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FRICTION COEFFICIENT ESTIMATION DURING FRICTION STIR WELDING WITH THE SINGLE SHOULDERED WELDING TOOL

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Abstract: *Friction stir welding utilizes friction forces on the contact of the welding tool and workpieces with the goal of heating and softening workpiece material before stirring and mixing it into the weld. The process of stirring, mixing and welding is quite complex: material of workpieces in the welding zone is drastically deformed/reformed, heated, translated, rotated and softened, and finally, deposed behind the welding tool to cool, plasticize, and recrystallize as a weld. In such conditions, it is difficult to recognize friction conditions, contact surface(s), and loads on the contact. There are no fully operational analytical models for estimation of the friction coefficient during friction stir welding. This paper is giving an overview on a friction coefficient research and presents experimental results from performed friction stir welding of aluminium alloy 2024 T351. Experimental results are used as input for the modified analytical model for estimation of friction coefficient in friction stir welding.*

Keywords: *Friction Stir Welding, Friction Coefficient, Heat Generation.*

1. INTRODUCTION

Friction is one of the most important parameters for successful friction stir welding (FSW) process – this is a sentence that no researcher of FSW will try to disapprove. Such influence to the process itself has motivated the inventor of FSW to use "friction" in the name of the process.

However, friction in FSW has been never presented and explained as a parameter that can be manipulated or adjusted in some manner to improve the FSW process itself. For example, when greater friction in FSW is needed, welding tool (figure 1, b) must have threads, facets, keys etc., when less heating is needed, welding tool has to travel faster what will result in shorter contact between welding tool and some particles of workpieces what results with less friction on contact.

Nowadays experiences in FSW usage recognize technological parameters of the process (travel rate, rotation speed, duration of welding etc.) and geometry of the welding tool (shape, dimensions etc.) as best parameters for successful management of quality of FSW. Principle of "trial and error" and parameters management were successful for FSW and it has been significantly improved. It is known that better the mathematical model explaining the physical process is, the more applicable the process becomes. "Try and error" principle uses no mathematical model for improvement but always gives results and improvements. Its main disadvantage is high resource / time consumption.

In a certain way, friction is very important for almost any aspect of the FSW, but its ambiguity and complex dependencies with the other parameters of FSW make it difficult to use for management of the process. That is the main reason why friction is the least investigated physical process of FSW.

2. SINGLE SHOULDERED FSW

The first application of the FSW was with the welding tool having one probe and one shoulder (figure 1, a). Such construction requires an anvil in order to make weld creation possible. There are newer constructions of the welding tool with two shoulders and/or more than one probe.

Application and technology of FSW with a welding tool with one shoulder is in detail explained in the literature [1-3].

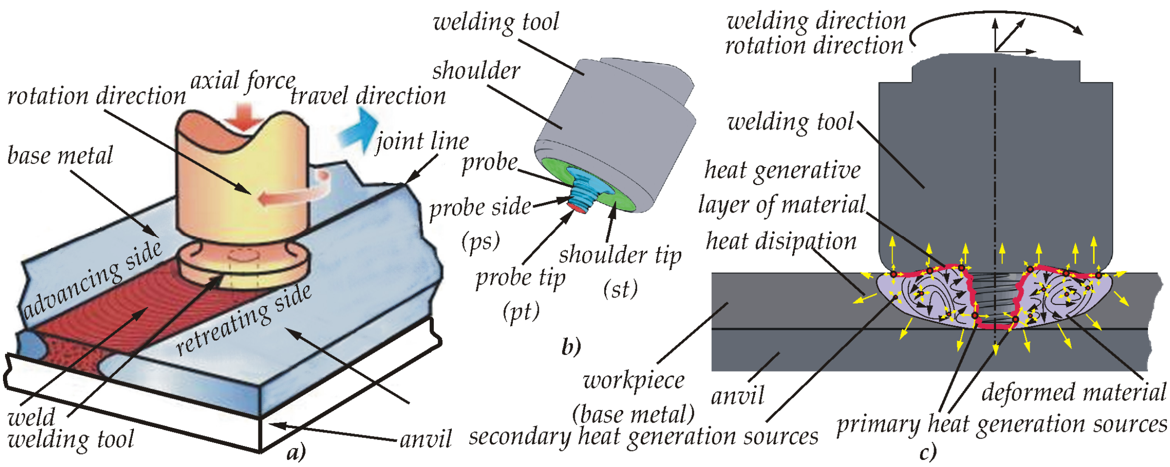

Figure 1. Friction stir welding
a – principle of FSW, b – welding tool and its active surfaces, c – heat generation and transport [1]

3. ESTIMATION OF THE FRICTION COEFICIENT DURING SINGLE SHOULDERED FSW

The newest improvement and development of the model for estimation of the friction coefficient in FSW is 4 years old Kumar's model [4] and relies on the estimation of the momentum of friction which is afterwards, with adequate mathematical model, transformed into the friction coefficient. There are several difficulties in application of such a model:

1. measuring the momentum of friction requires specific and limitedly applicable measuring/working configuration [1],
2. friction coefficient estimated during FSW by Kumar is a median value for all contacts surfaces – active surfaces of welding tool and workpieces (figure 1, b).

3.1 Specific time moments of the FSW

Mijajlovic *et al* [Ref. 5, Figure 4] gives a scheme of welding tools engagement during FSW. It is important to define specific moments of time during welding.

