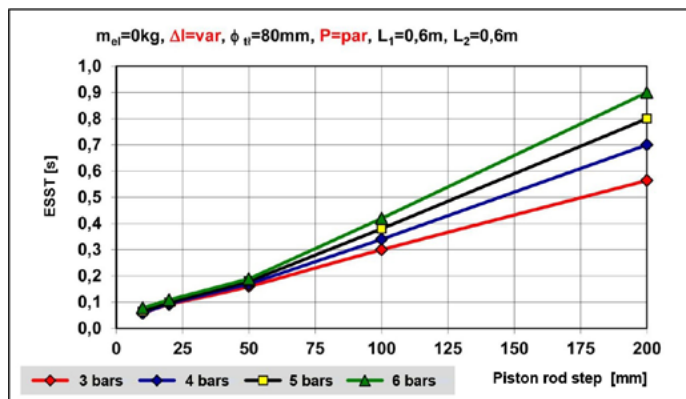

Fig. 7. ESST and force accretion pneumatics
(Table 2 – experiment E1)

Figure 8 presents ESST in relation to various piston rod step values. For instance, in relation to a piston rod step of 20 mm, ESST ≅ 100 ms. In terms of practical and economic point of view, the above-presented solution is not commonly used, yet it is practically viable, constituting a possible PFS optimisation direction, involving the use of actuators characterised by a relatively small piston rod step and enabling the improvement of PFS dynamics.

Figure 8 presents the variability of ESST in relation to actuator working pressure. In comparison with positioning pneumatics (Fig. 4e), where actuator working pressure did not affect ADOT, in relation to force accretion pneumatics, the above-named correlation is very important. In relation to a change in pressure restricted within the range of 3.0 bars to 6.0 bars, ESST increases by 50% (Fig. 8b, B1 and B2) for a piston rod step of 200 mm. Because of the fact that ESST depends on working pressure, in relation to welding characterised by higher electrode squeeze force, ESST will be unfavourably longer.

Summary

In relation to the PFS, it is necessary to differentiate and consider two phases affecting the time necessary to stabilise a preset value of electrode squeeze force, resulting from

Table 2. Preset parameters and simulation results in relation to PFS (force accretion pneumatics)

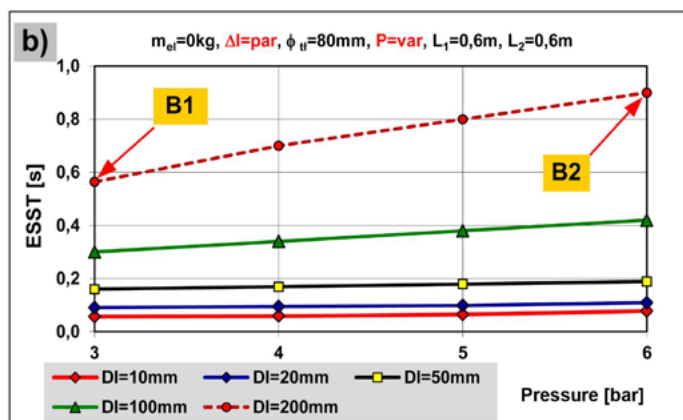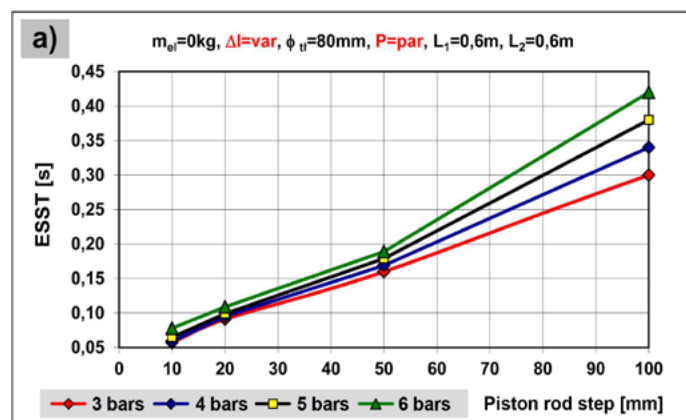|	No	Variant			E1				
Initial parameters		Two-sided operation actuator	type		DNC-100-(10-200)-PPV-A				
		Connection (internal diameter)	mm		7,0				
		Direction of movement (pushing out)	Y/N		Y				
		Check throttle	Y/N		N				
		Additional friction	Y/N		N				
		Shock absorber	Y/N		N				
	1	Piston diameter	φ_{tl}	mm	100				
	2	Actuator piston rod step	ΔL_{tl}	mm	150				
	3	Working pressure	P	bar	6				
	4	Length of conduit APU-EV	L_{ZPP}	m	1				
	5	Length of conduit EV-A	L_{EZ-S}	m	1				
	6	Weight moved	m_{el}	kg	0 (only piston rod)				
Preset parameters	1	Stabilisation time (3,0 bars)	CUD	s	0,057	0,091	0,160	0,300	0,564
	2	Stabilisation time (4,0 bars)			0,059	0,095	0,169	0,340	0,700
	3	Stabilisation time (5,0 bars)			0,065	0,099	0,179	0,380	0,800
	4	Stabilisation time (6,0 bars)			0,078	0,109	0,189	0,420	0,900

Fig. 8. Electrode squeeze stabilisation time (ESST) in relation to: a) piston rod step, b) actuator working pressure in relation to force accretion pneumatics (variant E1, experiment)

so-called **positioning pneumatics and force accretion pneumatics**. In the first case, in relation to positioning pneumatics and typical solutions, the time necessary to obtain assumed displacement (ADOT) amounts to 410 ms (variant P7). In the second case, i.e. in relation to so-called force accretion pneumatics, typical time necessary to stabilise the preset electrode squeeze force (ESST) amounts to 420 ms (variant E1: $P = 6$ b, $\Delta L_{tł} = 100$ mm). As a result, the delay in ESST amounts to more than 400 ms, being excessively long in order to control electrode squeeze force during welding (particularly during the flow of current).

In terms of force modulation possibility during the flow of welding current, the crucial factor is ESST. In typical PFS-related solutions, ESST is restricted within the range of 50 ms to 410 ms (variants P7–P9). It is possible to optimise the process by minimising a piston rod step, yet the actual minimum obtainable ESST amounts to 100 ms.

The above-presented solution proved feasible. Industrial practice has seen solutions where setting movements were performed using a servomotor, whereas a working movement (during the flow of current) was performed using a pneumatic actuator having a small step (of approximately 20–30 mm) [7].

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