Probe tip is active surface that is fully engaged in the FSW process from the beginning of the plunging phase (t_0) until the end of the second dwelling phase (t_4). At the beginning of the plunging phase probe tip slides over the top surface of welding plates and there is no significant plunging into material of the welding plates. Material of the welding plates is still capable to resist influence of the contact pressure on contact between probe tip and welding plates. Plunging force is rising as the plunging phase on goes and eventually plunging force will be intensive enough to produce contact pressure that will overcome resistance of the material and welding tool will penetrate into the material (in the moment of time $t_{ps'}$). This intensive plunging will enable contact between probe side and material of welding plates and increase of engagement of the probe side – it will reach some value until the end of the plunging phase (t_1). It will be kept steady or slightly will decrease during first dwelling phase (from t_1 to t_2) and it will increase again during welding phase (after t_2). When welding tool stabilizes (in welding phase, when it reaches constant speed, at the moment of $t_{ps''}$) probe side will reach maximal engagement.

It will be kept relatively steady until the end of the second dwelling phase (t_4) and after will slightly decrease until the minimal value – when welding tool gets pulled out, at the end of the pulling out phase (t_5). Shoulder tip will involve in FSW process when firstly touches (t_{st}) the material of welding plates that was pushed upwards while plunging phase lasted. Engagement of the active surface will increase to the maximum when plunging phase ends (t_1), it will keep steady value until the end of the second dwelling phase (t_4) when it will drop to minimum [5].

3.2 Contact over the probe tip

The probe tip (pt) of the welding tool is rather curved than flat due to the better distribution of the contact pressure [1]. Without concern on the topology of the welding tool's probe tip, when the probe tip is pressing the workpiece while loaded with the axial force $F_z(t)$ and torque $T_{pt}(t)$, equilibrium of the force and the torque (no relative movement of the welding tool and workpieces, nor rotation of the welding tool) is reached if:

$$T_{pt}(t) \leq \frac{\mu_{pt}(t) F_z(t)[d(t) - d_0(t)]}{3} = T_1(t) \qquad (1)$$

where: $\mu(t)=\mu_{pt}(t)$ – total coefficient of friction - coefficient of friction at pt, $d(t)$ – diameter of the probe, $d_0(t)$ – diameter of the technological hole in the workpieces, t - time.

In such condition, the momentum of friction $M_{fr}(t)$ is:

$$M_{fr}(t)=\frac{\mu(t)F_z(t)[d(t)-d_0(t)]}{3} \quad (2)$$

and therefore, friction coefficient at pt is:

$$\mu(t)=\mu_{pt}(t)=\frac{3M_{fr}(t)}{F_z(t)[d(t)-d_0(t)]},\ t_0\le t<t_{ps'} \quad (2)$$

3.3 Contact over the probe tip and the probe side

The probe side (ps) of the welding tool is cylindrical or coned surface with or without thread [1]. The thread is of great significance for the welding process, however, it makes great difficulties for the analysis of friction and it will be neglected in analysis.

If only the probe side is in contact with the workpieces, equilibrium between the forces, represented as the contact pressure at the probe side $p_{ps}(t)$, and the torque $T_{ps}(t)$ is:

$$T_{ps}(t)\le\frac{\mu_{ps}(t)d(t)^2h(t)p_{ps}(t)\pi}{2}=T_2(t) \quad (3)$$

where: $\mu(t)=\mu_{ps}(t)$ – total coefficient of friction – coefficient of friction at ps, $h(t)$ – height of the probe (side) plunged into the workpieces.

In such condition, the momentum of friction $M_{fr}(t)$ is:

$$M_{fr}(t)=\frac{\mu(t)d(t)^2h(t)p_{ps}(t)\pi}{2} \quad (4)$$

and therefore, friction coefficient at pt is:

$$\mu(t)\approx\mu_{ps}(t)=\frac{2M_{fr}(t)}{d(t)^2h(t)p_{ps}(t)\pi},\ t_4\le t<t_5 \quad (5)$$

When the probe tip and the probe side are simultaneously involved in the contact, equilibrium of loads and the torque at the probe tip and the probe side $T_{pt+ps}(t)$ can be expressed as:

$$T_{pt+ps}(t)\le T_1(t)+\frac{\mu(t)d(t)^2h(t)p_{ps}(t)\pi}{2} \quad (6)$$

In such condition, the momentum of friction $M_{fr}(t)$ is:

$$M_{fr}(t)=T_1(t)+T_2(t) \quad (7)$$

Assuming that the friction coefficients at the probe side and the probe tip are the same (only as a value):

$$\mu(t)=\mu_{ps}(t)=\mu_{pt}(t),\ t_{ps'}\le t<t_{st} \quad (8)$$

transforming the equation (7), friction coefficient becomes:

$$\mu(t)\approx\frac{6M_{fr}(t)}{2F_z(t)[d(t)-d_0(t)]+3d(t)^2h(t)p_{ps}(t)\pi}, \quad (9)$$
$$t_{ps'}\le t<t_{st}$$

3.4 Contact over the probe tip, the probe side and the shoulder tip

The shoulder tip (st) of the welding tool is cylindrical or coned surface with the greatest area [1, 2]. Shoulder tip is the last active surface of the welding tool involving into the welding process.

If only the shoulder tip is in contact with the workpieces, equilibrium between the loads and the torque at the shoulder tip $T_{st}(t)$ is:

$$T_{st}(t)\le\frac{\mu_{st}(t)F_z(t)[D(t)-d_{\max}]}{3}=T_3(t) \quad (10)$$

where: $\mu(t)=\mu_{st}(t)$ – total coefficient of friction – coefficient of friction at st, $D(t)$ – diameter of the st, $d_{\max}$ – maximal diameter of the probe.

However, shoulder tip is never involved in the welding process as the only active surfaces – shoulder tip is always involved in welding simultaneously with the probe tip and the probe side and in such case, equilibrium of loads and the total torque $T_{tot}(t)$ is:

$$T_{tot}(t)\le T_1(t)+T_2(t)+T_3(t) \quad (11)$$

In such condition, the momentum of friction $M_{fr}(t)$ is:

$$M_{fr}(t)=T_1(t)+T_2(t)+T_3(t) \quad (12)$$

Assuming that the friction coefficients at the probe side, the probe tip and the shoulder tip are the same (only as a value):

$$\mu(t)=\mu_{ps}(t)=\mu_{pt}(t)=\mu_{st}(t),\ t_{st}\le t<t_4 \quad (13)$$

transforming the equation (12), friction coefficient is:

$$\mu(t)\approx\frac{6M_{fr}(t)}{2F_z(t)A+3d(t)^2h(t)p_{ps}(t)\pi+2F_z(t)B}, \quad (14)$$
$$A=d(t)-d_0(t), B=D(t)-d_{\max},\ t_{ps'}\le t<t_{st}$$

3.5 Contact pressure at the probe side

Contact pressure at the probe side is mostly delivered by the welding force $F_x(t)$. Since welding force is active only during the welding phase

($t_2 \le t < t_3$), contact pressure at the probe side can be evaluated as:

$$p_{ps}(t)\begin{cases}\approx \dfrac{F_x(t)}{d \cdot h},\ t_2 < t < t_3 \\ \approx 0,\ t \le t_2,\ t \ge t_3\end{cases}, \quad (15)$$

where: d – median diameter of the probe, h – total height of the probe.

4. EXPERIMENTAL INVESTIGATION OF THE FRICTION COEFICIENT IN FSW

Experimental researches and investigation of the friction coefficient in FSW were performed on plates made of aluminium alloy 2024 T351 [1-8]. Welding was performed with the two types of welding tool: a) "theoretical" welding tool (cylindrical welding tool with non-threaded probe) and b) welding tool with the cone, threaded probe (Figure 2).

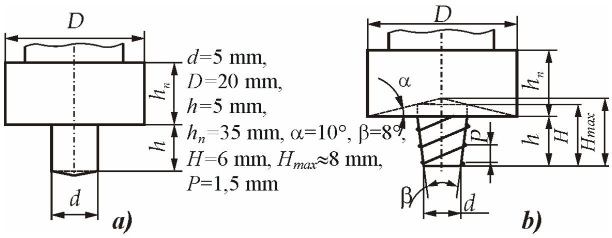

Figure 2. Welding tool

Welding was performed with the rotation speed of n=265, 600 and 910 rpm and the travel rate of v_x=1.5 to 2 mm/s. Initial plunging of the welding tool into the workpieces was performed into full material (diameter of the technological hole in workpieces d_0= 0 mm) and into technological holes with diameter of d_0= 2, 3.2 and 5 mm.

Experimental weldings were performed at the universal lathe with horizontal work axis in two measuring configurations to ensure the validity of the obtained results and consistency of the proposed measuring procedures [1].

5. THE RESULTS

First set of experiments was performed with the "theoretical" welding tool (Figure 2, a), changing the rotation speed from lower to higher and starting with the maximal dimension of the technological hole and decreasing it to the 0 – from minimal plunging force to the maximal. Measured values of torque and forces were used for calculating values of the friction coefficient (Figures 3 and 4).

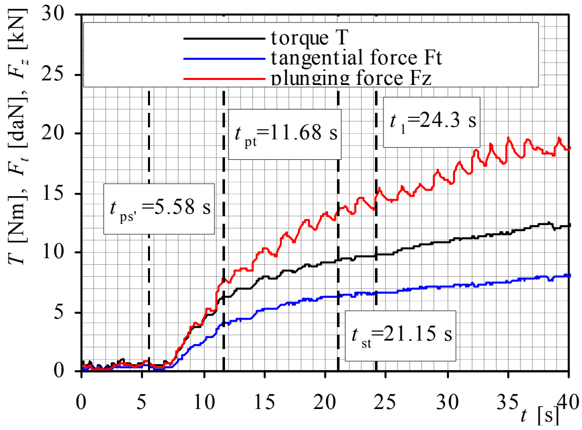

Figure 3. Diagram of measured loads: "theoretical" welding tool, n=265 rpm, d_0=5 mm

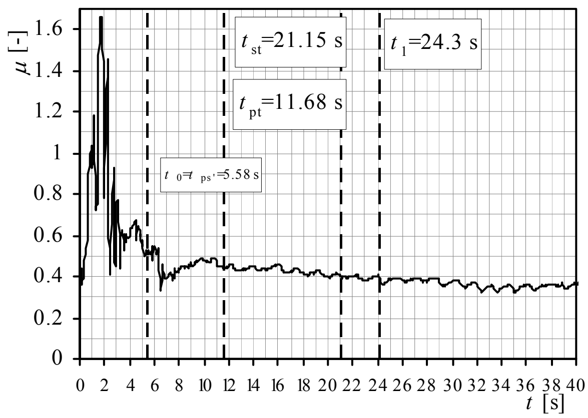

Figure 4. Friction coefficient: "theoretical" welding tool, n=265 rpm, d_0=5 mm

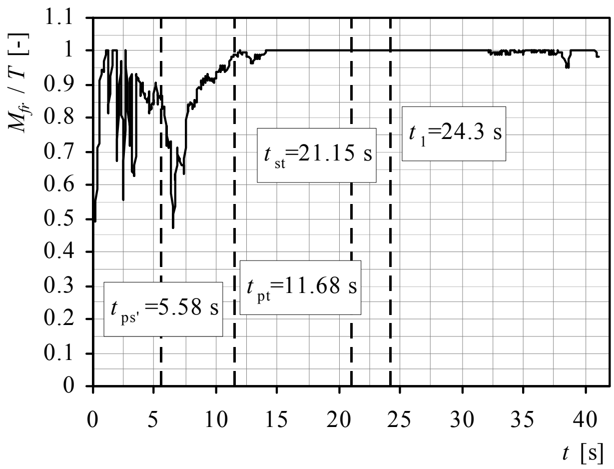

Figure 5. Ratio of the momentum of friction and the torque: "theoretical" welding tool, n=265 rpm, d_0=5 mm

Figure 5 is giving a ratio of the momentum of friction and the torque (M_{fr}/T) applied to the welding tool.

Second experiment with the "theoretical" welding tool was performed with the n=265 rpm, d_0=3.2 mm (technological hole is smaller than the diameter of the probe) and probe has cracked for 2 applied welding tools. Further experiments with the "theoretical" welding tool were cancelled.

Second set of experiments was performed with the conical welding tool - CWT (Figure 2, b), changing the rotation speed from lower to higher and starting with the maximal dimension of the technological hole and decreasing it to the 0 – from minimal plunging force to the maximal.

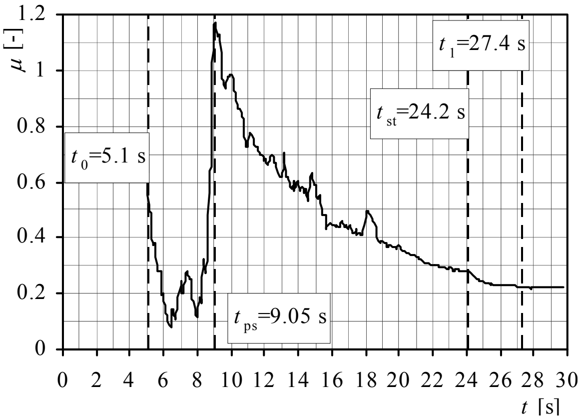

Figure 6. Friction coefficient: CWT, n=265 rpm, d_0=5 mm

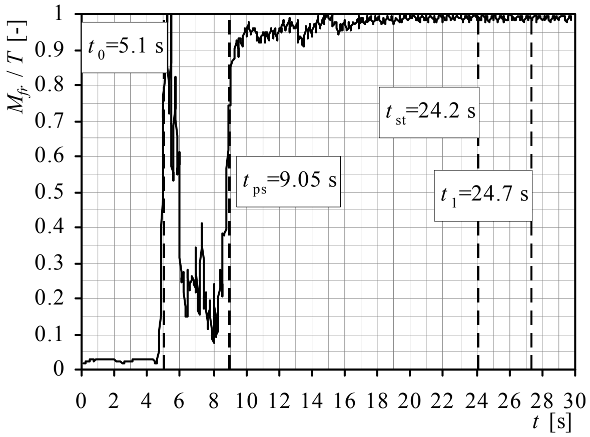

Figure 7. Ratio M_{fr}/T: CWT, n=265 rpm, d_0=5 mm

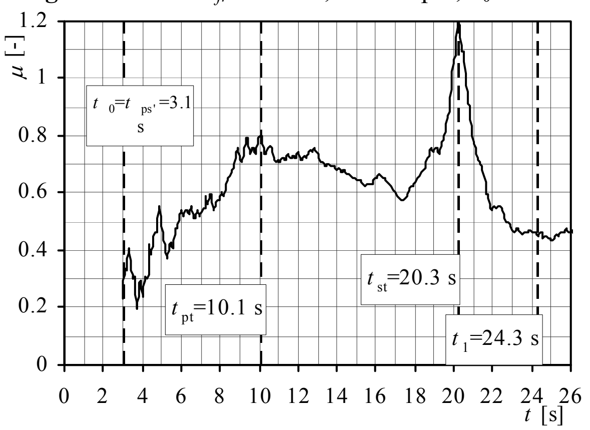

Figure 8. Friction coefficient: CWT, n=265 rpm, d_0=3.2 mm

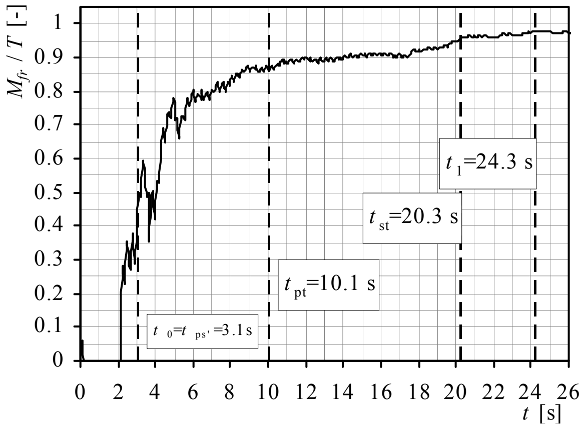

Figure 9. Ratio of the momentum of friction and the torque: CWT, n=265 rpm, d_0=3.2 mm

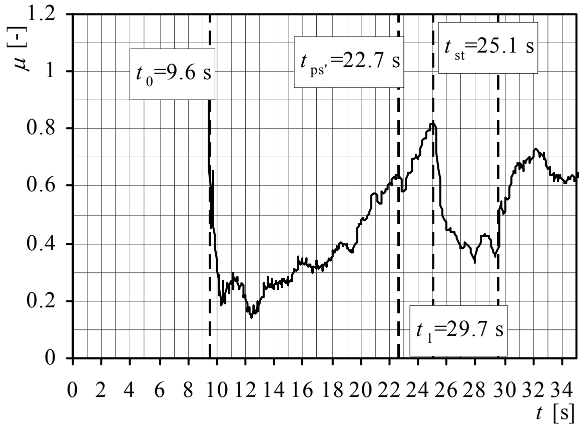

Figure 10. Friction coefficient: CWT, n=265 rpm, d_0=2 mm

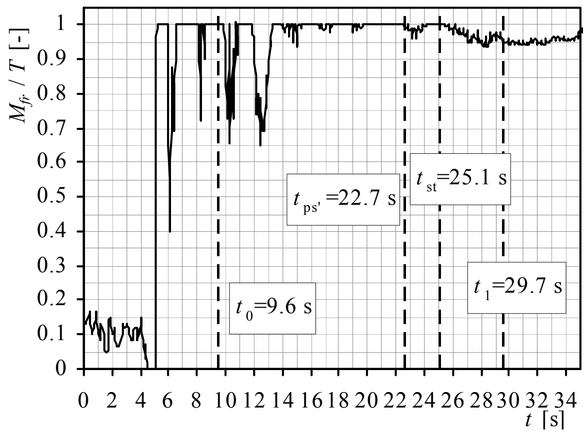

Figure 11. Ratio M_{fr}/T: CWT, n=265 rpm, d_0=2 mm

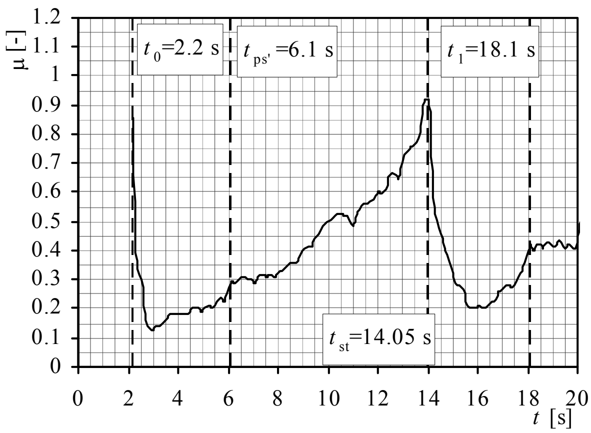

Figure 12. Friction coefficient: CWT, n=265 rpm, d_0=0 mm

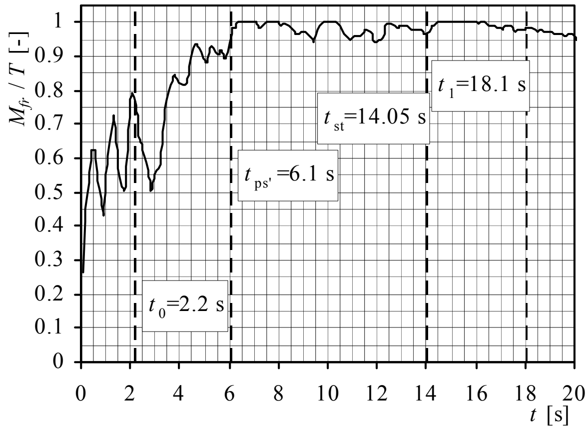

Figure 13. Ratio M_{fr}/T: CWT, n=265 rpm, d_0=0 mm

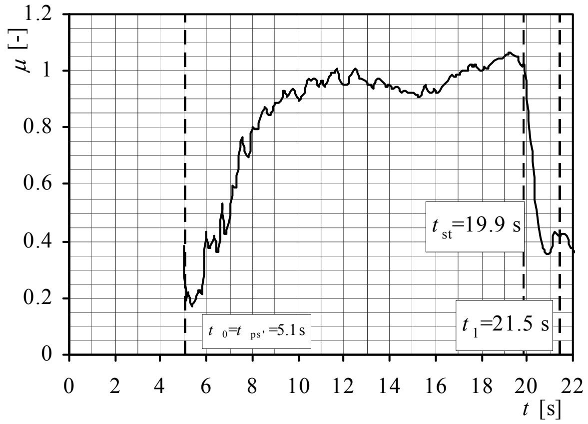

Figure 14. Friction coefficient: CWT, n=600 rpm, d_0=5 mm

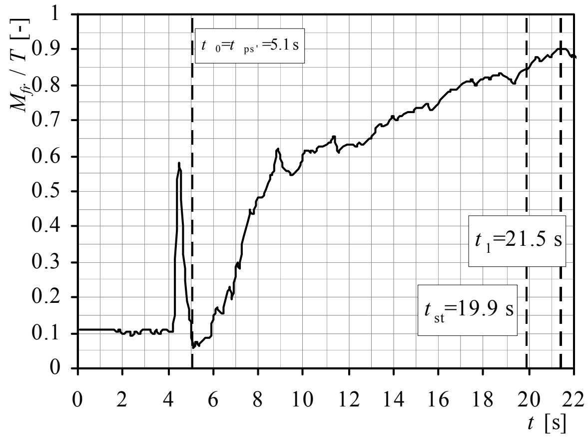

Figure 15. Ratio M_{fr}/T: CWT, n=600 rpm, d_0=5 mm

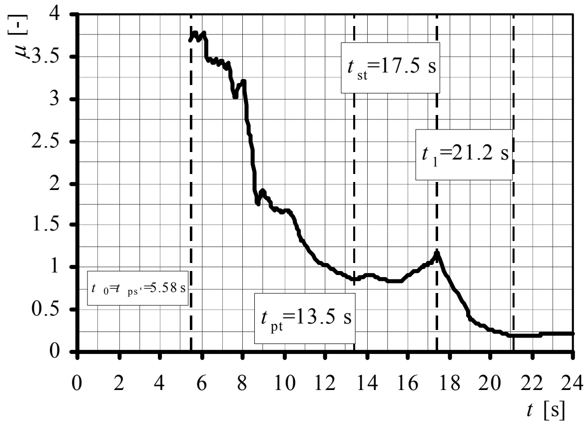

Figure 16. Friction coefficient: CWT, n=600 rpm, d_0=3.2 mm

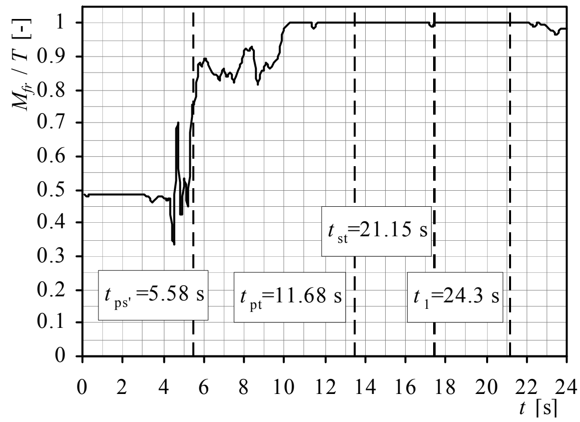

Figure 17. Ratio M_{fr}/T: CWT, n=600 rpm, d_0=3.2 mm

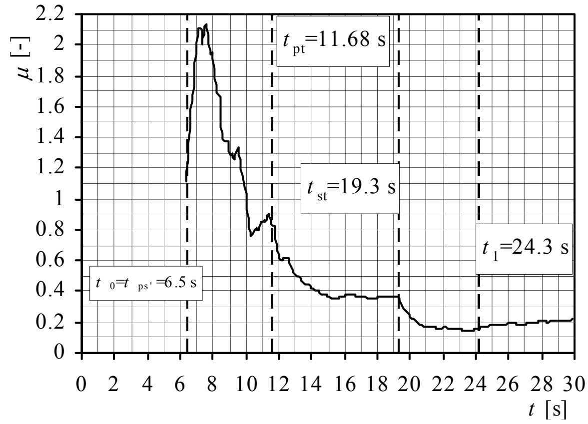

Figure 18. Friction coefficient: CWT, n=600 rpm, d_0=2 mm

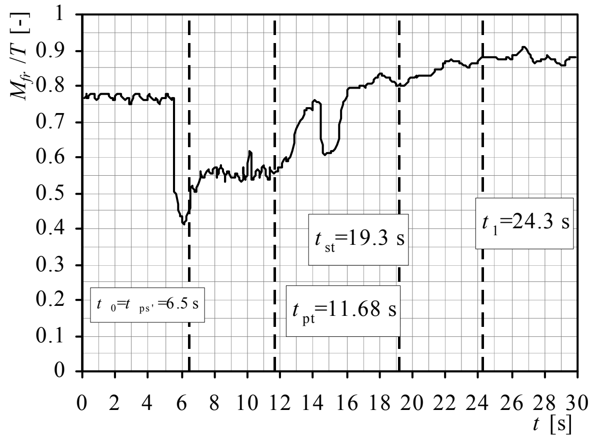

Figure 19. Ratio M_{fr}/T: CWT, n=600 rpm, d_0=2 mm

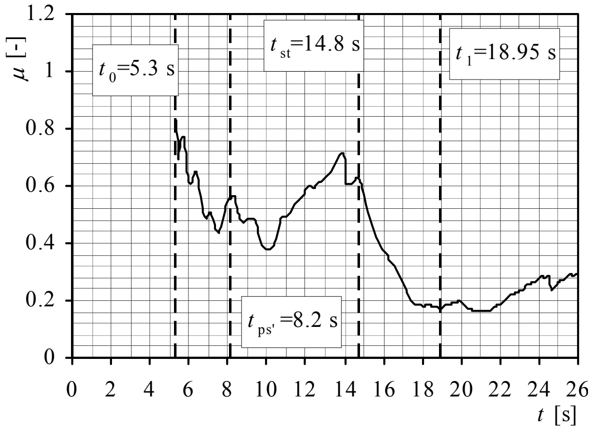

Figure 20. Friction coefficient: CWT, n=600 rpm, d_0=0 mm

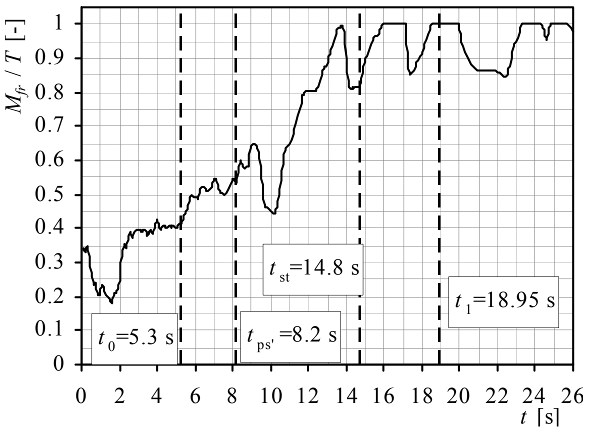

Figure 21. Ratio M_{fr}/T: CWT, n=600 rpm, d_0=0 mm

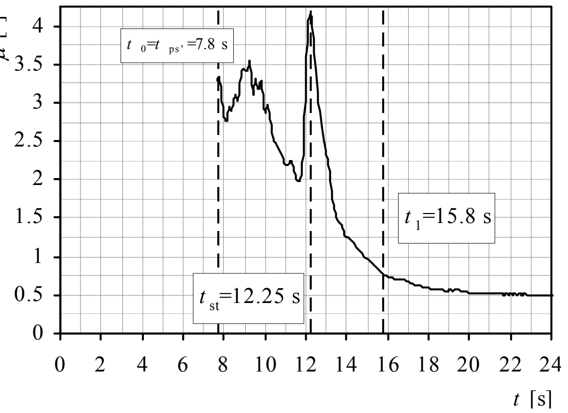

Figure 22. Friction coefficient: CWT, n=910 rpm, d_0=5 mm

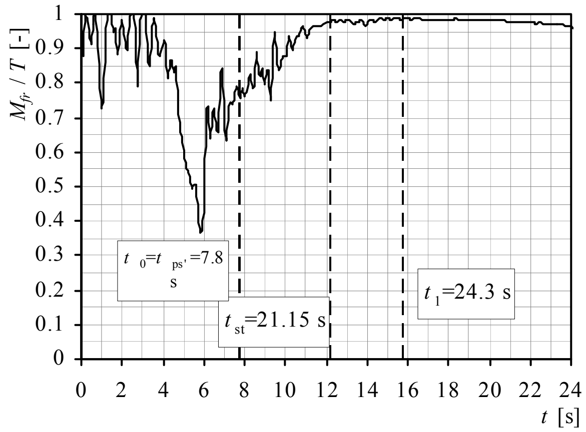

Figure 23. Ratio M_{fr}/T: CWT, n=910 rpm, d_0=5 mm

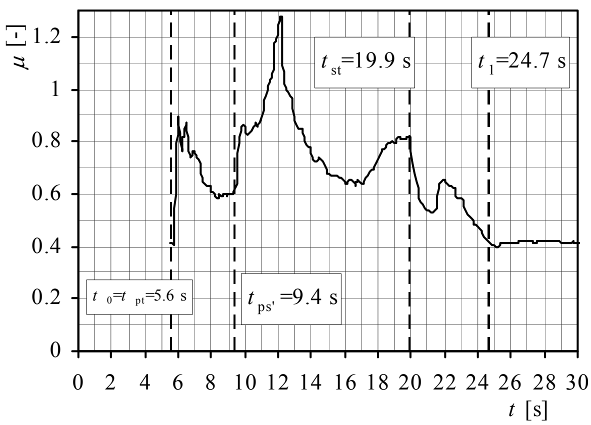

Figure 24. Friction coefficient: CWT, n=910 rpm, d_0=3.2 mm

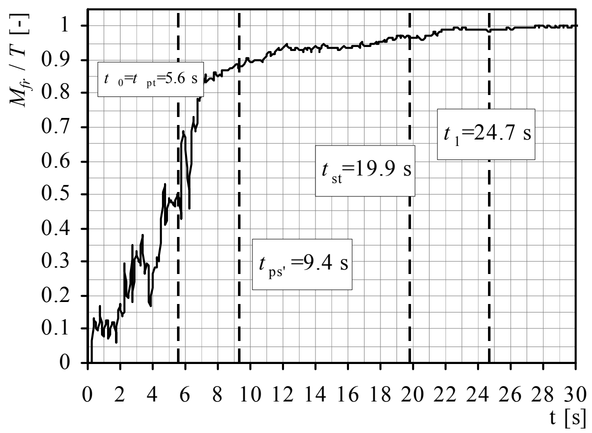

Figure 25. Ratio M_{fr}/T: CWT, n=910 rpm, d_0=3.2 mm

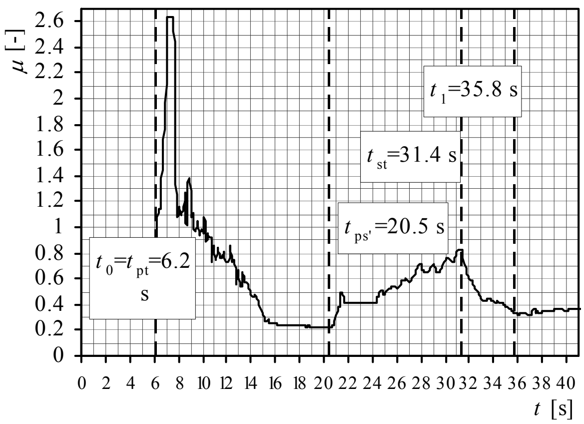

Figure 26. Friction coefficient: CWT, n=910 rpm, d_0=2 mm

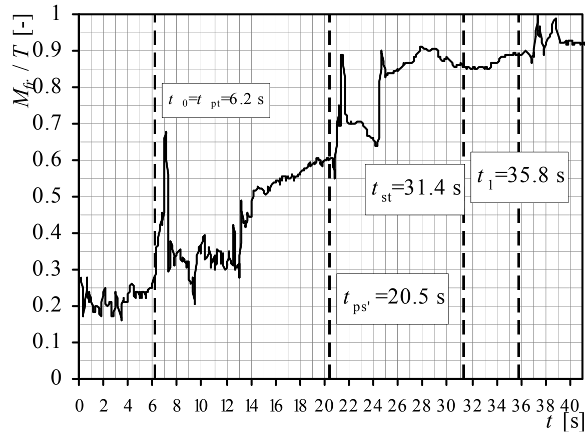

Figure 27. Ratio M_{fr}/T: CWT, n=910 rpm, d_0=2 mm

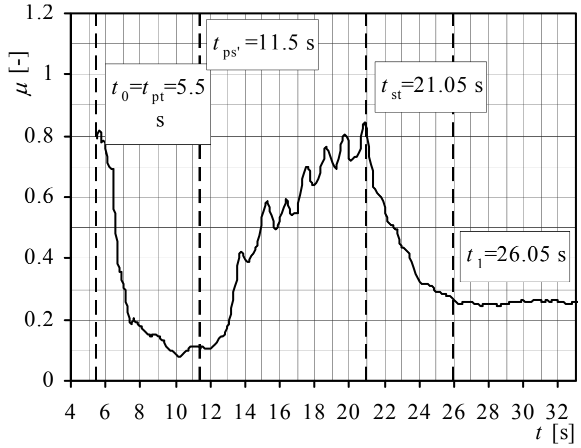

Figure 28. Friction coefficient: CWT, n=910 rpm, d_0=0 mm

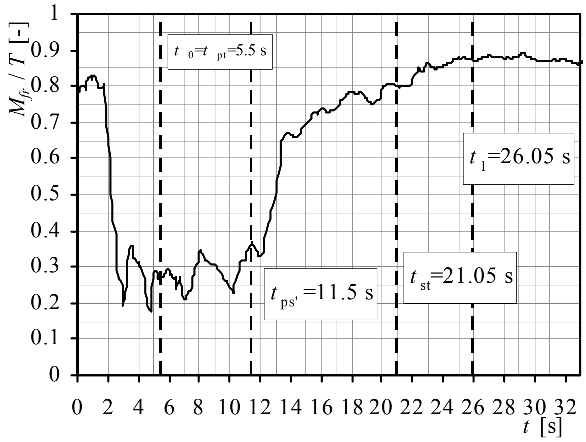

Figure 29. Ratio M_{fr}/T: CWT, n=910 rpm, d_0=0 mm

Measured values of torque and forces were used for calculating values of the friction coefficient and ratio of momentum of friction and the torque (Figure 6 to Figure 29).

6. DISCUSSION AND CONCLUSIONS

The first set of experiments with the “theoretical” welding tool has shown that welding tool without thread at the probe can not be used for welding of 2024 T351 alloy. Plunging of the welding tool into workpieces was possible only when diameter of the welding tool was the same as the diameter of the technological hole in the workpieces. During such experiment, appeared that friction coefficient, after initial stabilization, reaches almost constant value between 0.3 to 0.4 what is prescribed value for the FSW of AL 2024 T351 and the “theoretical” welding tool [1]. The ratio of momentum of friction and the applied torque has a value of 1 – there is no (or has minimal) deformation in the contact.

The conclusion was that the plunging of the “theoretical” welding tool in welding plates was impossible when small or no technological hole present what implies that welding couldn't even get started.

The second set of experiments was conducted with the coned, threaded welding tool with the prescribed technological parameters. Welding was possible, however, only welding with n=910 rpm has given the qualitative welds. During all weldings, trends and values of the friction coefficient were identical. Friction coefficient was rising from the beginning of the plunging until the moment of time when the shoulder tip involves in the welding. Common values of maximal friction coefficient reach about 1 but it is not uncommon to reach values of 2-5 (what is in correspondence with the literature-present values [1-4] but it is possible to have peak values as imperfections of the proposed method for estimation). From that moment, friction coefficient drops down and at the beginning of the first dwelling phase reaches value of about 0.2 to 0.7. However, at the end of the dwelling phase, friction coefficient in all experiments reaches the values of 0.2 to 0.5.

The ratio between the momentum of friction and the applied torque has the same trend for all experiments. It rises up to the maximal value of 1 and varies from 0.8 to 1, during every conducted experiment. The results are in agreement with the existing results [2, 3, 4].

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